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Analysing the design evolution of late 18th century *Prellzungenmechaniken*

An experiment-based multibody approach
applied to early piano actions

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Abstract

The modern piano is known as a standardised instrument, built almost exactly the same way all over the world. However, during the 18th and part of the 19th century, when some major pieces of today's repertoire were written, important differences in the design existed according to the geographic origin of the instruments. One of the earliest national schools of piano making, equipped with the so-called *Prellzungenmechaniken*, appeared in the second half of the 18th century in the regions of Vienna and southern Germany. The *Prellzungenmechanik* is a mechanism (or piano action) which transmits the motion of the finger from the key to the string. Roughly speaking, *Prellzungenmechaniken* can be divided in two types of schools. The first type, called 'German' actions, are attributed to Johann Andreas Stein, while the later 'Viennese' actions, a modification of the German actions, were devised by Anton Walter. The fact that the two types co-existed is a good indication that both designs had their own advantages.

This thesis focusses on the study of these two actions which were historically speaking of the greatest importance. One of the most significant differences between the two actions lies in a part called the 'pawl'. The pawl is responsible for the propulsion of the hammer and has a slightly different shape in the German and Viennese *Prellzungenmechanik*. This work compares both designs and attempts to explain why Walter changed Stein's traditional pawl disposition. To this end, a piano action with interchangeable pawls has been conceived.

An important fact to consider when studying piano actions is that these mechanisms are highly dynamic systems for which a quasi-static observation cannot reveal their behaviour when they are used under normal playing conditions. High-speed imaging of the actions revealed part of their true functioning, but was unable to provide the interacting forces between parts of the mechanism. We believe that these forces are of prime importance for the identification of the advantages of each type of action. Consequently, a multibody model of the two types of the actions has been conceived so as to compute the desired data. Special care has been taken to incorporate and to refine the following features in the model: constitutive laws of the leather and the cloth, detection of the subsequent intermittent contacts, a flexible hammer shank and a vibrating string. The results of the multibody model, coupled with experiments on the real actions, support the theory that Walter actions were probably devised to work under heavier conditions than Stein ones.

Contents

Introduction

Everyone knows the modern piano as a standardised instrument, built almost exactly the same way all over the world. Today's concept of nationalistic piano schools is merely based on piano technique, but not on the instrument's design. Important design differences did exist however when some major pieces of today's repertoire were written. Roughly speaking, German music was played on different instruments than those used for French or Italian music. One of the earliest distinct schools, equipped with the so-called 'German' and 'Viennese' actions, appeared in the second half of the 18th century. In this kind of action (Figure 1), the depression of the key (1) causes the hammer (2) to be propelled towards the strings thanks to the pawl (3) which flips the hammer shank. When the hammer (2) is close to the strings, it slips away from the pawl (3) and is free to impact the string unrestrained. The actions working on this principle are called *Prellzungenmechaniken*, from the German words that refer to its working principle: *prellen* and *Zunge*. The verb *prellen*, 'to flip', stands for the flipping movement of the hammer shank that is caused by a force applied on the opposite end of the shank (in this case, under the effect of the collision with the pawl).[1] *Zunge* refers to the pawl and thus further refines the naming of the obstacle against which the hammer rides in order to create the flipping movement. The analogy with a tongue is intended to underscore the fact that the pawl is a mobile element that can pivot at its base.

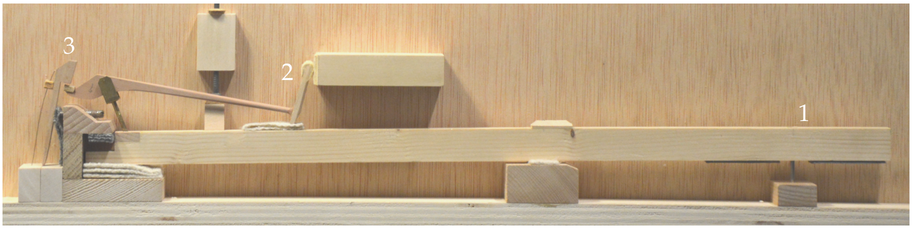

Figure 1: A typical *Prellzungenmechanik* is made of three main bodies: (1) the key, (2) the hammer and (3) the pawl.

The *Prellzungenmechaniken* were fairly simple and varied only slightly in

[1] Actions for which the hammer is directly linked to the key are classified as *Prellmechaniken*, as opposed to *Stoßmechaniken*, for which the hammer rotates around a pivot fixed on the frame. The verb *stoßen* recalls the fact that the hammer is pushed by a mechanical linkage that is driven by the key.

design during the time they were used. It is only in the late 19th century that they were abandoned and replaced by more complex and powerful actions. Nonetheless, some small but subtle variants in design existed among the *Prellzungenmechaniken* themselves. These variations lead to distinguish two types of actions; the Stein-type and the Walter-type, which are named after their most prominent and representative makers, Johann Andreas Stein (1728–1792) and Anton Gabriel Walter (1752–1826).

It goes without saying that the history of the *Prellzungenmechaniken* is far more complex and that it cannot be boiled down to this simple dichotomy. Nevertheless, the distinction between the Stein-type and the Walter-type can be applied to a great number of *Prellzungenmechaniken*. More importantly, it seems to have been directly used in the 18th century; Johann Ferdinand von Schönfeld (1750–1821), a Bohemian aristocrat who made a complete report on the musical activities in Vienna and Prague in 1796, divided the Austrian *pianoforte* makers in the same two categories. After describing each type of *pianofortes*, he associated a distinct playing technique and philosophy to each of them:

> The artist who has made himself the most famous so far, and who at the same time is the first creator of these instruments with us, is Herr Walter (...) His fortepianos have a full bell-like tone, clear response, and a strong, full bass. At first the tone is a little dull, but later, when one has played on it for some time, the treble becomes very clear. But when it is played a lot, the tone becomes sharp and metallic, which can be corrected by releathering the hammers.
>
> (...) [Description of the instruments made by Johann Schantz]
>
> The third master, or rather mistress, is Madame Streicher [Johann Andreas Stein's daughter] (...) Her instruments have not the strength of the Walter type, but in evenness of tone, clarity, lightness, sweetness and softness they are unmatchable. The tone is not jarring, but melting; the touch requires a light hand, flexible fingers, and a sensitive heart.
>
> (...)
>
> We can say in summary: we have two original makers, so we divide our fortepianos into two classes; the *Walterisch* and the *Streicherisch*. In the same way, by close observation we can also detect two classes among our best players. One of these classes loves a feast for the ears, that is, a powerful sound; to that end they play with a rich texture, extremely fast, study the most difficult runs and the fastest octaves (...) Thus force and sinewy strength are required; employing these, one shouldn't be restrained and needs a piano which won't be broken by such a beating. For the virtuosos of this kind we recommend the *Walterisch* fortepiano.
>
> The other class of player seeks nourishment for the soul, and loves not only clarity but also soft and melting playing. These can

> choose no better instrument than the *Streicherisch* or so-called *Steinisch* type.[2]

Focussing on the actions of the *pianofortes* made by Walter and Stein, it can be observed that Walter applied at least three modifications to Stein's initial design. He added a check to catch the hammer after it has hit the strings, he replaced Stein's wooden *Kapseln* with a brass version and he changed the inclination and the geometry of the pawl.

Chronologically speaking, the pawls of the first instruments, represented by the Stein-school, were mounted vertically, with a notch that forms an angle clearly less than 90° with respect to the body of the pawl (Figure 2, left).[3] Somewhat later, Walter's more inclined version appeared. In his action, the pawl is inclined and the angle of the notch is of 90° or slightly less (Figure 2, right). Even though most makers rallied to Walter's action design, others sturdily adhered to Stein's conception. Combined with Schönfeld's testimony, the fact that both types coexisted reinforces the idea that each design had its own advantages.

The exact reason for this morphological evolution is still strongly debated among piano makers and musicologists. Based on the works of Paul Poletti, we posit that Walter designed a *Prellzungenmechanik* that was able to withstand the strong solicitations required to produce what Schönfeld described as a 'feast for the ears'.[4] As will be shown throughout this work, the key to this feature of his actions may very well lie in the shape and orientation of the pawl.

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[2] J. F. von Schönfeld. *Jahrbuch der Tonkunst von Wien und Prag; 1796*. Vienna: von Schönfeldischen Verlag, 1796, pp. 87-91.

Derjenige Künstler, der sich bisher am berühmtesten gemacht hat, und der gleichsam der erste Schöpfer dieses Instruments bei uns ist, ist Hr. Walter (...) *Seine Fortepiano haben einen vollen Glockenton, deutlichen Anspruch, und einen starken vollen Baß. Anfänglich sind die Töne etwas stumpf, wenn man aber eine Zeitlang darauf spielet, wird besonders der Diskant sehr klar. Wird aber sehr viel darauf gespielet, so wird der Ton bald scharf une eisenartig, welches jedoch durch frisches Beledern der hämmer, wieder zu verbessern ist.*

(...)

Der dritte große Meister, oder rielmehr Meisterinn is Madame Streicherinn (...) *Ihre Instrumente haben nicht die Stärke der Walterschen, aber an Ebenmaaß der Töne, Reinheit, Schwebung, Anmuth, und Sanftheit, sind sie unerreichbar. Die Töne sind nicht anstossend, sondern schmelzend, das Traktament erfodert eine leichte Hand, elastischen Fingerdruck und ein fühlbares Herz.*

(...)

Da wir nun zwei Originalinstrumentenmacher haben, so theilen wir unsere Fortepiano in zween Klassen; die Walterischen un Streicherischen. Eben so haben wir auch bei genauer Aufmerksamkeit zwei Klassen unter unsern größten Klavierspielern. Eine dieser Klassen liebt einen starken Ohrenschmauß, das ist, ein gewaltiges Geräusche; sie spielt daber sehr reichtönig, außerordentlich geschwind studirt, die häckeligsten Läufe und die schnellsten Oktavschläge. Hiezu wird Gewalt und Nervenstärke erfordert; diese anzuwenden, ist man nicht mächtig genug, eine gewisse Moderazion zu erhalten, und bedarf also eines Fortepiano, dessen Schwebung nicht überschnapt. (...)

Den Virtuosen dieser Art empfehlen wir walterisches Fortepiano. Die ander Klasse unserer großen Klavierspieler sucht Nahrung für die Seele, und liebt nicht nur deutliches, sondern auch sanftes, schmelzendes Spiel. Diese können kein besseres Instrument, als ein Streicherisches, oder sogenanntes Steinisches wählen.

The translation is mainly based on M. Cole. *The Pianoforte in the Classical Era*. Oxford: Clarendon Press, 1998, pp. 220-221. Some excerpts were taken from P. Poletti. 'Die Tangente Terminology, Form, and Function'. 1994, some others were translated by Anne-Emmanuelle Ceulemans.

[3] To be more precise, when we consider the typical Stein instruments, we refer to his *pianofortes* in which the hammer beak is flat. Some of his earlier actions have hammers on which the beak is rounded.

[4] P. Poletti. 'Leaning-forward/forward looking'. 1994.

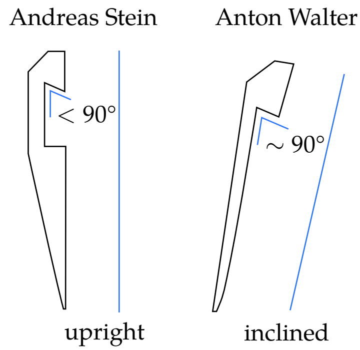

Figure 2: The Stein and Walter schools display different pawl designs.

With this work, it is aimed to shed new light on the proposed hypotheses by analysing the *Prellzungenmechaniken* with modern engineering tools. Some excellent studies have already proposed comparisons of the actions based on high-speed imaging. We propose to add a complementary approach in the form of a multibody model of each action. Even if models are inevitably less precise than the real actions, their added-value lies in their ability to compute just about any desired physical value of the model (forces, torques, displacements) without perturbing its functioning. Moreover, a model enables us to perform sensitivity analyses of any parameter without any restriction. Given these assets, advantage will be taken of the model to study other interesting phenomena of the *Prellzungenmechanik* such as the influence of the escapement height on the response of the action, on the timing of events within the action, etc. Contrary to most organological studies on piano actions which are often restricted to geometrical considerations, the dynamic aspects of the action's behaviour are taken into account, sometimes giving contrary results to what can be found in literature.

This work is the fruit of a combined master's degree in mechanical engineering and musicology. It has therefore not only an uncommon subject for a thesis in mechanical engineering, but also a hybrid structure and methodology. The thesis is consequently divided in two parts; the first one is oriented towards musicological matters and contains the first two chapters. The second part is more technical and describes the means that were used to study and model the piano actions.

A contextual setting of the two main *pianoforte* makers that represented the South German and Viennese school of piano making is given in the first chapter. On the one hand, Johann Andreas Stein represents a rather conservative style of piano making (and playing), though he was a very inventive man. On the other hand, Anton Walter seems to have taken advantage of his scientific knowledge to adapt his pianos to the evolving artistic context of the late 18th century. The difference between the design of the Stein and Walter *Prellzungenmechanik* is presented.

The second chapter studies the *Prellzungenmechaniken* from a practical point of view. The regulation and functioning of the action are explained, accompanied with simulation results that illustrate the influence of those regulations. Secondly, we study the reasons that can explain the evolution from Stein's upright pawl to Walter's inclined version. The theory elaborated by Paul Poletti and completed with our observations is verified with high-speed imaging analysis and the results of our multibody model.

The technical part of this thesis starts with a chapter that could be considered as a tool-box that will be used throughout the following chapters. A great deal of this thesis has consisted in observing the behaviour of real *pianoforte* actions built by Paul Poletti. The techniques used to observe them, measure the motion of their components, the force of the finger and to reproduce an identical key stroke are detailed in this chapter.

In chapter 4, the multibody framework is presented. A general introduction to multibody dynamics is given, followed by a literature overview of the projects concerning the modelling of piano actions. The morphology of our model is detailed with the underlying simplification assumptions. Finally, the method used for contact detection is outlined.

The three following chapters focus on elements of the multibody model that we consider to be crucial in order to model the actions correctly. In this sense, chapter 5 deals with the constitutive laws that govern the interaction forces between parts of the action. Given the complexity of the subject, an in-depth state of the art is provided and commented. A new type of constitutive law based on our observations is proposed for the hammer-string interaction. The other pairs of contacts in the model are treated with a simplified law, which is detailed along with the expression of the friction forces.

As explained in chapter 6, the constitutive law of the hammer-string interaction is coupled with a model of a vibrating string. The purpose of this model is to reproduce the mechanical behaviour of the hammer-string interaction rather than to study its acoustical response. After a state of the art review, the equation of the string is derived and the modelling via the finite difference method is presented. Since we are dealing with reproductions of ancient strings that do not display the same characteristics as their modern counterparts, their physical characteristics have been measured.

The deformation of the hammer shank can play an important role in the behaviour of the *Prellzungenmechanik*. This subject is studied in chapter 7, starting with a literature overview of the few studies in which hammer shank flexing is investigated. In most piano actions, shank vibrations are particularly important for the acoustics, but as is shown in the literature overview and in the experimental observations, the shank deformation can also play an important role in the action dynamics.

With these different elements, the model is complete and can be validated with the experimental data that were measured. This is done in the last chapter for two types of touch at the input of the action: a typical *forte* touch and a *piano* touch.

The appendices contain three articles that illustrate the larger framework in which this thesis was inscribed. The first focusses on a multibody model of a *Prellzungenmechanik* by Johann Andreas Stein of which a reproduction is kept at the Musical Instrument Museum of Brussels. We could not dispose of this action for a long period of time, and after the publication of this research, it turned out to be historically inaccurate. Nevertheless, it served as a starting point for developing a first, simple model, the results of which are already very insightful for studying the regulation of the *Prellzungenmechanik*. This model also served as a benchmark on which different enhancements were tried out. One of them, which is neither presented in the article nor in this thesis, consists in a real-time simulator of a piano action. This work was presented in conference, but has not been published since.[5] The results were encouraging though, as the model was able to be simulated three times faster than reality under heavy solicitations. The model, which ran with a fixed time-step integrator, was left aside when the string model was integrated since the high frequency components of the string required very small time steps, ideally an adaptive time-step solver.

The second article in appendix relates to the same *Prellzungenmechanik* by Johann Andreas Stein and the multibody model of a double escapement action. The aim of this publication was twofold: first of all it intended to explain the functioning of the complex and highly dynamic double escapement action with the help of a multibody model. In a second place, we studied the response of both actions to different types of touch that were extracted from literature. Both actions displayed characteristic behaviours in terms of hammer response and timing of events of interaction between the parts of the contact.

The last article of this appendix follows a more historical path, namely the origins of the *pianoforte*. In this essay, we study how the invention of the *gravicembalo col piano e forte* by Bartolomeo Cristofori, a Paduan instrument maker at the Medici Court, was spread through a literary journal. The article in question is signed by Scipione Maffei, a true humanist in terms of his scientific curiosity, and contains a schematic drawing of the action devised by Cristofori. On the basis of the surviving notes taken by Maffei during his interview with Cristofori, it is argued that the article was probably written by Cristofori himself and then rephrased by Maffei.

In the same vein as the previous article, a part of our project consisted in studying the striking action of Henri Arnaut de Zwolle. Arnaut de Zwolle was a medical astrologer of the early 15th century, in some ways comparable to Leonardo da Vinci as his interest in various matters made him write a manuscript containing drawings, explanations and calculations on various subjects ranging from planetary motion, polishing tools for precious stones, clockwork to musical instruments. Among the instruments he describes, one finds a set of actions that are to be installed in one of the following keyed string instruments; the *clavisimbalum*, the *dulce melos* or the *clavicordium*. One of the actions he very briefly describes is supposed to strike the strings with a metallic tangent that would be free to rebound after the impact. A full-scale replica of this action has been built by Manu Frederickx, former restorer at the Brussels Musical Instruments Museum, now associate conservator at the Metropolitan Museum, New York (an illustration of the action is provided in Appendix E). However,

[5] B. Bokiau et al. 'Real-time simulation of ancient piano actions: a step towards the technician's experience'. In: ECCOMAS Thematic Conference on Multibody Dynamics. Barcelona, 2015.

as our research progressed, it became clear that Arnaut de Zwolle described instruments that he did not intend to build himself; most of his descriptions are logical and complete, but as Paul Poletti pointed out to us, through some details, such as his instructions to divide the keyboard, it is evident that he never made an instrument himself, and that he was describing something he had learned but did not fully master. The actions that are described in his manuscript cannot be found in any other source, their use as a true musical instrument is thus largely hypothetical. The initial idea to model this action in order to rebuild it with the ideal dimensions has been left aside, thus allowing us to focus on the Stein-Walter issue.

Chapter 1

Towards a German school of piano making

During the end of the 18th century and the beginning of the 19th century, the *Prellzungenmechaniken* were the most used action in Vienna and southern Germany. Johann Andreas Stein and Anton Walter were probably the most renown makers of the *Prellzungenmechanik*. The first is often credited to be its inventor, while the second is known for having 'enhanced' the already existing action design. This chapter aims at providing a succinct biography of both makers, while highlighting the elements of their life that could have influenced their building and design process. The chapter firstly focusses on Andreas Stein, and then on Anton Walter. Besides the important steps of their life as piano makers, the specific features of each of their action is presented.

1.1 Johann Andreas Stein

Johann Andreas Stein: the starting point of a dynasty

Thanks to his great inventiveness and the innovative inventions he handed over to his successors, Johann Georg Andreas Stein (b Heidelsheim, 6 May 1728; d Augsburg, 29 Feb 1792) was and is still considered as one of the most interesting piano makers of the 18th century.[1] His high quality craftsmanship and desire to continuously strive for an enrichment of his instruments rather than for his financial welfare made him to be considered as an artist by his pairs.[2]

Stein discovered the secrets of organ making under the supervision of his father Johann Georg Stein (1697–1754).[3] Upon his departure from his home

[1] M. Latcham. 'Stein, Johann (Georg) Andreas'. In: *Grove Music Online. Oxford Music Online* (2001). URL: http://www.oxfordmusiconline.com/subscriber/article/grove/music/26631 (visited on 18/10/2011).

[2] M. Cole. *The Pianoforte in the Classical Era*. Oxford: Clarendon Press, 1998, pp. 192–193.

[3] M. Latcham. 'Johann Andreas Stein and the search for the expressive Clavier'. In: *Cordes et claviers au temps de Mozart. Bowed and Keyboard Instruments in the Age of Mozart*. Actes des Rencontres Internationales harmoniques, Lausanne 2006 Proceedings of the harmoniques International Congress, Lausanne 2006. (Lausanne). Ed. by T. Steiner. Bern: Peter Lang, 2010, p. 133.

town Heidelsheim in 1748, Johann Andreas Stein started a notebook that he was to keep up to date until at least 1777. In his cahier, he kept notes of personal events of his daily life, but also of technical matters concerning keyboard instruments and their makers, among which Bartolomeo Cristofori (1655–1731) and Franz Jakob Spath (1714–1786).[4] A much discussed step in his early career was his apprenticeship at the Silbermann brothers' workshop in Strasbourg in 1748–1749.[5] According to his notebook, the work that was expected from him as a young journeyman only concerned matters related to organ building.Having travelled and worked with organ builders, he settled at Spath's workshop in Regensburg for about seven months.[6]

Quite logically, when he established in Augsburg around 1750, Stein became first of all famous as an organ builder, not as a *pianoforte* maker. He even gained access to very interesting commissions for his young age. The first of those was a commission for an organ that he built in 1755–1756 for the *Barfüsserkirche* in Augsburg where he was himself organist. The second commission dates from the mid-1760s for the *Heilig-Kreuz-Kirche* in Augsburg.[7] During the 1760s, he also produced other keyboard instruments, some of which very modest.[8]

It is not very clear when (or even if) Stein devised his own piano action, but he acquired a solid reputation doing so. Stein had many apprentices in his workshop, most of them closely following his methods and traditions. This apprenticeship was a powerful catalyst for the propagation of his methods, for his students established in various cities across Germany and Austria.[9] His daughter Anna Maria (1767–1833), nicknamed 'Nanette' and his son Andreas

[4] *Ibid.*, p. 133.

[5] The four Silbermann brothers are Johann Andreas (1712–1783), Johann Daniel (1717–1766), Johann Gottfried (1722–1766) and Johann Heinrich (1727–1799). The most famous *pianoforte*–maker of the Silbermann family is Gottfried Silbermann (1683–1753), the uncle of the four brothers. M. Schaefer, F.-H. Gress and P. Fritsch. 'Silbermann'. In: *Grove Music Online. Oxford Music Online.* (2016). URL: http://www.oxfordmusiconline.com/subscriber/article/grove/music/45447 (visited on 04/08/2016).

Maunder provides a clear view on the laborious path to become an instrument maker in Vienna. Though Stein started his career travelling in various cities, the example of the Austrian capital is extremely insightful. Professional instrument making in Vienna was dictated by an elaborate guild system in which one started as an apprentice (*Lehrjunge*) for a period of usually three to five years. Having finished his apprenticeship, a maker could become journeyman (*Geselle*) by joining a kind of trade union (*Bruderschaft*). As in all steps of his career, the candidate had to pay an entrance fee to this *Bruderschaft*. If he desired to progress further and become *Meister*, he had to serve as a journeyman for several years and produce a test piece (*Meisterstück*). This step represented an important financial investment, but not nearly as much as the right for a *Meister* to run his own workshop, called the *Besitzrechte*. This ultimate rank was in consequence only available to candidates from comfortable backgrounds. To circumvent this problem, the *Besitzrechte* could also be obtained by inheritance or by marrying his master's widow. R. Maunder. *Keyboard instruments in eighteenth-century Vienna*. Oxford: Clarendon Press, 1998, pp. 17–18.

[6] Latcham, *op. cit.*, p. 135.

[7] Cole, *op. cit.*, p. 180.

[8] According to Michael Latcham, he was reknown for his harpsichord making, but Michael Cole points out that he did not really appreciate making them. Latcham, 'Stein, Johann (Georg) Andreas'; Cole, *op. cit.*, p. 180.

[9] Michael Cole notes that among Stein's students, Schauz, Wirt and Senft established in Augsburg, Dulcken in Munich, the Schiedmayer brothers in Erlangen and Nuremberg, Heilmann in Mainz, Schmid in Salzburg, Lengerer in Kufstein and the Gräbner brothers in Dresden. *Ibid.*, p. 195.

Matthaüs (1776–1842) are probably his most famous apprentices. Upon their fathers' death in 1792, they settled in Vienna under the name *Geschwicht Stein* and perpetuated his traditional piano building.[10] In 1794, Nanette married Johann Andreas Streicher, a professional pianist. The brotherly association was dissociated in 1802, Andreas Matthäus establishing his own workshop in the same city under the name 'André Stein'. Nanette, who labelled her later pianos *Nanette Streicher, née Stein, à Vienne* strictly followed the design of her father until 1805. After that period, she adapted her instruments to the requirements of her clients. It is said that she did this partly under the influence of Beethoven.[11] Finally, the Streicher firm was taken up by their son Johann Baptist Streicher (1796–1871) who built it up to a world-famous piano manufacture.[12] Johann Baptist's son, Emil Streicher, took in turn control of the company after his father's death. The factory was ultimately sold in 1896 to the Stingl brothers.

Stein's *Prellzungenmechanik*

It is generally accepted that Johann Andreas Stein is at the origin of the development of the *Prellzungenmechanik* in the 1770s,[13] though it has never been proven formally. A periodical of 1769 by J.A. Hiller claims a certain Herr Stein of Augsburg is the first to circumvent the two disadvantages of the *pianoforte*: a dull tone and the difficulty to perform ornaments.[14] Unfortunately, it is most probable that this description has no direct link with the actions of Stein we have in mind; it is more likely that this excerpt praised one of the many other inventions of Stein.[15] The maker of Augsburg displayed a great inventiveness; from his beginnings as organ builder in the 1760s to his latest pianos in the late 1790s, he continuously kept on experimenting and inventing instruments that could combine different tones.[16] In particular, he spent a great deal of his time associating multiple instruments in order to combine their tones.[17] The most famous among these experimentations being the *Vis-à-vis* instrument of 1777,

[10] Some instruments were still signed 'Johann Andreas Stein' after his death. *Ibid.*, p. 193. Two of these instruments still exist. Latcham, *op. cit.*

[11] *Ibid.*; A. Botticelli. '"Creating Tone": The Relationship Between Beethoven's Piano Sonority and Evolving Instrument Designs.' PhD thesis. University of Toronto, 2014.

[12] G. Keeling. 'Liszt and J. B. Streicher, a Viennese Piano Maker'. In: *Studia Musicologica Academiae Scientiarum Hungaricae* 28.1/4 (1986), pp. 35–46.

[13] Cole, *op. cit.*; S. Birkett. '"Nourishment for the soul" or "feast for the ear"? A comparative study of the Stein and Walter fortepiano actions'. In: *Chopin et son temps. Chopin and his time.* Actes des Rencontres Internationales *harmoniques*, Lausanne 2010. Proceedings of the *harmoniques* International Congress, Lausanne 2010. (Lausanne). Ed. by V. Hug and T. Steiner. Vol. 54. 2. Bern: Peter Lang, 2016, p. 146.

[14] J. A. Hiller. *Wöchentliche Nachrichten und Anmerkungen die Musik betreffend*. Leipzig, 1769.

[15] Cole, *op. cit.*, pp. 180–181.

[16] M. Latcham. 'Notes on the history of the Viennese piano, 1800 to 1830'. In: *Chopin et son temps. Chopin and his time*. Actes des Rencontres Internationales *harmoniques*, Lausanne 2010. Proceedings of the *harmoniques* International Congress, Lausanne 2010. (Lausanne). Ed. by V. Hug and T. Steiner. Vol. 54. 2. Bern: Peter Lang, 2016, pp. 201–216.

[17] See for example his *Vis-à-vis* instrument, his *Poly-Toni-Clavichordium* or his *Clavecin organisé*. Cole, *op. cit.*, pp. 182-183.

a combination of a harpsichord and a *pianoforte* at opposite ends of the case.[18]

Given his immense resourcefulness, it is not surprising that he was the first to successfully design the frame of his *pianofortes* in a personal manner, adapting it to his inventions, and not simply converting a harpsichord frame.[19] More in line with our concerns, the action Stein devised (Figure 1.1) completely differs from the then existing variations of Cristofori's design; its simple design made of three components ensured excellent playing characteristics according to the many admiring testimonies one can find.[20]

The school of so-called 'German actions', as defined by Stein's conventional *pianoforte*, shares common characteristics throughout its instruments. First of all is the fact that the hammer is directly mounted on the key, and not hinged to a rail. The hammers are inserted in U-shaped wooden *Kapseln* and pivot in the latter thanks to a metal axle nested in two leather bushings. The axle is fixed to the hammer and rotates in the bushings. The inverted mounting of the hammer (the hammer head is near the keyboard) allows to maximise the lever arm length ratio within the action. Thanks to this geometrical design, once the beak is stopped by the pawl, the hammer head undergoes a high propulsion speed whose amplitude is largely increased with respect to the finger velocity.

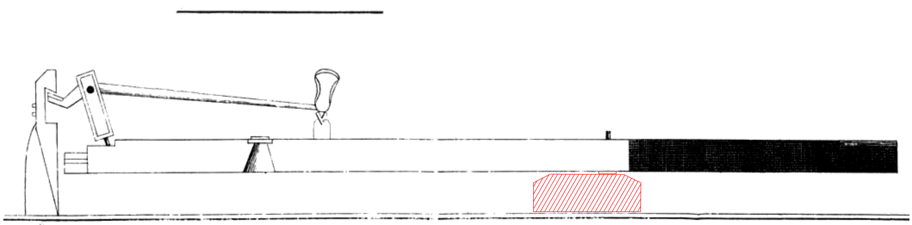

Figure 1.1: Drawing of the Stein-type action as illustrated in Streicher's 1801 manual *Kurze Bemerkungen über das Spielen, Stimmen und Erhalten der Fortepiano*. The image has been cleaned, reverted and the original annotations have been removed. The balance rail has been added by the author.

Another interesting aspect of Stein's design is that he never incorporated a check in any of his *pianofortes*, nor did his daughter and son-in-law in their Streicher firm. The check restrains the hammer from bouncing on the key after having impacted the string. Consequently, when a Stein-type action is played upon with force, it can happen that the hammer bounces on the key sufficiently high so that it causes multiple strikes.

[18] J. A. Rice. 'Stein's "Favorite Instrument" A Vis-à-vis Piano-Harpsichord in Naples'. In: *Journal of the American Musical Instrument Society* 21 (1995), pp. 30–64 Two of those instruments have survived, one is kept at the Museo Civico di Castelvecchio, Verona (1777) and another in Naples Conservatory (1793). Rita Steblin shows that Stein may not have been the first to have built such a *vis-à-vis* instrument; newly discovered historical sources suggest that a certain Johann Georg Volkert built a *Doppelflügel* with the same principle in Vienna before 1778. R. Steblin. 'Early Viennese Fortepiano Production : Anton Walter and New Inventions by Johann Georg Volkert in 1777-1783'. In: *Studien zur Musikwissenschaft* 55 (2009), p. 281.

[19] Cole, *op. cit.*, pp. 186–187.

[20] *Ibid.*, pp. 192-193.

The most interesting element in Stein's German action is certainly the ability of the hammer to escape from the rest of the action. Stein added this feature with the help of a small contrivance, called the *Tangente* or *Auslösung* in German. Translating this term rigorously is a complex task.[21] The terms 'escapement', 'hopper' and 'tangent' are often used as misnomers. Paul Poletti proposed to name it *pawl*, in reference to the ratchet and pawl, a device found in clocks, winches, weaponry and milling machines.[22] By definition, a pawl is a hook-shaped part of a mechanism that allows a movement in one direction, but restrains it in another. This is basically what the *Tangente* does: when the hammer beak flips the hammer by pushing on the pawl, the latter stays in position. After escapement, the hammer beak pushes the pawl backwards so that the beak could re-engage itself for a second strike. As a rule, the Stein pawls are generally oriented in a vertical upright position.

Authors generally distinguish three periods in Stein's pianistic production for which only the aspects related to the action will be addressed here. The first type corresponds to the 1777 action of the *Vis-à-vis* instrument. This type of action is a considered as 'transitional' as their conception is at midway between the Cristofori-Silbermann design and the later German actions. The hammer heads of these instruments were made of uncovered, bare wood.[23] The second type of instruments covers the 1781–1783 period. They follow the typical 'German' design of the *Prellzungenmechanik* attributed to Stein. These instruments are also characterised by their hollow wooden hammer heads covered with leather, graduated from bass to treble.[24] The hollow hammers may clearly be seen as a reminiscence of the Cristofori-Silbermann tradition. From *ca* 1783 on, Stein produced his third type of actions, with full hammers where the lower part had been adapted so as to reduce their weight.[25] Most makers who adopted Stein's design (imitators or apprentices) reproduced the third type of instruments, often replicating the shapes and sizes of its parts in the smallest of detail.[26]

1.2 Anton Walter

Anton Walter's contribution

In a simplified historical perspective, Gabriel Anton Walter (b Neuhausen an der Fildern, 5 Feb 1752; d Vienna, 11 April 1826) is sometimes seen as the rival and successor of Johann Andreas Stein. Indeed, for a long time it has been stated that he had arrived in Vienna around the 1780s,[27] and that his actions

[21] P. Poletti. 'Die Tangente Terminology, Form, and Function'. 1994.
[22] *Ibid.*
[23] M. Latcham. 'Mozart and the Pianos of Johann Andreas Stein'. In: *The Galpin Society Journal* 51 (1998), p. 136.
[24] *Ibid.*, p. 138.
[25] Cole, *op. cit.*, p. 195.
[26] *Ibid.*, p. 195.
[27] In this version, his arrival would have coincided with his marriage to the widow Elisabeth Schöfstoß. He would have started his workshop at that time. J. A. Rice. 'Anton Walter, Instrument Maker to Leopold II'. in: *Journal of the American Musical Instrument Society* 15 (1989), p. 383; Cole, *op. cit.*, p. 218.

started being 'mass'-produced in the 1790s by him and all other makers except Stein. Recently discovered documents have shown that Walter probably came to Vienna for the first time more than a decade earlier; in 1772, he worked for six months as an apprentice in the organ workshop of Johann Michael Panzner (*ca* 1715–1779) after which he must have left the city.[28] He returned in Vienna around 1775. In 1778, he submitted a request to obtain the special status of *Schutzverwandt* that would allow him to make musical instruments for his own account, without having to answer to the guild of musical instrument makers.[29] At this point in time, Walter claimed to have already built several *Flieg* (*Flügel*) that received great appraisal by connoisseurs.[30] In his application, he also argues that he feared for the envy of the other makers because his instruments were less expensive than theirs.[31] Although the guild of *Orgelmachers* firmly expressed its opposition to his application and managed to rally the City Authorities to its cause, a direct intervention of the Crown overruled this decision and Anton Walter received the desired status in 1779.

From then on, his fame seems to have kept growing as he received the Court title of *k. k. Kammerorgelbauer und Instrumentenmacher* under Leopold II in 1790.[32] Records mention that he was employing fourteen assistants and used seven apartments to house his workshop for a total rent of 298 Gulden. In comparison, the long established Gottfried Mallek, head of the *Orgelmacher* guild spent 66 Gulden on housing. The high rent of Walter's apartment gives a good image of his success.[33]

Walter's early application to the status of *Schutzverwandt* and his claim to have already built some instruments that received great approbation may somewhat change the strictly sequential view according to which Anton Walter's work was an enhancement of a well-established manufacturing tradition developed over almost two decades by Johann Andreas Stein. Indeed, if one focusses on the available sources regarding the traditional Stein action (of the second or third period), it appears that he started producing them around the beginning of the 1780s. That is, when Walter was already active in instrument making, maybe of some *pianofortes* as we know them now.

An important point not to overlook in Walter's career is his education. While Stein started his professional life under the tutelage of his father as an organ builder, Walter had a training as carpenter. With his arrival in Vienna, he had the chance to study geometry, arithmetic, algebra, mechanics, architecture,

[28]R. Steblin. 'Anton Walter's Difficult Early Years in Vienna: New Documents, 1772-1779'. In: *Journal of the American Musical Instrument Society* 33 (2007), p. 53.

[29]This is in contradiction with the normal enrolment in the guild of *Orgel und Instrumentenmacher* as seen in note 5. Instead, Walter asked for a special status that would allow him to make instruments outside this guild. Steblin, 'Early Viennese Fortepiano Production : Anton Walter and New Inventions by Johann Georg Volkert in 1777-1783', pp. 269-270.

[30]Steblin, 'Anton Walter's Difficult Early Years in Vienna: New Documents, 1772-1779', pp. 56-57. Rita Steblin translates the term *Flieg* as 'wing-shaped (grand) keyboard instruments' without being able to clarify if they were plucked or quilled instruments. Steblin, 'Early Viennese Fortepiano Production : Anton Walter and New Inventions by Johann Georg Volkert in 1777-1783', p. 271.

[31]*Ibid.*, p. 271.

[32]Rice, *op. cit.*

[33]Steblin, 'Anton Walter's Difficult Early Years in Vienna: New Documents, 1772-1779', pp. 54–56.

and music.[34] It is supposed that Walter has attended classes at the Imperial-Royal Engineering Academy, for two professors of this institution supported him in his request of 1778. In their patent letters, they emphasise not only his skill as an instrument maker, but also his profound desire to experiment on and enhance his production. The first testimonial, by Friedrich Wilhelm Gerlach (1728–1802) insists on Anton Walter's interests in research:

> (...) I have observed, through frequent associations with Mr. Anton Walter, that he has a particular facility and knowledge, especially in his art or profession; that he aspires to conduct ever more intensive and painstaking investigations, and that he strives to determine the relationship between the components of the musical instruments with regard to sounds and motion, according to the correct principles of physics and mechanics. Thus, he has not only already made several improvements and new discoveries, but also it is to be hoped, if no hindrances occur, that he will make still more (...)[35]

The second testimonial by, Johan Adam Grünwald (*ca* 1735–1804), stresses the academic background of Walter and the fact that he brought innovation in the sphere of the instrument making:

> (...) [Anton Walter] has applied himself with true industry to various special and useful sciences, such as calculation, geometry, and several divisions of physics and mechanics, acquiring vast knowledge. (...) [His instruments] can always be considered among the first of the best works, because they are not merely constructed according to the old mechanisms, but rather according to his own invention and efforts, supported by secure principles (...)[36]

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[34] Letter from Anton Walter to the Lower Austrian Government, 7 July 1778, Wiener Stadt- und Landesarchiv, Alte Registratur A2-Berichte: 4/1779. *Der Hang, mehr als meine in der Jugend erlernte Tischler* Profession *zur Vollkommenheit zu bringen, brachte mich in andere Landen und endlich nach Wien, wo es mir dann, als dem Sammelplatz der Künste, glückte, in der Geometric, Arithmetick, Algebra, Mechanick, Architektur und Tonkunst so weit zu kommen, daß ich mich entschloßen, durch lezteres mein ehrliches Fortkommen zu suchen.* This and all subsequent transcriptions and translations of the documents concerning Anton Walter's petition of 1778–1779 come from *Ibid.*

[35] Testimonial for Anton Walter by Friedrich Wilhelm Gerlach (1728–1802), Teacher of Physical Mechanics at the Imperial Royal Engineering Academy, dated Vienna, August 13, 1778. Wiener Stadt- und Landesarchiv, Alte Registratur A2-Berichte: 4/1779.

(...) *Anton Walter, durch öftern Umgang, besondere Fähigkeit und Kenntnisse, insonderheit in seiner Kunst oder Profession, beobachtet habe; daß er solche immer tiefer und gründlicher zu erforschen trachte, die Verhältniß der Theile der musikalischen Instrumente nach richtigen Grundsätzen der Physik und Mechanik, in Ansehung der Töne und Bewegung zu bestimmen sich bemühe; daher sowohl schon manche Verbesserungen und neue Erfindung gemacht, als auch zu hoffen stehe, daß, wenn keine Hindernisse vorfallen, er zum Nutzen und Vergnügen des Publikums, noch mehrere, oder doch wenigstens vortreffliche Instrumente machen werde* (...)

[36] Testimonial for Anton Walter by Johann Adam Grünwald (*ca* 1735–1804), Professor at the I. R. Engineering Academy, dated Vienna, August 14, 1778. Wiener Stadt- und Landesarchiv, Alte Registratur A2-Berichte: 4/1779. (...) *bezeuge, d[a]s derselbe [Anton Walter] seit seines hiesigen Aufenthalts sich auf besondere und verschiedene nützliche Wissenschaften, als Rechnung,* Geometrie *einige Theile der* Physic *und* Mechanic *mit wahren Fleiß verwendet, und sich große Kentnüß beygeleget hat.* (...) *solche [Instrumenten] immer unter die ersten der besten Werke genohmen werden können, weil sie nicht bloß*

Looking at one of the books written by Friedrich Wilhelm Gerlach that was in use at the royal-imperial engineering school less than a decade after Walter's admission, one can grasp the content of what Walter must probably have learned.[37] The first part of Gerlach's *Anfangsgründe der Mechanik* is nothing more than a treaty of solid mechanics which includes exactly the same subjects as a modern-day engineering course: rational mechanics, mechanics of the movement, vectorial decomposition of the forces, etc. (Figure 1.2). Combining the testimonials of Walter's professors and the courses they taught at university, it can be assumed that Walter was able to analyse and enhance the functioning of the *Prellzungenmechanik* on the basis of rational considerations.

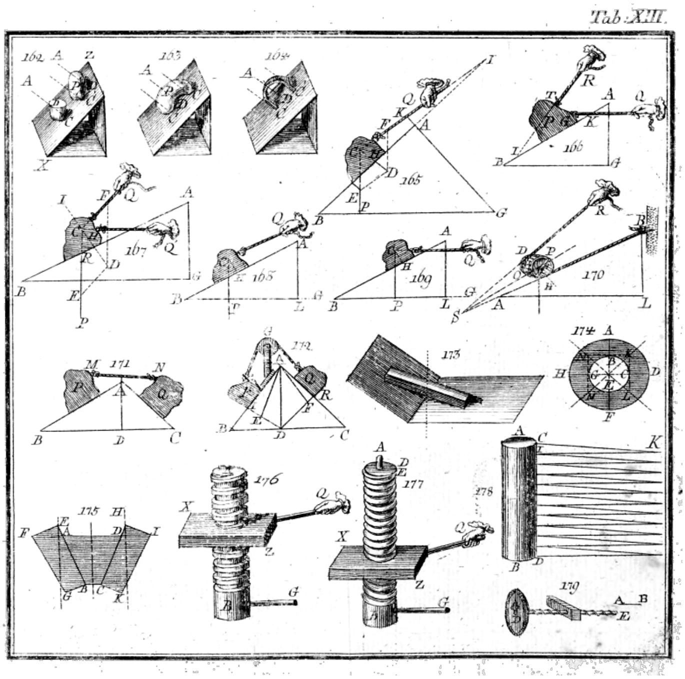


Figure 1.2: Through his courses at university, Anton Walter probably had the ability to rationally study his piano actions. Illustration taken from F. W. Gerlach, *Anfangsgründe der Mechanik zum Gebrauche der k. k. Ingenieursschule*, tab. XIII.

Steblin posits that Walter could have entered university in 1775 and that he opened his workshop a year later.[38] The short term between his entry at the engineering school and the opening of his workshop would have left him with very few time to study sciences. It may nonetheless be that he combined both activities, as he was said to have performed experiments on his instruments.

Anton Walter's *Prellzungenmechanik*

Anton Walter's experience seems to have provided him with solid grounds for developing an action that would conquer Vienna's pianistic stages. Indeed, the

nach den alten Mechanismum *sondern nach eigner durch sichere Grundsätze unterstützte Erfindung und Bemühung eingerichtet sind* (...)

[37] F. W. Gerlach. *Anfangsgründe der Mechanik zum Gebrauche der k. k. Ingenieursschule. Erster Theil*. Vienna: Trattner, 1786. (13217166 Augsburg, Staats- und Stadtbibliothek – K-K 182 -2, http://www.mdz-nbn-resolving.de/urn/resolver.pl?urn=urn:nbn:de:bvb:12-bsb11254951-2).

[38] Steblin, *op. cit.*, pp. 53–54.

invention of the so-called 'Viennese action', a variant of Stein's *Prellzungenmechanik*, is attributed to him (Figure 1.3).[39] Walter brought three main innovations to the *Prellzungenmechanik*. First of all is the addition of a check that catches the hammer after its rebound on the string. It consists of a leather surface against which the hammer rubs, placed in such a manner that during the rising phase, the combined rotational motion of the key and the hammer prevent the latter from interfering with it. When the hammer performs its descent with the key kept depressed, its trajectory intersects with the leather layer and it is halted.

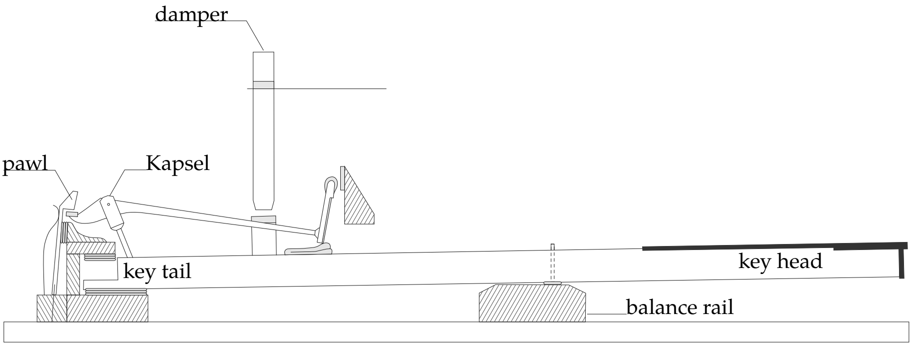


Figure 1.3: Action of the Anton Walter *pianoforte* in the Germanisches Nationalmuseum catalogue number MINe109 as drawn by Susanne Wittmayer. Image adapted from Poletti, *Classical Viennese and south-German Piano Actions*.

Walter replaced the wooden *Kapseln* of Stein with a brass version. As noted by Paul Poletti, the wooden versions are extremely labour intensive in their production.[40] Besides a relative easiness of manufacture, the use of *Kapseln* made out of metal completely changes the nature of friction that appears with the hammer axle; instead of rotating inside leather bushings, the conical extremity of the pin of the hammer provides an almost punctual and rigid contact with the *Kapsel*, resulting in potentially much less friction than in its Stein counterpart. Other advantages of this system include the ease to dismount and replace the hammer (in Stein *pianofortes*, when removed, the hammer axle has to be replaced with a larger one so that it would still be sufficiently tightened in the *Kapsel* bushing). Also, as friction is proportional to the tension between the two branches of the U and the axle, it is easily adjusted by squeezing or moving apart these branches.

The last and most important element Walter introduced is a different shape of the pawl; whereas most pre-1805 Stein instruments feature a pawl that is

[39]Several historical sources, including Walter himself state that he was the inventor of the *pianoforte* in use at the time, though none describe what exactly he had invented. Asking the title of *k. k. Kammerorgelbauer und Instrumentenmacher* in 1790, he claimed in his petition that 'he was the first to make pianofortes here as they are now in general use'. *Ibid.*, pp. 43-44. Von Schönfeld states that 'The artist, who has, so to say created the instrument *Fortepiano* in our regions, and who has already made himself famous before, is Mr Walter, residing in Vienna (. . .)'. *Derjenige Künstler, der sich bisher am berühmtesten gemacht hat, und der gleichsam der erste Schöpfer dieses Instruments [fortepiano] bei uns ist, ist Hr. Walter, wohnhaft an der Wien* (. . .) J. F. von Schönfeld. *Jahrbuch der Tonkunst von Wien und Prag; 1796*. Vienna: von Schönfeldischen Verlag, 1796, pp. 87-88.

[40]P. Poletti. 'Leaning-forward/forward looking'. 1994.

standing straight-up, those made by Walter are inclined, with a notch that is only very slightly (if not) inclined with respect to the base body of tha pawl. The consequences of this design will be discussed in Section 2.2.

The period at which Walter started producing his Viennese actions has not been defined with precision yet. His oldest conserved *pianoforte* is an instrument that belonged to Mozart, bought in 1782 but refitted by Walter himself with a new action in 1800 (Figure 1.3).[41] It seems that Walter originally equipped it with some kind of *Stoßmechanik* that he later replaced with one of his *Prellzungenmechanik*.[42]

The generally accepted large picture is that until *ca* 1790, Stein's models dominated the Viennese piano market. After this point, almost every maker who equipped its instruments with a *Prellzungenmechanik* switched to Walter's version with the brass *Kapseln*, adding a check and using the inclined pawl.[43] The most notable exception to the almost unanimous adherence to Walter's modifications is Stein's (later Streicher's) company that kept its design unchanged until 1805. This is all the more striking considering the extremely high pace marked by the evolution of the piano during the last two decades of the 18th century.

[41] M. Latcham. 'Mozart and the pianos of Gabriel Anton Walter'. In: *Early Music* 25.3 (1997), p. 393.

[42] In his article, Huber goes even further and argues that most early pianos in Vienna were equipped with *Stoßmechaniken*. According to Huber, even the instruments made by Stein and Walter before they started the production of the actions that made them famous could have been equipped with *Stoßmechaniken*. A. Huber. 'Was the 'Viennese Action' Originally a Stossmechanik?' In: *The Galpin Society Journal* 55 (2002), pp. 167, 169–182.

[43] Cole, *op. cit.*, p. 219.

Chapter 2

The *Prellzungenmechaniken*

In this chapter, some functional principles of the *Prellzungenmechanik* will be explored and the results of the multibody model will be presented. In the first section, a sequential description of the functioning of the *Prellzungenmechanik* is provided. At the same time, the regulation principles for each step are detailed. The second part of this chapter focusses on the difference between the Stein and the Walter action. Based on correct principles for designing a *Prellzungenmechanik*, we show how Walter devised an action that escapes well before the geometrical escapement if it was depressed too violently. In the last section, we focus on various observations and simulation results that were obtained with the multibody model and through high-speed imaging. This last part thus includes experiments and simulations concerning the regulation of the escapement, the displacement ratio between the hammer and the key, and the function of the slap rail.

2.1 Functioning and regulation of the *Prellzungenmechanik*

The exact functioning of the *Prellzungenmechanik* as well as the issues related to its regulation are explained in this section.[1] Even though some noticeable differences exist between the Stein and Walter-type actions, these peculiarities do not intervene disturbingly in the regulation process. The adjustments explained hereafter follow the normal functioning cycle of a key blow. There are essentially three phases that can be identified in the entire key-stroke: (1) lost motion; (2) working key dip and escapement (3) aftertouch and string contact. To these three phases, a fourth is worth mentioning; the position of the key when it is at rest.

It is important to note that in practice, regulation is performed through a quasi-static observation of the action. In other words, by moving the action very slowly, no dynamic effect intervenes in this process (even though pi-

[1] The regulations explained in this section are largely based on the works of Paul Poletti, *pianoforte* maker, researcher at the Museu de la Música of Barcelona and professor at the Escola Superior de Música de Catalunya. P. Poletti. *Classical Viennese and south-German Piano Actions. An introduction to regulation*. 2016. URL: http://polettipiano.com/Pages/actionsengpaul.html (visited on 14/05/2016)

ano actions are highly dynamic mechanisms). This means that the regulations given hereafter are performed with reference configurations that are unlikely to be reached in when the action is played for dynamics louder than a *piano*.

The key at rest The rest position of the key is defined by the lower key stop on which the key tail rests (Figure 2.1). The stop is made of two or three folds of heavy woollen cloth stitched together, hence the name 'rest cloth'.

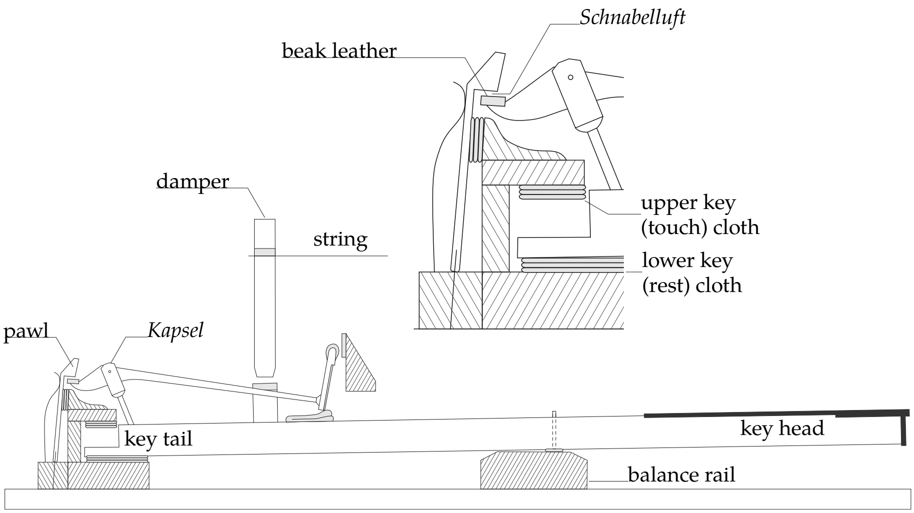


Figure 2.1: The action at rest. Image adapted from Poletti, *Classical Viennese and south-German Piano Actions*, *op. cit.*

The distance between the hammer beak leather and the underside of the pawl is called *Schnabelluft*, literally translated as 'beak-air' (Figure 2.1). *Schnabelluft* is mainly important for a safe re-engagement of the key after a first strike (this and some other reasons will be tackled in depth in the following steps).

The design and the regulation of many parts can influence the amount of *Schnabelluft* present in an action. Considering that the rest position of the key is determined, *Schnabelluft* is in the first place defined by the position of the hammer pivot. The hammer rotates in a *Kapsel* that is fixed on the key tail (Figure 2.1). According to the building tradition, *Kapseln* can be made in wood or in metal, but they are all screwed in the key (Figure 2.2). For this reason, they must be inserted appropriately from the first stage on as they cannot be repositioned afterwards.

The orientation of the hammer at rest is a second important factor: the lower the hammer-head, the less *Schnabelluft* there will be. The initial position of the hammer is set by the thickness of the pad on which it rests (the pad can consist of several layers of cloth or of a more complex cloth loop). Other factors influencing *Schnabelluft* include the height of the leathered beak and the inclination at rest of the pawl. Influence of the beak thickness is pretty straightforward, and pawl inclination will be discussed later because its rest position is dictated by other considerations than *Schnabelluft*.

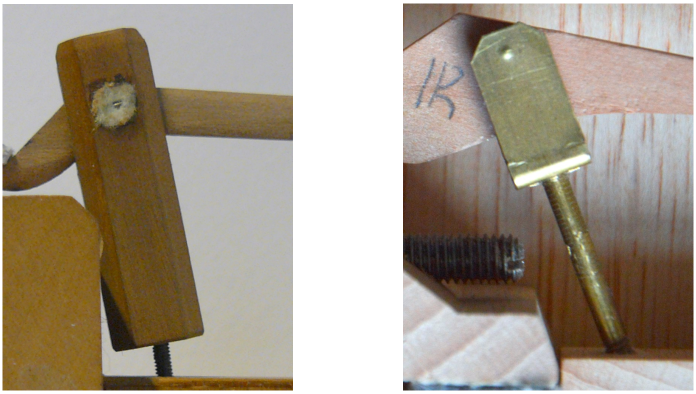


Figure 2.2: *Kapseln* can be built in wood or in brass. Whatever the used material, they are screwed on the upper surface of the key.

Practically speaking, when confronted to an existing action, all these parameters are already defined. The only process left to finely regulate *Schnabelluft* is by gluing shims in the form of small plies of paper to the undertail of the hammer.

Lost motion The term 'lost motion' is used to describe the phase during which the key travels from its rest position to the point where the hammer beak engages the underside of the pawl (Figure 2.3). In other words, it corresponds to the keystroke required to cover the *Schnabelluft*. As Paul Poletti points it out, lost motion wrongly implies that this portion of the motion is useless for the functioning of the action. It even happens that modern pianists who are unaware of the purpose of *Schnabelluft* and who are used to play on modern pianos, require the *Schnabelluft* to be suppressed.

In fact, lost motion (and thus *Schnabelluft*) is essential as it ensures proper repetition of the action. Indeed, when the key is depressed a first time, a second blow of the same note can only take place if the hammer beak is repositioned under the pawl. If no *Schnabelluft* has been foreseen at all, the key will have to be fully released in order to repeat.

Moreover, according to Paul Poletti, *Schnabelluft* provides an extra security with regards to changing weather conditions. In an action where lost motion is already reduced, an increase in humidity can cause its parts to move and to expand to the point that *Schnabelluft* is cancelled out. A typical order of magnitude for *Schnabelluft* would be 1 mm for earlier actions, 1.5 mm for the later (heavier) models. Some musicians and makers set up their action with more lost motion in the bass notes than in the treble notes.

Working key dip and escapement Working key dip corresponds to the moment during which key travel is effectively propelling the hammer through the beak-pawl contact. The lever system formed by the key and the hammer is designed to propel the hammer head at a higher speed than that of key de-

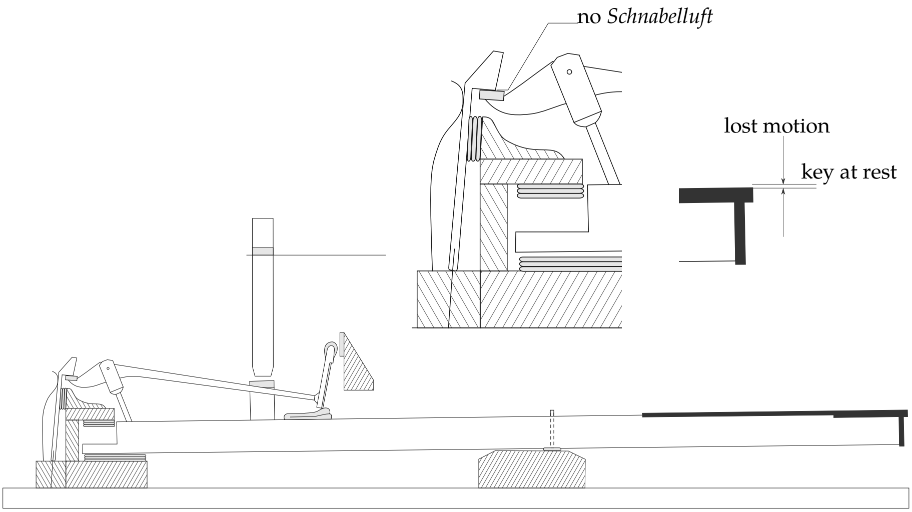


Figure 2.3: At the end of the lost motion, the hammer beak is in contact with the horizontal pawl face. Image adapted from Poletti, *Classical Viennese and south-German Piano Actions*, *op. cit.*

pression. In a typical *Prellzungenmechanik*, one can expect a displacement ratio between the motion of the key and the hammer of 8 to 10.[2] The consequence of this leverage system is that the hammer will also feel 8 to 10 times heavier. The initial contact between the hammer and the pawl thus represents the most serious obstacle and shock for the finger when it depresses the key. These kind of abrupt energetic demands arise during percussive contacts between components. Three of them can be distinguished when a key is played: (1) the key (supporting the hammer) is brought in motion; (2) the hammer starts flipping at the instant of the beak pawl contact; (3) the damper is lifted (though this last action requires less energy). If these events occurred simultaneously, the action would lose its lightness due to the instantaneous requirement for a higher energy input in the system. Hence a second argument that emphasises the importance of *Schnabelluft*; lost motion enables to stagger the steps during which a sudden increase of energy has to be provided to the key to ensure its intended motion.

The end of the working key dip is marked by the escapement (or let-off) of the hammer: the kinematical chain of the action in combination with the contact slope of the pawl are so conceived that after a certain key dip, the leather beak and the pawl lose contact (Figure 2.4). For key depressions softer than *pp*, that is, for key strokes where dynamic effects are negligible or non-existent, this moment of let-off corresponds to the *geometrical* escapement (Figure 2.4). By contrast, under normal playing conditions, complex dynamics come into play, retarding or anticipating the moment of escapement. Under these conditions, let-off is called dynamic escapement. Let-off is usually characterised by the so-called escapement height, which corresponds to the distance between

[2]Displacement ratios will be discussed in Section 2.3, p 29.

the top of the hammer head and the underside of the string at the moment of escapement.

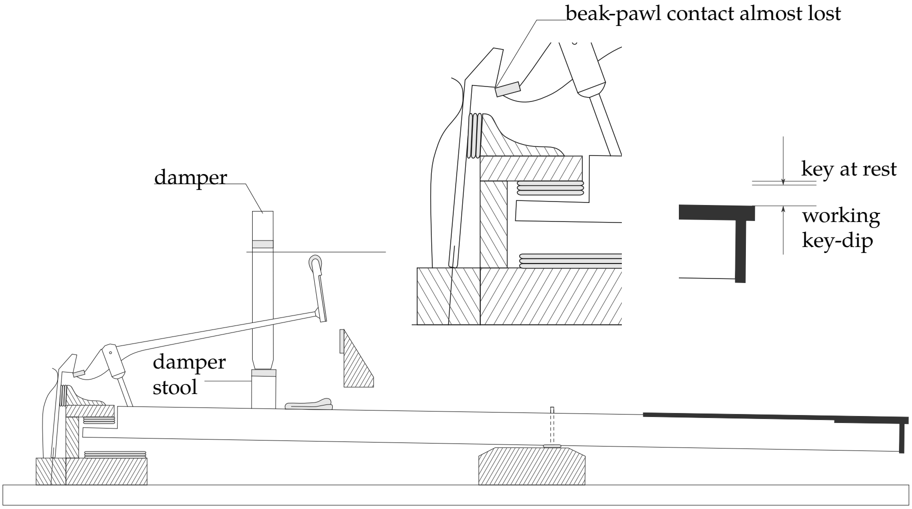


Figure 2.4: Geometrical escapement occurs when the beak leather and the pawl lose contact. Image adapted from Poletti, *Classical Viennese and south-German Piano Actions*, *op. cit.*

Right before the hammer impacts the string, the damper stool enters in contact with the damper and lifts it away from the strings (Figure 2.4). The damper is made of a wooden piece (here a small wooden slat) on which a leather pad is glued. When the key is at its rest position, the leather is in contact with the strings and damps any possible vibration. When it is raised by the damper stool the strings are free to sound. As soon as the key is released, the leather part of the damper falls back on the strings, causing the vibrations to be damped.

Aftertouch Aftertouch is defined as the portion of key-stroke after the hammer release, that is, between the point of escapement and the maximum dip the key can reach (Figure 2.5). This part of key travel contributes for a very minute part to the propulsion of the hammer as the latter has already escaped but is still moving along with the key.

In a normal key stroke, the hammer hits the strings during the aftertouch. When the hammer rebounds on the strings and if the key is kept depressed, the hammer gets caught by the check (if it is present, as in Figure 2.5). The check is installed in such a way that the hammer does not interfere with it during its upward trajectory. Because of its circular movement, the hammer approaches the check as the key is depressed. This small lateral shift is sufficient for the hammer to get caught by the check on its return trajectory.

The total amount of aftertouch is not as well defined as the *Schnabelluft* during lost motion. Often, it will be a question of personal taste of the musician. The main reason for this is the feeling aftertouch provides: as Paul Poletti il-

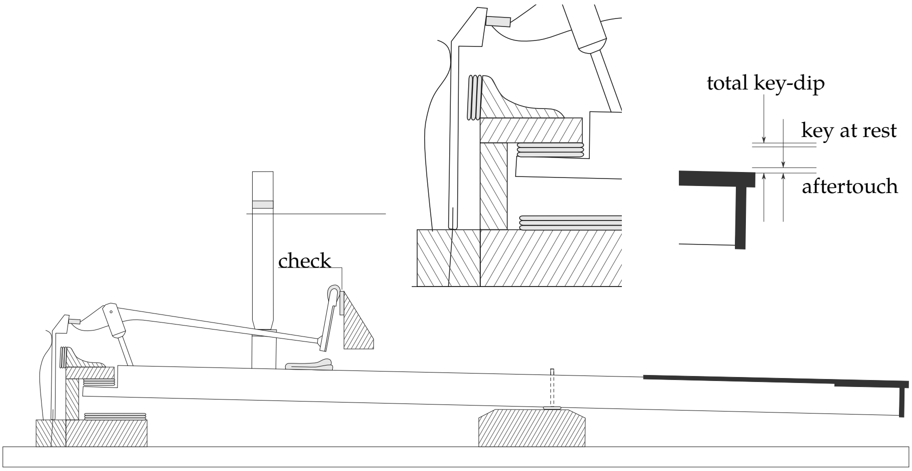


Figure 2.5: Aftertouch is the portion of key stroke after the escapement of the hammer. If the key is kept depressed, the check will catch the returning hammer. Image adapted from Poletti, *Classical Viennese and south-German Piano Actions*, *op. cit.*

lustrates it, aftertouch can be seen as the 'following-through' when throwing a ball with the hand. A similar example is the swing of a golf player. All these movements aim at achieving a precise control of the element that is propelled towards a well-defined objective. The continuation of the trajectory by the finger or the hand after release makes it easier to control the behaviour of the thrown object, even if it does not participate to the trajectory of the object any more. The inaccuracy of the total amount of aftertouch is also due to the cloth pad that defines its end point. Here again, as for the lower touch rail, the stop is composed of multiple layers of cloth sewed together on a piece of paper, which in turn is glued on the underside of the lower touch rail. This set-up confers a unique type of touch that cannot be reproduced with modern felt counterparts.

In the same way as lost motion, aftertouch may seem devoid of any function. In effect, it ensures proper functioning of the action under any circumstance. Even with the relative freedom of definition, some restrictions have to be brought to the lower and upper bound of aftertouch. No or negative aftertouch, meaning the hammer escapes at the precise moment of or right after the escapement, would transform the action in a non-escaping one. Obviously, this is not a desired behaviour. The effect of excessive aftertouch is more subtle; if, after hitting the strings, the hammer is caught by the check well before the key has reached its full dip, the hammer lies in a constrained position. On the one side, it is blocked by the catch, on the other side, it is pushed by the circular movement of the *Kapsel* that pushes it even more towards the check. Excessive stress of this nature applied to the hammer head and the *Kapsel* are clearly damaging for the action. The final amount of aftertouch can be fine-tuned by adding paper to the back-end of the key-tail. Conversely, aftertouch can be increased by thinning down the key-end.

2.2 The evolution towards a different pawl design

As we have seen in the previous chapter, the *Prellzungenmechanik* has shown little evolution during the period it was used.[3] Only three parts of the action have considerably evolved: the *Kapsel*, the presence or absence of a check and the design of the pawl.

In a general sense, the pawl evolves from an upright position, generally associated to Stein, to a forward inclined version whose invention is attributed to Walter. This evolution has been explained through many different reasons, but none are truly convincing enough. Among the reasons given for this evolution, it has sometimes been argued that the new design of the pawls was intended to diminish friction when the hammer returned in rest position.[4] It is true that in the upright Stein pawls, once the hammer has escaped, the pawl is pushed further backwards, which could lead to greater resistance when the hammer returns to its rest position. In contrast, with the forward leaning Walter pawl, the vertical face of the pawl approaches tangency with the arc of motion described by the hammer beak. It therefore forms a much lower impediment to returning motion of the hammer. We believe that this reconfiguration of the pawl was rather designed so as to prevent the hammer from blocking against the strings when the key is depressed violently.

Designing a proper *Prellzungenmechanik* escapement mechanism

In order to fully understand the origin of this shift in pawl design and its consequences, it is interesting to sum up the principles which allow to make a perfectly working pawl.

Beak-pawl orientation As we have seen in Section 2.1, the most important force contribution in the key rise is due to the initial contact between the pawl and the hammer beak. In order to prevent wear and damage of the leather beak, the upper surface of the latter should be parallel with the underside of the pawl at the moment of impact. If this condition is not respected, the disadvantages can be multiple. For the sake of clarity, let us consider a hammer beak that is horizontal at the moment of impact and that hits the underside of the pawl (Figure 2.6a). If the angle formed by the lower face of the pawl and the beak is positive ($\alpha > 0$) the left end of the leather beak will always be the first to be hit, leading to a mashed extremity. This wear will in turn lead to a constant variation of the geometrical escapement height, as the geometry of the contacting surfaces varies over time. A negative angle is also a bad idea ($\alpha < 0$), because the sharp edge will soon score a line in the leather (Figure 2.6b). Paul Poletti states that the pawl might even grab the beak and prevent it from escaping, which seems quite possible in view of the grabbing effect of the angle that has been observed in the well-conceived actions that were studied with high-speed imaging.[5] According to Paul Poletti, some instruments with these

[3] This section has been mainly inspired by Paul Poletti's observation, summarised in P. Poletti. 'Leaning-forward/forward looking'. 1994.

[4] M. Cole. *The Pianoforte in the Classical Era*. Oxford: Clarendon Press, 1998, p. 223.

[5] These actions, made by Paul Poletti are described in Section 3.1.

mistakes can be found, but he believes the makers of these instruments were unaware of the consequences of their bad conception, or simply did not care.

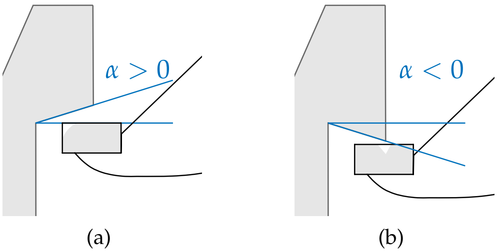


Figure 2.6: Negative and positive beak-pawl orientations lead to a gradual dysfunction of the actions. If the angle between both parts is positive (a), the left end of the beak will get mashed, if it is negative (b), the pawl will entail the beak.

Functional axis One of the key elements in the design and consequent behaviour of the pawl is the notion called 'functional axis' by Paul Poletti. The functional axis is defined as the imaginary straight line that runs from the notch edge to the pawl pivot. In the Stein-like instruments, the front face and the functional axis coincide (Figure 2.7a), but with Walter-type pawls, it is clear that the edge and the functional axis refer to two different notions (Figure 2.7b).

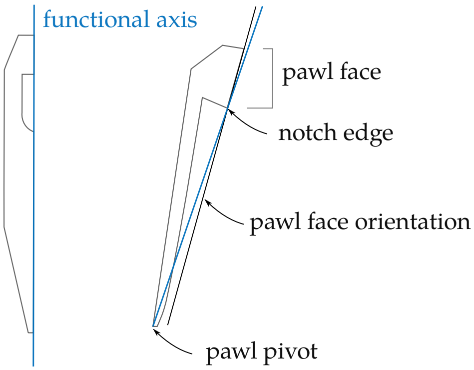


Figure 2.7: In the upright actions, the functional axis is confounded with the orientation of the pawl face. In forward-leaning actions, the two axes are often different.

Under the assumption that the upper beak surface and the underside of the pawl notch are parallel, we can study the effect of inclination of the functional axis. The orientation of the functional axis is critical after a first impact with the string, when the hammer beak re-engages itself under the pawl. If the functional axis and the beak/pawl are not perpendicular, then the rightwards movement of the pawl will cause extra *Schnabelluft* (Figure 2.8). This space does not contribute to the pawl getting back in position, but simply adds lost motion to the key. Consequently, any forward or backward regulation of the pawl will induce variations in lost motion along the keyboard, making it uneven. When the angle between the functional axis and the pawl is of 90°, this extra 'air gap' disappears and the action can have evenly distributed lost motion (Figure 2.9).

Paul Poletti thus has observed that (1) the pawl and beak need to be parallel, and (2) that the angle of these two elements has to be at 90° with the functional axis. Given that the hammer beak and the hammer shank are approximately parallel and inclined, it results that the pawl also has to be inclined. These design principles are indeed applied in Walter actions. It could thus be argued

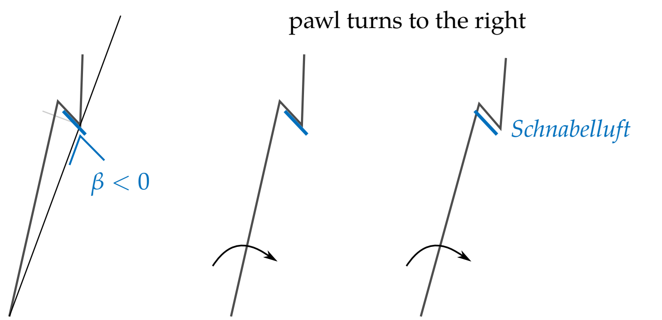


Figure 2.8: When the angle between the pawl/beak and the functional axis is not at 90°, undesired *Schnabelluft* is created when the pawl moves to the right.

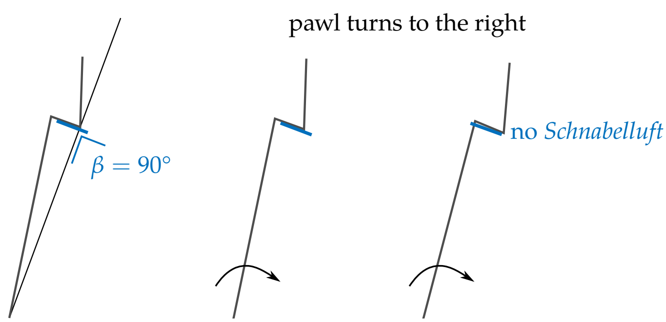


Figure 2.9: When the angle between the pawl/beak and the functional axis is at 90°, no extra *Schnabelluft* is created when the pawl moves to the right.

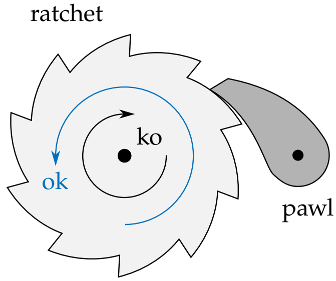
that Walter decided to incline his pawl in order to increase the lifespan of his leather beak and in order to counteract undesired *Schnabelluft*. Nevertheless, an important functional difference which will be explained hereafter can be found between straight and inclined pawls.

The ratchet and pawl system

Paul Poletti assimilates the escapement mechanism of the *Prellzungenmechanik* to a well-known mechanical device: the ratchet. A ratchet is a device that allows a movement in one direction, but restrains it in the other direction. The part called ratchet is a wheel or a linear rack that is covered with several angled teeth (Figure 2.10). A hinged hook, called pawl, slides on the teeth when the ratchet is moving in the right direction, and blocks its movement when the movement is reversed. The *Prellzungenmechanik* can be compared to a ratchet mechanism in which the ratchet is the hammer beak, hence the name given to the pawl.

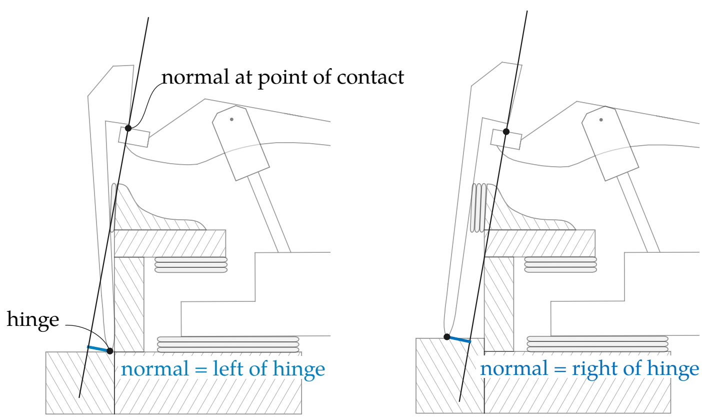
Ratchet and pawls could be found in many applications in the 18th century (capstans, clocks, mills, etc.). Considering his close link with the Imperial Royal Engineering Academy it seems more than possible that Walter was well acquainted with these subjects. Applying those design principles to a piano action, Paul Poletti suggests dividing the *Prellzungenmechaniken* in three groups. The distinction of each group is based on the line perpendicular to the pawl, at the point of contact with the hammer beak. This line is called the normal of the pawl. The main functional difference between the Stein and the Walter pawl would thus lies in the relationship between the position of this normal

Figure 2.10: The hinged pawl allows the movement of the toothed ratchet in one direction and blocks it in the opposite one.



with respect to the pivot of the pawl. Unlike the classical ratchet, the hammer beak changes its position and so does its contact point with the pawl. With this respect, three types of actions can be defined according to their pawl;

1. 'Grabber' pawls, typical of Stein instruments: the normal to the beak is always behind the pawl hinge point (Figure 2.11a). The pawl constantly grabs the pawl until it effectively escapes.
2. 'Slipper' pawls, typical of post 1805 Walter instruments: the normal to the beak is always in front of the pawl hinge point (Figure 2.11b). The pawl consequently has a tendency to slip off and this tendency increases as the hammer approaches the strings.
3. 'Grabber-slipper' actions start with their normal behind the hinge point and move in front, starting as grabbers and ending as slippers. Some transitional makers like Hoffman made these type of actions.

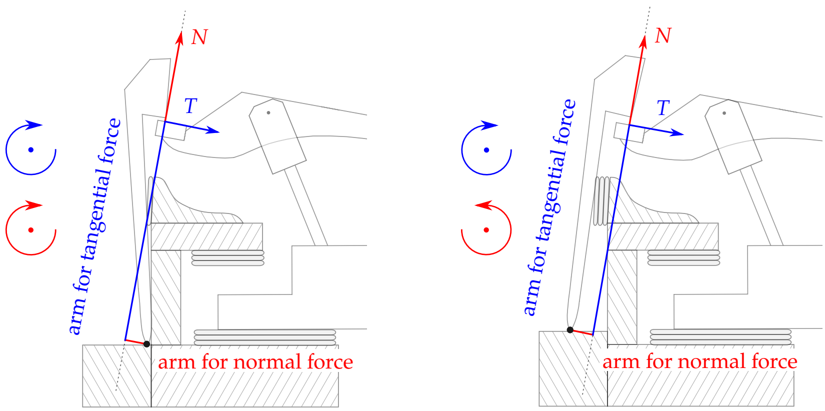


(a) Grabber pawl (b) Slipper pawl

Figure 2.11: If the normal passes on the left side of the pawl hinge (a), the *Prellzungenmechanik* is a grabber one; conversely if the normal passes on the right of the pawl hinge, the *Prellzungenmechanik* is a slipper one.

In slipper actions, the hammer can slip away from the pawl before having reached the traditional escapement point, whereas the grabber pawl firmly keeps the hammer in place. Slipping off can happen not only close to the end of key travel, but also at the beginning of key travel under a forte impulse. However, these are theoretical assumptions based on kinematic properties, in practice, the angle has to be steep enough in order to overcome friction between beak and pawl. In the case of Walter actions, two factors will influence the condition at which the pawl will slip: the inclination of the pawl is the main parameter, second comes the tension in the pawl spring which counteracts it.

Taking a closer look at the reasons that can explain the grabber or slipper characteristic of an action, one can decompose the interacting force between the hammer beak and the pawl. Looking at the straight Stein pawl or the inclined Walter version of Figure 2.12, it is possible to decompose the force of the beak on the pawl into a normal (N) and tangential (T) direction with respect to the pawl surface. The torque contribution of the beak force with respect to the hinge point (fix point) that will make the pawl rotate in one direction or in the other is determined by the product of each force component and its associated lever arm. In both cases, the lever arm for the normal component is small, but on the other hand, the normal force is logically of greater amplitude than the tangential component which is bounded through a friction force.



(a) Stein (b) Walter

Figure 2.12: Force decomposition for a Stein and a Walter pawl

In any event, looking at the initial rest position of the action, one can give some tendencies concerning the future behaviour of the pawl. In the Stein setup (Figure 2.12a), both force components will apply a clockwise torque on the pawl, meaning the pawl will have a grabber movement. On the other hand, with the Walter pawl (Figure 2.12b), this effect is made somewhat more complex, as the normal component tends to push the pawl backwards, while the tangential component contributes to a grabber behaviour. To those two elements, a third has to be added: the action of the spring which will add a clockwise torque component whatever its orientation. However, the amplitude of the spring torque will vary, as Walter and Stein actions are equipped with pawl springs of different stiffness.

The relative contribution of these three components is very difficult to measure on a real action, but can be deduced from the multibody model. Three conditions of key stroke are considered: a quasi-static, a *piano* and a *forte* depression. In the following results, the sign convention for the torque is chosen so that a positive torque pushes the pawl towards the pianist (to the right in Figure 2.12). The sign convention for the lever arm of the normal force is taken as positive when the line of action of the normal force passes on the right side of the pawl hinge.

Quasi-static stroke With this type of stroke, the key is fully depressed in about 6.5 s, which is even too slow to allow the hammer to hit the strings. Let us start by analysing the behaviour the Stein pawl (Figure 2.13). Compared to the other torque contributions applied to the pawl, the spring torque τ_{spr} is of equal importance (Figure 2.13). Furthermore, it is approximately constant and always positive, hence pushing the pawl to the right. Similarly, torque due to friction between the hammer and the pawl τ_T is always positive, but of smaller amplitude than the spring contribution. The most interesting component is the contribution of the normal force translated in torque τ_N; at the beginning of the key stroke, it contributes to the grabber nature of the Stein action. At 2.4 mm of key depression, τ_N changes sign (a in Figure 2.13, top). This can be explained by the fact that the normal to the hammer beak moves from left to right with respect to the pawl hinge, hence changing sign (a′ in Figure 2.13, bottom). Our Stein pawl thus seems to behave as a grabber-slipper action. In fact, the transition between the grabber and slipper behaviour occurs a bit later, as the effect of the friction force also needs to be taken into account. The real point of transition appears at 2.9 mm of key dip, when the sum of the tangential and the normal torque $\tau_N + \tau_T$ changes sign (b in Figure 2.13).

The resulting torques for the Walter set-up follow the same shape but shifted. The spring torque for example is of greater amplitude. This counteracts the effect of the negative torque of the normal force. The effect of the normal force is important enough so as to result in a negative torque, even when it is summed up with the friction torque. The Walter action is thus clearly a slipper action all the way through its key dip.

***Piano* stroke** The previous results were obtained from a simulation in which the dynamic effects of the action were negligible. When the key is depressed with a *piano* touch, the model behaves partly in the same way (Figure 2.14).[6] Let us first provide a discussion of the common features of both actions before analysing their own specificities.

The most striking result of this simulation is the relative importance of the torque that is due to the tangential force (Figure 2.14, top and middle). Not only is it important with respect to the normal torque component τ_N of the present simulations, it is also proportionately much more significant than in the quasi-static simulation (Figure 2.13, top). In both cases, the torque due to the tangential force τ_T largely dominates the torque component due to the normal force. Since the lever arms are precisely defined geometrically, we believe that this result comes from an overestimated value of the friction coefficient between the beak upper edge and the pawl. Let us not forget that the torque is

[6] The movement of key depression that is imposed in this simulation is described in Section 8.2.

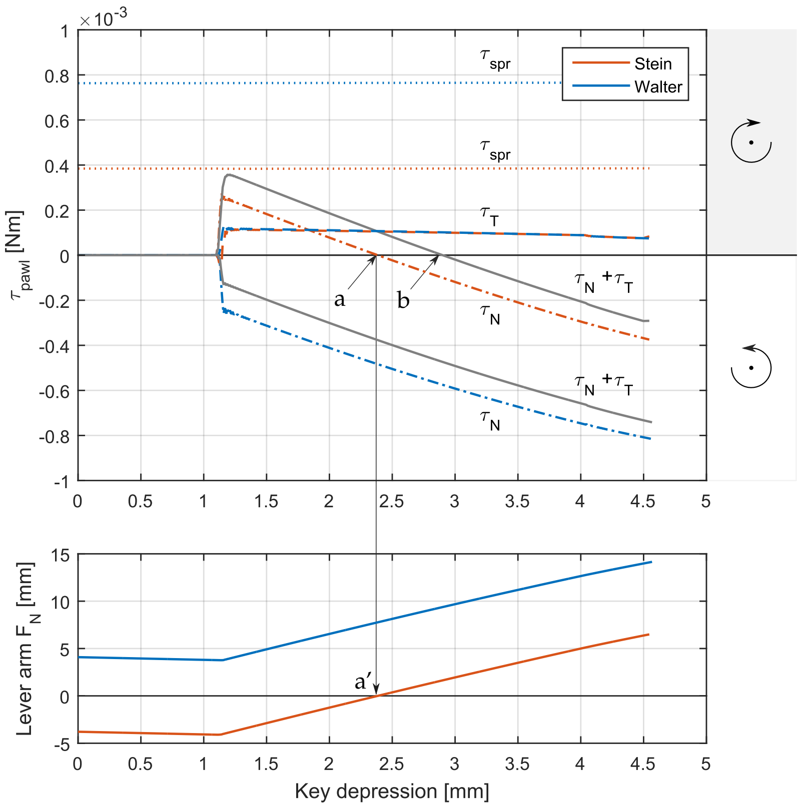


Figure 2.13: Analysing the torque applied on the pawl confirms the grabber nature of the Stein pawl and the slipper nature of the Walter action. Note that the Stein action transitions from grabber to slipper.

the product of a force and a lever arm. In the case of the friction force, the lever arm is about 10 times longer than for the normal force. As a result, inaccuracies in the computation of the friction force are felt more significantly in the total torque. Due to this overestimated friction torque, the model predicts both actions to work as grabbers during the major part of the key stroke. However, the contribution of the normal force behaves exactly the same in the quasi-static simulation. In case of the Walter action, τ_N is always negative, and thus causes the action to be slippery. For the Stein action, the normal component is of much smaller amplitude, but it does follow the grabber-slipper scheme that was already observed previously. Even though a change in friction forces (for example by lowering the friction coefficient) would certainly impact the results for the normal forces, we believe the correct tendencies for the net contribution of both.

The fact that the sign for the lever arm of the Stein action changes through a continuous movement also means that approaching a zero value, the lever arm is accordingly small. As a consequence, in this part of key stroke, the tangential torque will always dominate the effect of the normal force.

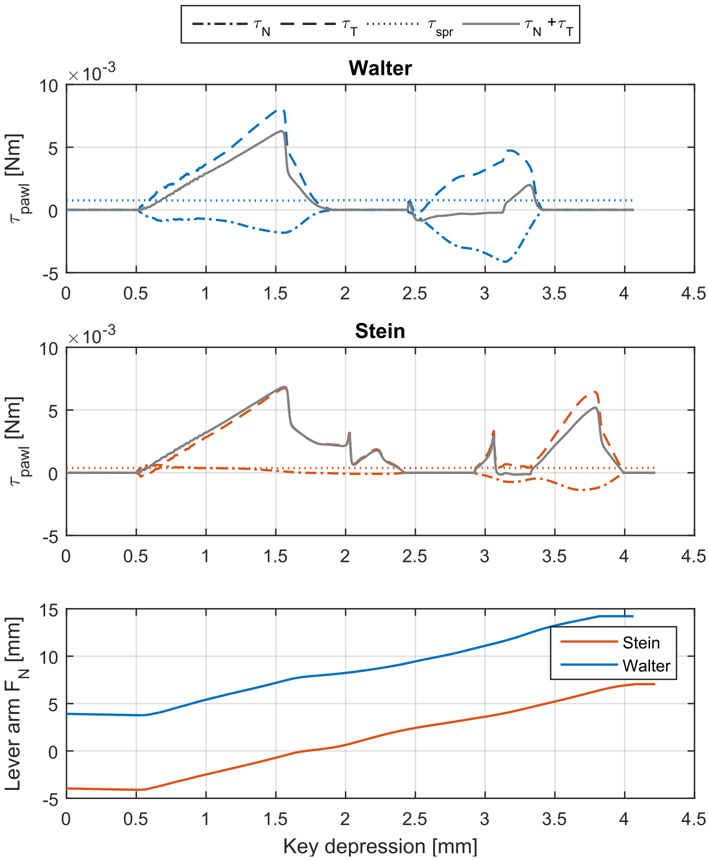


Figure 2.14: Torque components applied to the pawl under a *piano* key stroke for the Walter action (top) and the Stein action (middle). The lever arm for both cases (bottom) explains the shift in sign for the normal force in the Stein action.

***Forte* stroke** For a key stroke that produces *forte* dynamics, the excessive contribution of the tangential component is less pronounced (Figure 2.15).[7] With the Walter pawl, the normal force contributes to the slipper nature, the tangential force to the grabber nature of the action. Overall, the tangential torque component has the upper hand and the action is a grabber one. The Stein pawl follows a more complex behaviour; as expected, τ_N is first positive before becoming negative under the change of sign of its lever arm. Unexpectedly, the tangential component switches from a negative torque to a positive one. In the end, the action is also a grabber action all along the key stroke. Although the torque decomposition for each action follows a different behaviour, the resulting torque is very similar for both of the actions. The portion of key stroke during which the hammer beak and the pawl interact is thus almost identical.

[7]The movement of key depression that is imposed in this simulation is described in Section 8.1.

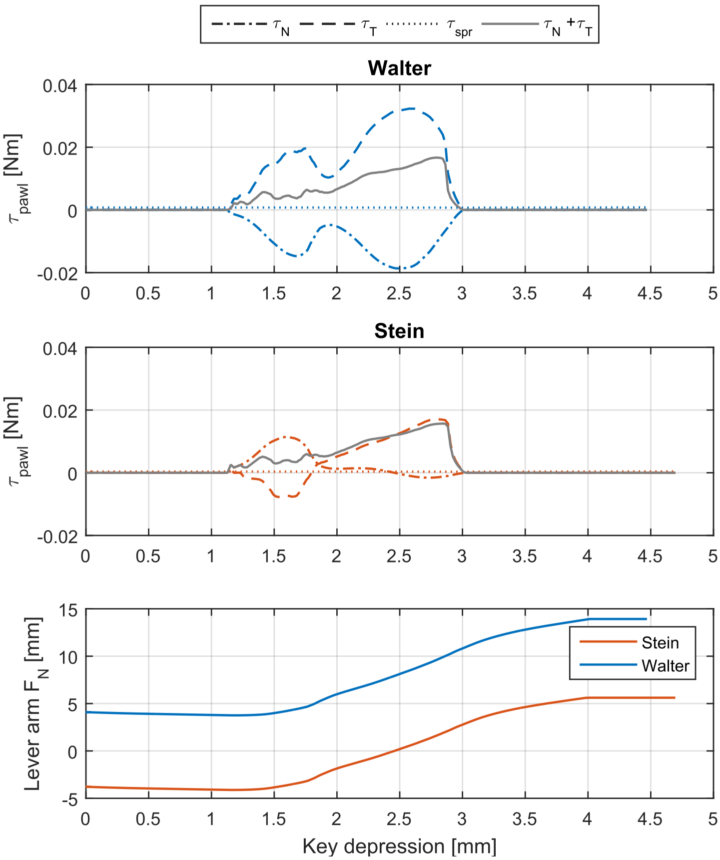


Figure 2.15: Torque components applied to the pawl under a *forte* key stroke for the Walter action (top) and the Stein action (middle). The lever arm for both cases (bottom) explains the shift in sign for the normal force in the Stein action.

2.3 Model/experiment-based characterisation of the action

Besides the comparison between the geometry of the Walter and the Pawl action, the multibody models that have been developed and the experiments that have been led enabled us to explore other interesting characteristics of the *Prellzungenmechanik*. Three of these investigations are developed here. The first results that are presented concern the regulation of the escapement. These numerical experiments were carried out via a multibody model of a *Prellzungenmechanik* held at the Musical Instrument Museum Brussels. In a second place, we discuss the displacement ratios between the key and the hammer. Usually, these ratios are considered with the action working statically. In this study we observe what these ratios become under dynamic conditions. Lastly, we propose to shed light on the function of a small component of the action; the slap rail.

Regulation of the escapement height

The escapement height of an action strongly influences the way it behaves and consequently, the sense of touch felt by the pianist. When the escapement height is small, it means the hammer escapes near the strings. In this case, the hammer is in free flight during a limited portion of its travel towards the string. Actions set up with a small escapement distance are felt by pianists as being 'stiff', but seem to ensure a good control of the action response. A drawback of such a regulation is that the hammer can get jammed against the string, particularly if the key is hit with much force. Increasing the escapement height gives the feeling of a smoother action, but goes together with a loss of precision; it will for example be much more complex to produce a controlled *piano* sound because the portion of stroke during which the hammer is in free flight is larger. Another drawback is the fact that the sound loses power.

Regulation of the escapement height is done by changing the initial inclination of the pawl. Since the pawl is pressed against a cloth stop under the action of a spring, its rest position can be adjusted by shifting its stop forward or backward. In early (and even in some later) *Prellzungenmechaniken*, no special device was foreseen to this end, and technicians had to place thin plies of paper of varying thickness behind the cloth stop. Later instruments were equipped with a regulation screw that pushed a common stop-rail for several actions. Fine-tuning of each individual pawl still had to be performed with the paper method.

If the pawls are moved towards the pianist, let-off will occur closer to the strings and thus provide larger control over the hammer travel (Figure 2.16). This is especially beneficial for the softer dynamic range of the instrument, for which the hammer disposes of less momentum to reach the strings. Moreover, the short free-flight of the hammer enables the pianist to finely bring the hammer close to the string. If the pawl is too much inclined towards the pianist, the hammer never escapes and gets jammed against the strings. The ideal regulation is achieved when the hammer escapes as close to the string as possible, without jamming under forceful keystrokes. In practice, it is often said that this corresponds to a geometrical escapement height set approximately at 2 mm from the strings.

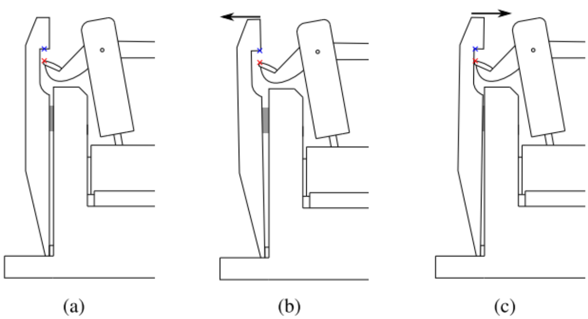


Figure 2.16: The escapement height is regulated by changing the position of the pawl stop (grey rectangle). Compared to the reference case (a), escapement-height increases when the pawl is away from the pianist (b), and decreases when the pawl is positioned closer to the pianist (c).

The consequence of the regulation of the pawl, and thus of the escapement height, have been studied with a multibody model of a Stein action.[8] After the study had been carried out, it appeared the action in question was historically inaccurate. It is thus logically slightly different than the one reproduced by Paul Poletti. Nonetheless, in view of the planned investigations, its functioning is globally speaking identical and it provides correct and insightful results and conclusions.

Sensitivity of the regulation Let us define Δx the displacement of the stop with $\Delta x > 0$ a movement of the pawl to the right (towards the pianist, see Figure 2.16). With respect to a reference regulation for which the hammer escapes dynamically[9] at 2.2 mm (Figure 2.17), simulations confirm that a shift of the stop to the right ($\Delta x > 0$) causes a decrease of the escapement height, whereas a shift to the left ($\Delta x < 0$) causes an increase of this value. More interestingly, one notes the steep slope of this quasi-linear relationship between escapement height and the initial position of the pawl. Indeed, the relationship of 1/20 means that moving the regulation screw by 0.1 mm changes the escapement position with 2 mm. Knowing that a homogeneous touch of the piano throughout its entire range can only be assured if the escapement height is regulated with a precision in the order of 1 mm, one can understand how meticulous the technician proceeds in his work. It is also remarkable to note the limited range of action the technician disposes of. Outside of the pictured bounds, the model shows that the action does not work any more, that is, if the pawl stop is shifted more than 1.25 mm to the left or 0.2 mm to the right. When $\Delta x < 1.25$ mm, the pawl notch is simply too far from the hammer beak for both bodies to enter in contact. Letting the pawl lean too much to the right prevents the hammer from escaping.

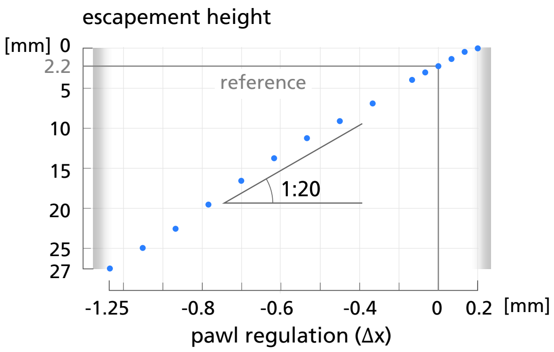


Figure 2.17: The relationship between the pawl stop and the dynamic escapement height is quasi-linear. Negative displacement values indicate a shift of the stop to the left.

Event timing of the action Let us now observe the influence of the escapement height regulation on the full key stroke. In order to have a more precise

[8] The model is described in B. Bokiau, A.-E. Ceulemans and P. Fisette. 'Multibody dynamics as a tool for historical research. Study of an 18th century piano action of Johann Andreas Stein'. In: *Multibody System Dynamics* 37.1 (2016), pp. 15–28. The article detailing the elements of the model is reproduced in Appendix B

[9] The key is depressed with a 100 g mass, causing a movement that cannot be considered as quasi-static any more.

idea of what happens when the escapement height varies, it is interesting to observe the timing of two events during a key stroke for each regulation. Figure 2.18 has to be read bottom-up, starting at $t = 0$ s where the key is hit. The first marker shows the moment at which the hammer escapes; the more the pawl is shifted to the left, the earlier the hammer escapes. This is also in agreement with the increase in escapement height (Figure 2.17); escaping earlier means the action escapes further from the string. Conversely, it is fairly logical that the escapement is delayed as the pawl is moved more to the right.

The upper markers indicate the moment at which the hammer hits the string. Going from left to right, this event appears asymptotically sooner when the pawl is moved to the right. This is a first hint indicating the sense of control the action confers to the pianist; the earlier the hammer escapes, the later the sound will be produced. Another important factor is the so-called 'free flight' during which the hammer moves towards the strings, without the pianist being able to control it any more. The free flight of the hammer happens between the escapement and the impact of the string. Intuitively, it seems logical that being unable to control the hammer over a long period of time gives rise to a less controllable action.

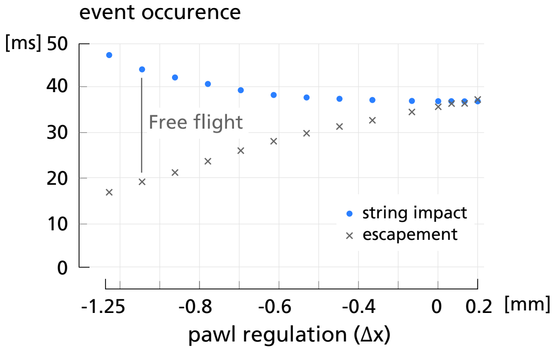


Figure 2.18: The moment at which the hammer escapes and at which it hits the string is conditioned by the regulation of the pawl. The free flight of the hammer is the period between those two events, when the hammer flies independently of the action of the pianos.

When $\Delta x > 0$, the markers are almost indistinguishable. With a closer look, one even realises that the hammer escapes after having hit the string for a regulation near $\Delta x = 0.2$ mm. When this happens, the finger of the pianist controls the hammer until it reaches the string, but has to force the movement of the key in order to let the hammer beak escape from the pawl notch. This phenomenon goes together with an audible 'click' caused by the forced escapement of the hammer. The musician masters the behaviour of the hammer throughout its entire movement, but the produced sound will certainly be poor and muffled because the prolonged contact of the hammer on the string mutes the first vibrations of the latter. From the touch point of view, forcing the escapement is not acceptable since it requires a more important force and leads to a non-smooth action.

String impact force Another important and logical characteristic of the free flight of the hammer is the fact that the hammer stops being propelled by the pawl notch, causing it to decelerate. This does not only affect the response time of the action, but also the force with which the string is struck (Figure 2.19).

The relation between the peak force on the string and the displacement of the pawl is linear to a large extent. This is especially the case for $\Delta x < 0$; on this side of the reference, the action loses approximately 1 N for every 0.2 mm the pawl stop is displaced. However, when $\Delta x > 0$, the force keeps approximately constant. When this happens, the pianist controls the hammer up to the point where it hits the string, meaning the hammer never decelerates, but is also unable to accelerate even more. Having reached a threshold limit in terms of impact speed, the force is also limited.

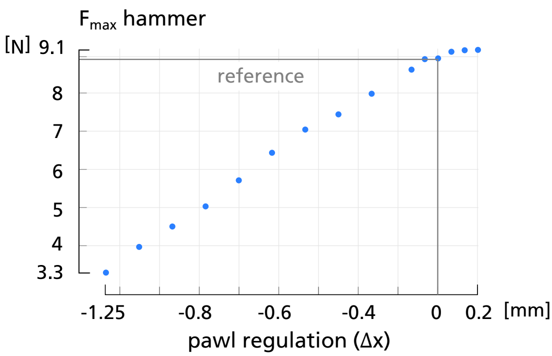


Figure 2.19: The maximal force applied by the hammer on the string diminishes linearly when the pawl is moved to the left. Shifting the pawl to the right does not significantly increase the force which saturates.

Discussion Let us summarise these different observations and confront them with the experience of pianists and technicians. It seems the terms 'rigid' and 'smooth' used to define the feedback of the key is influenced by the instant of escapement and string impact, and probably even more by the duration of the free flight of the hammer. The sense of control is linked to the same values, as a large escapement height not only induces an increase of free flight duration (that is, of uncontrolled hammer travel), but also a longer time between the key depression and the produced sound. Considering the auditory feedback, it appears that pushing the pawl to the left potentially has a strong decreasing influence on the amplitude of the sound. Conversely, diminishing the escapement height even more than in the reference cases induces a very limited effect.

Having observed this via the model, we can appreciate the advantages of a well-regulated action with the escapement height set between 2 mm and 3 mm. Set at this distance, the free flight is limited to a very small portion of the hammer travel; it enables the pianist to control the motion of the hammer up to the very end and to benefit from an ideal maximal force.

Is the PZM a decelerating action?

It is often stated that the *Prellzungenmechanik* is by nature a decelerating action. Arguments used to support this claim are based on the fact that the motion of the hammer is a combination of circular trajectories; the first being the circular movement of the key, the second that of the hammer head that pivots with respect to the key. Thanks to this combination of rotations, the hammer beak of the *Prellzungenmechanik* moves away horizontally from the pawl in order to escape. Another consequence of this horizontal movement is that the leverage ratio of the action changes along with key depression, as it has already been observed by many scholars.[10]

A quasi-static simulation in which the key was depressed very slowly (a full key depression of 4.62 mm in 6.4 s) applied to the Stein and the Walter multibody models showed that both actions behaved exactly the same way. Hence, only one curve will be presented as the quasi-static reference curve in what follows (Figure 2.20). A common way to observe the effect of the key depression consists in displaying the hammer rise as a function of key depression (Figure 2.20, left). The displacement ratio between the depression of the key and the hammer head corresponds to the slope of this curve (Figure 2.20, right).

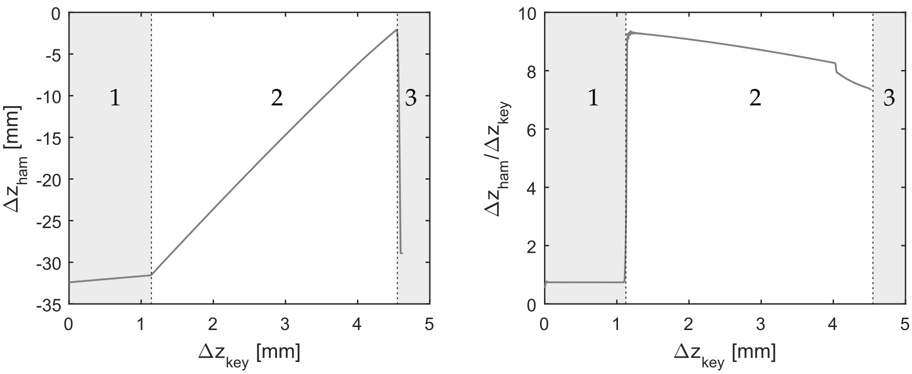


Figure 2.20: Left, the hammer-string distance as a function of key depression. Right, displacement ratio between the hammer and the key as a function of key depression. The three different phases of hammer motion are clearly visible: (1) lost motion, (2) working key-dip, (3) aftertouch.

Three different phases are clearly distinguishable (Figure 2.20): the first is the lost motion that goes until a little more than 1 mm of key stroke. At this point, the hammer simply rises along with the movement of the key. The second stage, the working key-dip, begins after the end of the lost motion, that is, when the hammer beak starts engaging the pawl. At this point, the double leverage system of the action comes into effect, displaying an advantageous geometrical ratio of a little more than 9 at the beginning of the working key-dip. As the key is further depressed, the ratio slowly diminishes to a value slightly inferior to 8. The last phase is the aftertouch, which corresponds to the moment after the hammer has escaped. The action has been regulated so that this would happen when the hammer is 2 mm away from the strings. In this quasi-static simulation, the hammer directly falls back on the key as it does not have enough momentum to close the distance with the string. From this first observation, it thus looks like the *Prellzungenmechanik* is a decelerating action, though it would be more appropriate to speak about a decreasing displacement ratio.

[10] Cole, *op. cit.*, pp. 292-306.

Observing the same quantities for an action that functions under a normal key blow enables us to nuance the previous observations. The Stein and Walter model were regulated with an escapement distance of 2 mm from the strings under static let-off. When the action is played with soft dynamics,[11] it is already clear that the displacement ratio deviates from the quasi-static reference curve as it fluctuates around this curve (Figure 2.21, bottom). Even more interesting is the fact that the displacement ratio can increase during the key stroke instead of decreasing. The ratio curve for the Walter action shows such a behaviour; towards the end of the key stroke, the ratio reaches a peak value of 12 (Figure 2.21, bottom). In the Stein action, this effect is also present, but to a lesser extent.

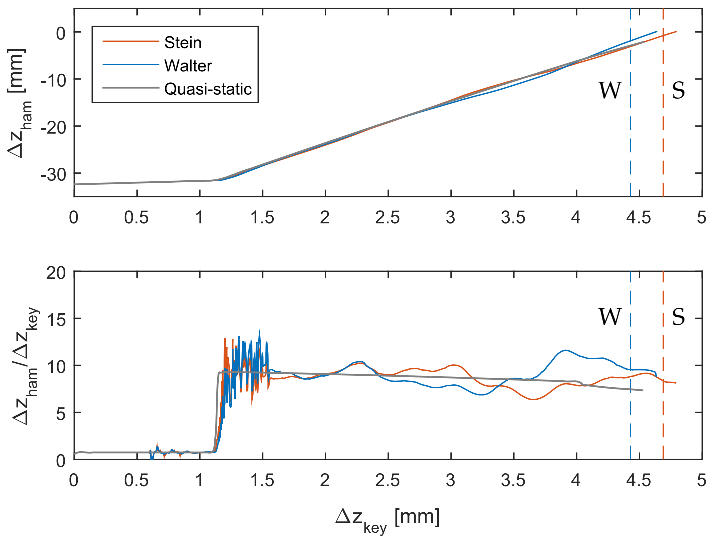


Figure 2.21: Top, the hammer-string distance as a function of key depression. Bottom, displacement ratio between the hammer and the key as a function of key depression. Even with a *piano* touch, the displacement ratio does not follow the quasi-static reference. The moment of escapement is indicated with a vertical dashed line.

Unlike the quasi-static results for the reference curve (Figure 2.20), the results for the dynamic simulations are shown until the maximal string deformation. The beginning of aftertouch is also displayed as the moment of escapement is represented by a vertical dashed line (Figure 2.22). We learn from this that escapement occurs earlier in the Walter action than in the Stein one. The escapement distance seems to confirm the grabber and slipper character of the actions: the Stein one escapes at 0.77 mm and the Walter at 1.90 mm. Nevertheless, as will be seen with the *forte* impulse, this cannot always be verified. As an indication of the speed of key depression, let us finally note that for this *piano* impulse, the 4.88 mm of key depression were reached in 0.12 s. In other words, the results displayed in Figure 2.21 covers an interval of a little more

[11] The movement of key depression that is imposed in this simulation is described in Section 8.2.

than 0.1 s, while the quasi-static results of Figure 2.20 cover a period of about 6.5 s.

When the actions are played upon with more force (*forte* touch),[12] the variations in terms of displacement ratios are even more obvious (Figure 2.22, middle). Observing this side by side with the vertical deformation of the hammer shank (Figure 2.22, bottom), it can be seen that the moments at which the ratio is the highest correspond to the instant at which the hammer shank recovers its initial deformation. Birkett concluded that the indirect relation between key depression and hammer rise is due to key flexing.[13] Our model does not contain any key flexing, but it does incorporate hammer flexing. In view of Figure 2.22, it is thus clear that the deformation of the hammer also plays a very important role in the displacement ratios. However, given the absence of key flexing in our model, it could not be evaluated which of the key or hammer flexing is the most significant contributor.

For this type of *forte* input, the two curves for the Stein and the Walter action almost exactly coincide and let-off occurs at the same point of key-depression for both actions. This is probably due to the fact that for stronger impulses, the impact model between the beak leather and the pawl is not enough damped. Consequently, at high dynamics, the interaction between both components is stiffer than in reality and does not reflect their complex interaction well; instead of riding against the pawl, the beak bounces forcefully against it; this suggests us to improve and to refine the model to better capture the impact in case of high dynamic situations.

The function of the slap rail

In a real action, there is a stop rail about 1 cm behind the pawl. Some musicologists and piano makers are of the opinion that the rail is there to protect the pawls when the action is removed from the frame, hence calling it in German *Auslösserschützleist*. Others think that it is to prevent extreme backward movements of the pawl and call it a 'slap rail'.

Birkett studied the motion of the pawl under different types of key strokes and concluded that a slap rail was only needed for the Walter action, when its static escapement was set too close to the strings.[14] He also asserts that the geometry of Stein's action mechanically constrains the motion of the pawl. From our high-speed imaging experience, the pawl displays an extreme backward movement both for the Walter and the Stein actions when they are depressed with much force. This phenomenon does not necessarily require the escapement to be set extremely close to the strings. Three snapshots of the pawl motion enable to visualise this: the pawl when the key is at rest (Figure 2.23a), the rightward movement of the pawl just before escapement (Figure 2.23b) and

[12] The movement of key depression that is imposed in this simulation is described in Section 8.1.

[13] S. Birkett. '"Nourishment for the soul" or "feast for the ear"? A comparative study of the Stein and Walter fortepiano actions'. In: *Chopin et son temps. Chopin and his time*. Actes des Rencontres Internationales *harmoniques*, Lausanne 2010. Proceedings of the *harmoniques* International Congress, Lausanne 2010. (Lausanne). Ed. by V. Hug and T. Steiner. Vol. 54. 2. Bern: Peter Lang, 2016, p. 167.

[14] *Ibid.*, p. 163.

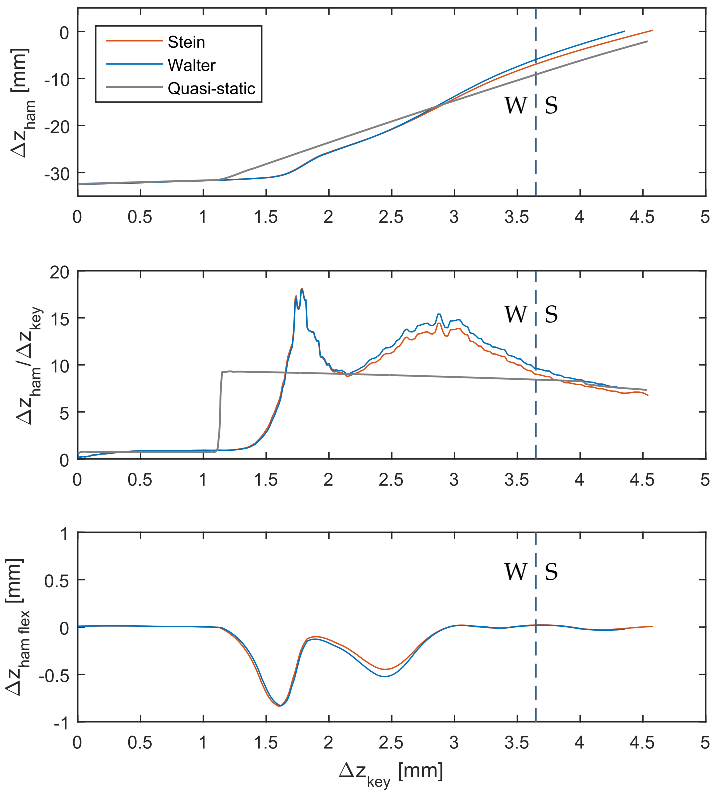
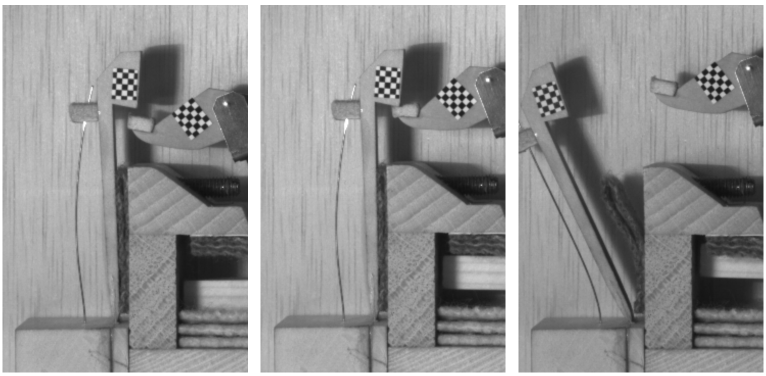


Figure 2.22: Top, the hammer-string distance as a function of key depression. Middle, displacement ratio between the hammer and the key as a function of key depression. Bottom, vertical deformation of the hammer shank measured at the hammer head. The origin of a higher displacement ratio is partly due to the deformation of the hammer shank.

the kickback of the pawl after escapement (Figure 2.23c). This phenomenon could not be captured via the model, due to the simplifications of the contact between the hammer beak and the pawl, as explained in Chapter 8. Two paths of research can be envisaged to study this in more depth. The first consists in a refinement of the leather beak model in the multibody model, in particular by taking the beak tip deformation into account. A second idea would be to exploit our high-speed videos in greater depth. In any case, these first results obtained via high-speed imaging tend to confirm that the slap rail was intended to limit extreme movements of the pawl when the piano was played with much force.



(a) (b) (c)

Figure 2.23: Evolution of the pawl for a Stein action during a *fortissimo* key stroke. (a) The pawl at rest, (b) the pawl is pulled to the right, (c) the pawl is propelled to the left at a great distance.

Chapter 3

Experimental set-up

The behaviour of the real *Prellzungenmechaniken* that are presented in this document has been observed and tracked via different methods which have constituted very useful tools for this research: they are detailed in this chapter. By experimental set-up, we designate the means that were used to measure and reproduce the effect of a pianist playing a note on a *pianoforte*. Experimental set-ups used for other more targeted purposes, like the hammer string-deformation, are presented in the corresponding chapters.

In the first part of this chapter, an action with interchangeable Walter and Stein parts is presented. After this, the tools and methods used to track the dynamics of the action are described. Subjects related to this are the finger-key force measurement, high-speed photography and the methods used to track the movement of the action components. Finally, the experimental trichord comprising all these elements is presented.

3.1 Action

The aim of our study being to assess the importance of the pawl design in the pianos of Johann Andreas Stein and Anton Walter, a hybrid piano action that can easily incorporate the two types of pawls (the inclined and the straight version) has been conceived by Paul Poletti. The result is an action that features the characteristics of Viennese actions as they were built by Walter from the mid-1790's on (Figure 3.1).[1] The action thus comprises a brass *Kapsel*, a catch and a low cloth damper for the hammer. The choice for this approach is obviously historically less correct than comparing two distinct actions made by makers that adhered to these distinct schools, but it has the great advantage of minimising the differences between the observed configurations, and thereby isolating the phenomenon that is to be studied.

Just as in the modern piano, the actions and strings for pianos of the late 18th century were usually designed differently for bass and treble notes. As strings for bass notes were thicker (and thus heavier), the hammers that bring

[1] The instrument is in a privately held collection, bearing a 'Walter und Sohn' nameplate. Indications concerning its fabrication date are inexistent, but it has most likely been built around 1803.

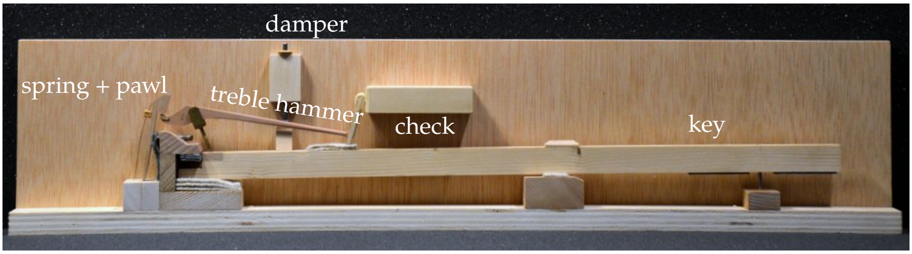
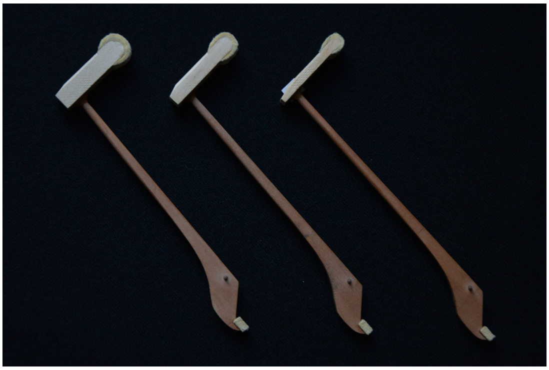


Figure 3.1: A hybrid action in which both the Stein and the Walter type pawls can be used has been built by Paul Poletti. The pawl and the hammer can be replaced and the check regulated in order to function properly with every hammer.

them in vibration were also more imposing. Dynamically speaking, it can thus be expected that with a unique action, the response of bass and treble notes indubitably display different properties. In view of this, the action assembly has been designed by Paul Poletti so that it would be suitable for bass, medium and treble notes. Three hammers for the pre-cited registers can easily be exchanged in the action thanks to the brass *Kapsel*.[2] Each of them has different lengths and mass distribution (the treble hammer being the longest and lightest).

Figure 3.2: The three hammers (for bass, medium and treble notes) used in the experimental set-up.



Usually, the variation in mass properties of the hammers throughout the range of the piano is counterbalanced by adapting the mass distribution of the keys. This ensures a balanced touchweight throughout the entire range of the keyboard.[3] Also, the length of the key can be dictated by the strike distance of the hammer with respect to the string, meaning that the length of the keys also varies. These two variants have not been incorporated as it is supposed that they are of little influence in studying the effect of pawl design. It has instead been chosen to use the exact weight and length of a c^1 key.

Two types of pawls can be installed in the action: an inclined Walter-type pawl, and an adapted Stein-pawl which engages the hammer at a much more

[2]As discussed in Section 1.2, the wooden *Kapseln* used in the Stein-type actions require a much more complex and non-reversible process to remove or install hammers.

[3]This does not necessarily mean that every key has the same touchweight; most often, bass keys intentionally feel a bit heavier.

upright angle. Each type of pawl also has its own spring that goes with it; the Walter-pawl requires a different spring for each hammer, whereas the Stein-pawl is equipped with the same spring whatever the register. For each configuration, the rest position of the pawls can be adjusted with a regulation screw.

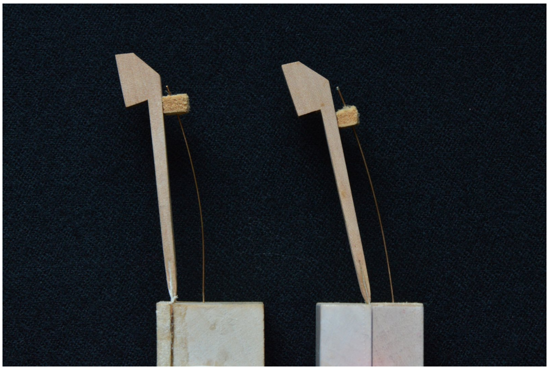


Figure 3.3: (left) The Stein-type pawl is of the upright type, with a marked notch angle. The spring used to keep it in place is the same for all the hammers. (right) The Walter-type pawl has its hinge further away from the hammer and is consequently more inclined. The spring and its wooden support behind the pawl hinge can be removed when the pawl-spring has to be exchanged.

The action set-up is mounted with an adjustable catch that can be adapted to the changing length of the keys. A dummy string damper in the form of a nail of the exact weight of a normal damper is included in the action. Nonetheless, it has been decided to remove it from the action as its contribution was considered to be negligible.

In the initial stage of experimentation, the action was deprived of a stop rail for the pawl. Extremely large movements of the pawl incited us to add this feature in the form of a simple wooden block behind the pawl (not visible in Figure 3.1).

The materials used in the reproduction of the action have been carefully selected by Paul Poletti, so that they would closely correspond to those found in the original *Prellzungenmechaniken*. A summary of the materials can be found in Table 3.1. The materials are classified by the component on which they can be found or with which they interact.

3.2 Force Measurement

In all experimental set-ups, the great challenge of measuring data consists in limiting the perturbation caused by the measurement. In the case of force measurements of the finger impetus in piano actions, this is particularly true as musicians are very sensitive to the feel a key provides. Most, if not all load cells are a few millimetres thick and therefore form a disturbing ledge on the perfectly flat key surface. Moreover, the surface of measurement is often limited. These drawbacks are of special importance when one tries to reproduce different types of finger-touch, especially for ancient piano techniques where the finger 'squeezes' the key. Indeed, this type of movement requires the finger to slide upon the surface of the key, which is impossible when an obstacle refrains momentum of the finger.

The sensor that has been chosen for our experiments is a FlexiForce thin-film force sensor developed by Tekscan Inc., which uses a resistive-based ap-

Table 3.1: The action is exclusively made with materials that were available to *pianoforte* makers of the late 18th century.

Key	
body	common European or 'Norway' spruce (*Picea abies*)
rest cloth	woolen cloth
touch key cloth	woolen cloth
balance rail	woolen cloth
Kapsel	brass
Hammer	
shank	common pear (*Pyrus communis*)
head	common lime (*Tilia x europaea*)
beak leather	calfskin
head leather	sheepskin
axle	steel
catch leather	deerskin
Pawl	
body	common pear (*Pyrus communis*)
stop cloth	woolen cloth
spring leather	steel
spring	brass
articulation	parchment
Strings	
C	brass
c^1	iron (Malcolm Rose B)
f^3	iron

proach (Figure 3.4). It has been selected for its very low thickness (0.203 mm), low weight (0.72 g) and ease to install on the key surface without causing too big a difference in height. The active zone for force measurement is a circular area with a diameter of 1 cm. When the key motion is driven by the actuator, the contact surface of the actuator rod is too small to produce correct measurements. For this reason, a rigid plastic cover has been glued on top of this zone in order to distribute the force of the finger on the active area of the sensor. Unfortunately, this significantly increased the height of the sensor. It was also clear that *forte* squeezed touches would be difficult to measure, as they require a greater contact surface for the sliding finger. Nonetheless, all other types of key depressions were found to be reasonably easy to measure.

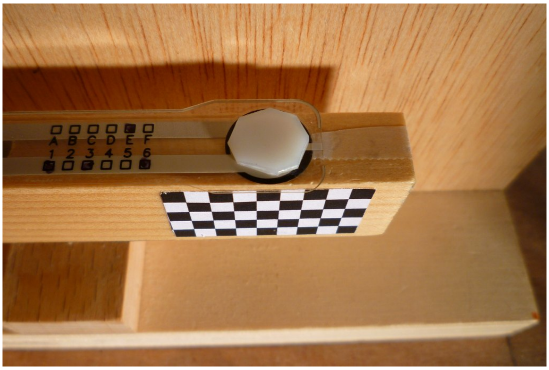


Figure 3.4: The Tukscan FlexiForce sensor has been chosen for its compact size. A plastic cover has been glued on top of the active sensing area so that the force would be restricted to it.

Several FlexiForce sensors with different basic dynamic ranges exist, their maximal force measurement capacities being respectively limited to 4.448 N, 111.2 N and 444.8 N. Maximal force amplitudes of 30–40 N have been measured by Hirschkorn for *forte* blows on a modern grand piano.[4] Thorin obtained values up to 16 N.[5] For the same dynamics, but on a modern upright piano, Masoudi measured force peaks at *ca* 15 N.[6] *Prellzungenmechaniken* being much lighter than their modern counterparts, the maximal amplitudes of the forces that will be measured are expected to be closer to 10 N than 100 N. The first sensor with a capacity up to 4.448 N has therefore been selected, and its range has been extended by adapting the reference resistor in its force-to-voltage circuit.[7] The whole measurement set-up has been calibrated statically with small masses so as to define a tension-force curve. Data are acquired with a National Instruments NI USB–6521 acquisition card at a sampling rate of 10 kHz (Figure 3.5).

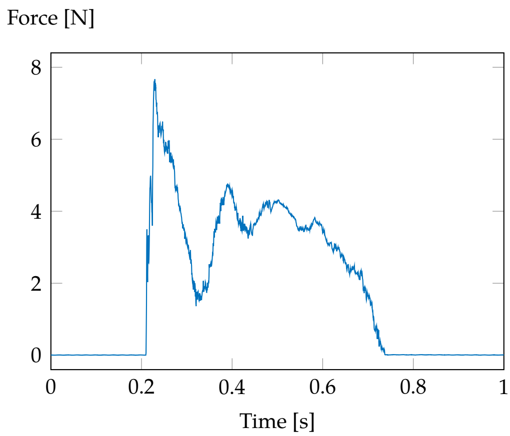


Figure 3.5: A typical force profile for a slightly maintained *forte* blow that is performed with the finger starting from above the keyboard. Note the strong peak at the beginning due to the sudden contact between the finger and the key.

3.3 High-speed photography

Many observations have been performed with the help of high-speed imaging. A Photron FASTCAM SA3 model 120K-M1 camera has been used to this end. The camera can record up to a frequency of 120 kHz at low resolution (128 × 16 pixels). At the maximal resolution of 1024 × 1024 pixels, the frame rate is limited to 2 kHz. A trade-off between those extreme values of spatial and temporal resolution was chosen according to the nature of the phenomenon that was observed. As a convention, the frame rate and resolution of each experiment is

[4] M. Hirschkorn. 'Dynamic Model of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2004, p. 35.

[5] A. Thorin. 'Non-smooth model of the grand piano action'. PhD thesis. Paris: École Polytechnique, Université Paris-Saclay, 2013, p. 27.

[6] R. Masoudi. 'Micromechanics of Fiber Networks Including Nonlinear Hysteresis and its Application to Multibody Dynamic Modeling of Piano Mechanisms'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2012, p. 101.

[7] $R_f = 47\text{k}\Omega$.

detailed in a footnote at the place where it is discussed. For all photographs, lens distortion has been minimised by using a lens with 50 mm focal length.

3.4 Motion tracking

Observation of the motion of the components of the actions has been performed with the help of two different target tracking methods: the so-called chequerboard and circle methods, named according to the patterns that were used as targets.

Chequerboard detection method The chequerboard method consists in tracking all the intersections of a series of alternated black and white squares drawn on a rectangular target (Figure 3.6). For each target of each frame, the average of the intersection's coordinates provides a reference point that locates the centre of the gridded target. The chequerboard detection is performed using the `detectCheckerboardPoints` routine implemented in Matlab and based on the works of Geiger *et al.*[8]

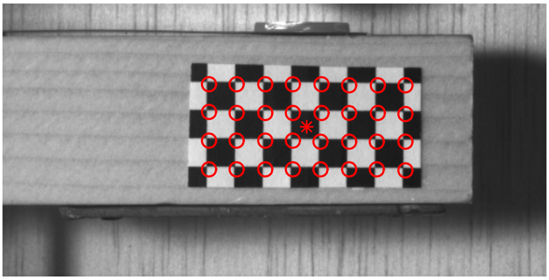


Figure 3.6: With the chequerboard method, each intersection of the inner squares that form up the chequerboard is tracked (o). The average of these points is the centre of the target (∗).

Circle detection method The second detection method that is used is directly implemented in an existing software produced by the high-speed camera manufacturer. Photon FASTCAM Analysis uses a correlation tracking algorithm that enables the user not only to define points to be tracked, but also to define dynamic frames that follow moving bodies. This has proven to be very useful for tracking relative deformation motion of the hammer for example. The software has been intentionally kept user-friendly with the negative consequence that it is limited to a simple use, without any possible regulations.

3.5 Motion and force reproduction

A linear actuator has been used for the displacement reproduction of a previously measured key-stroke and the measurement of certain forces in the system. We opted for a Faulhaber LM1247–020–01 linear brushless DC micro mo-

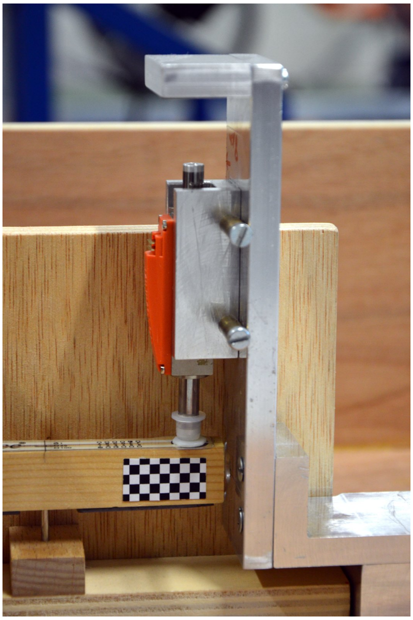


Figure 3.7: The actuator has been mounted on the key so that it would be in contact with the force sensor.

tor. The actuator has a stroke length of 20 mm and is able to produce a peak force up to 10.7 N (3.6 N in continuous force).

Dynamic force reproduction is complex because it requires a regulator that counteracts the rod weight. Moreover, in the case of the interaction force between finger and key, the rod dynamics cannot be neglected because the force variations can occur brutally, especially for loud dynamic blows (Figure 3.5). For this reason, it has been chosen to reproduce the action of the finger via a motor-based approach.

The actuator has also been exploited to measure force-displacement relationships between specific elements of the action. The actuator driver is able to provide the time history of the motion of the rod and of the corresponding current. It has therefore been calibrated statically in order to obtain a correct current-force (proportional) gain.

3.6 Experimental bench

As we have seen in Section 3.1, the experimental action can be equipped with three sets of parts representative of a bass, medium and treble note. Given the importance of the hammer-string interaction in the action dynamics, among others, in terms of contact duration, a wooden framework has been conceived by Pierre Gevaert, the piano technician of the Musical Instruments Museum Brussels (Figure 3.8). With this framework, three types of strings can be hit by the action. The bass note (C) consists of two brass strings, the medium note

[8] A. Geiger et al. 'Automatic Camera and Range Sensor Calibration using a single Shot'. In: *International Conference on Robotics and Automation (ICRA)*. St. Paul, USA, May 2012, pp. 3936–3943.

(c^1) of two iron strings and the treble note (f^3) of three iron strings.[9] The experimental bench has been designed so as to provide an unimpeded view for the high-speed camera on the portion of the action where the internal interaction is the most important and where the hammer hits the string. The action can be easily inserted or removed from the frame to position it under the right group of strings. The location of the action is set with a mechanical stop so that the hammer precisely hits the strings at the desired position. An area has been dedicated to the linear actuator of Section 3.5 where it can be installed and fixed on the frame.

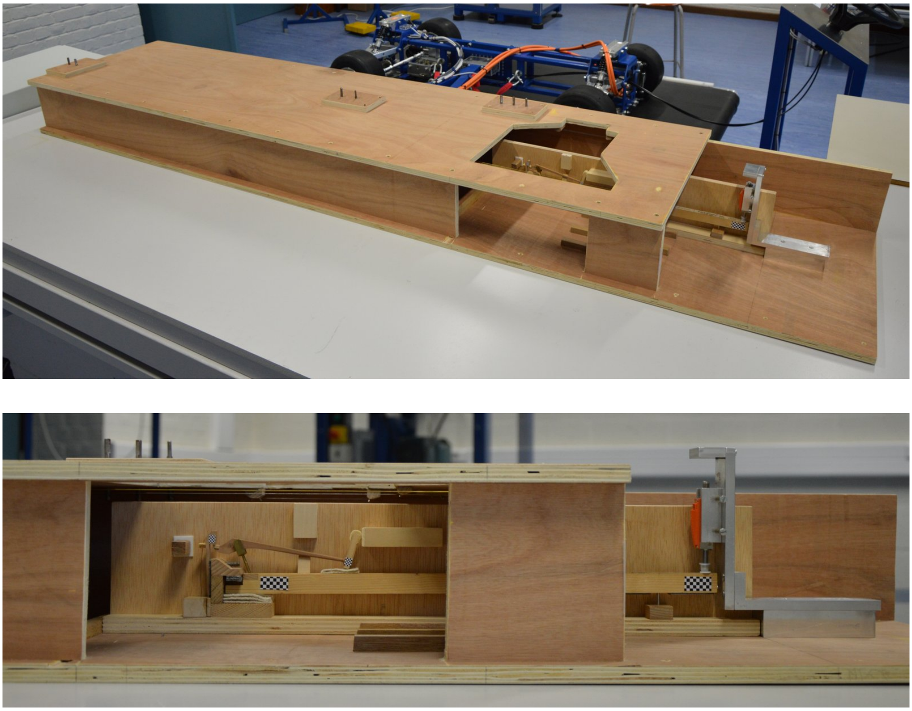


Figure 3.8: (top) Upper view of the entire framework. The open area is the part where the hammer interacts with the string. The tuning pins show from top to bottom the treble, medium and bass string length. (bottom) The action can be easily inserted or removed from the frame to position it under the right string.

[9]Further details about the stringing can be found in Chapter 6.

Chapter 4

Multibody model

A multibody system (MBS) is the generic term that designates any polyarticulated mechanical system to which internal and external forces are applied and for which the motion is studied. Multibody dynamics is the field that studies those systems and that aims at simulating their behaviour on the computer via a mathematical representation (and thus simplification) of reality. Multibody systems cover a large field of applications that are often grouped in categories according to their application: rail and road vehicles, mobile and manipulator robots, articulated actuators, transmission mechanisms, the human body, articulated prosthetic devices, etc.

Given the high degree of generality in terms of morphology, number of articulated bodies, types of articulations and environments of these applications, specialised software has been developed by various research teams since the 80s. In this study, Robotran, a multibody software based on the symbolic generation of the equations of motion has been selected to perform the modelling tasks.[1]

4.1 Multibody system modelling

In the present context, a general multibody system (MBS) is a mechanical system composed of n rigid bodies connected by joints. A tree-like structure (Figure 4.1a), in which there are no loops of bodies, is always used to describe the topology of the system, *i.e.* the way the bodies are connected. Serial robots, the human body and piano actions are examples of tree-like multibody systems.

In contrast, each time a closed-loop of bodies is present in the system, a particular procedure has to be used to ensure their geometrical, kinematic closure and to compute the associated constraints forces (Figure 4.1b). Parallel robots, vehicle multi-link suspensions, four-bar and slider-crank mechanisms are examples of closed-loop multibody systems.

To our best knowledge, the closed loop topology is never encountered in piano actions. These types of models will therefore not be developed in the

[1] J.-C. Samin and P. Fisette. *Symbolic Modeling of Multibody Systems*. Dodrecht: Kluwer Academic Publishers, 2003; N. Docquier, A. Poncelet and P. Fisette. 'ROBOTRAN: a powerful symbolic generator of multibody models'. In: *Mechanical Sciences* 4.1 (2013), pp. 199–219.

present document, though our underlying multibody formalism is able to deal with them.

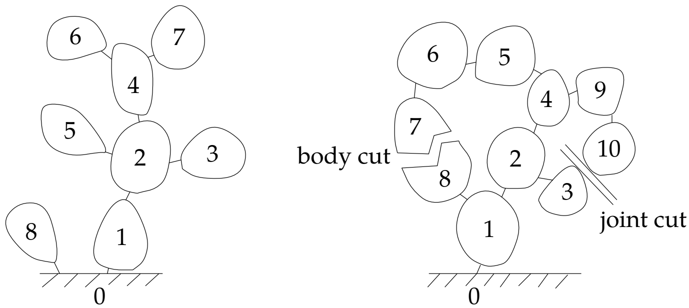


Figure 4.1: (left) a tree-like structure, (right) a closed-loop structure with loops cuts that transform it in a tree-like structure.

Frames, vectors and tensors

Before listing the necessary model data, let us introduce the following notations to define vectors and tensors. Let $\{\hat{\mathbf{X}}^i\}$ be an orthogonal right-handed body-frame that is rigidly attached to each body i and conveniently located at their centre of mass CM^i (Figure 4.2). It is generally simpler to choose this frame in such a way that its axes correspond to the principal inertia axes of the body, but this is not indispensable in the present formalism. Let us also define $\{\hat{\mathbf{I}}\}$, the inertial frame attached to the base body (Figure 4.2).

A vector $\mathbf{a}$ is described in a given body frame $\{\hat{\mathbf{X}}^i\}$ by its three components a_x, a_y, a_z:

$$\mathbf{a} = a_x\, \hat{\mathbf{X}}^i_x + a_y\, \hat{\mathbf{X}}^i_y + a_z\, \hat{\mathbf{X}}^i_z \tag{4.1}$$

Writing the frame $\{\hat{\mathbf{X}}^i\}$ under the form of a 3×1 column matrix of unit vectors:

$$[\hat{\mathbf{X}}^i] \triangleq \begin{pmatrix} \hat{\mathbf{X}}^i_x \\ \hat{\mathbf{X}}^i_y \\ \hat{\mathbf{X}}^i_z \end{pmatrix} \tag{4.2}$$

and applying classical matrix multiplication rules, we can write vector $\mathbf{a}$ in the following concise form:

$$\mathbf{a} = [\hat{\mathbf{X}}^i]^t\, a, \text{ where } a \triangleq (a_x \;\; a_y \;\; a_z)^t \tag{4.3}$$

where the superscript t denotes the transpose of the matrix. The same notation holds for a tensor $\mathbf{T}$ of order 2 (ex: the inertia tensor of a body with respect to its centre of mass):

$$\mathbf{T} = [\hat{\mathbf{X}}^i]^t\, T\, [\hat{\mathbf{X}}^i] \text{ with } T = \begin{pmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{pmatrix} \tag{4.4}$$

Bodies

Let us consider a body i, its parent body h and its 'children' bodies j and k (Figure 4.2). By convention, a joint which precedes a body in the structure has the same index as this body (ex.: joints i, j and k in Figure 4.2). For any joint i, two reference anchor points are defined: the first one, O^i, on body h and the second one, O'^i, on the parent body i. Each body i ($i = 1 : n$) is described by the five following quantities:

1. $\mathbf{d}^j = [\hat{\mathbf{X}}^i]^t\, d^j$, the *joint vector* which locates on body i the connection point O^j of joint j with respect to the connection point O'^i of joint i. Body i being rigid, the components of $\mathbf{d}^j$ are constant in the $\{\hat{\mathbf{X}}^i\}$ frame. Such a vector is obviously defined for each of the children $j, k, ...$ of body i (Figure 4.2);
2. $\mathbf{l}^i = [\hat{\mathbf{X}}^i]^t\, l^i$, the position vector of the centre of mass CM^i of body i with respect to the connection point O'^i of joint i. The components of $\mathbf{l}^i$ are constant in the $\{\hat{\mathbf{X}}^i\}$ frame;
3. m^i, the mass of body i;
4. $\mathbf{I}^i = [\hat{\mathbf{X}}^i]^t\, I^i\, [\hat{\mathbf{X}}^i]$, the symmetric inertia tensor of body i with respect to its centre of mass CM^i. Its components are constant in the $\{\hat{\mathbf{X}}^i\}$ frame.

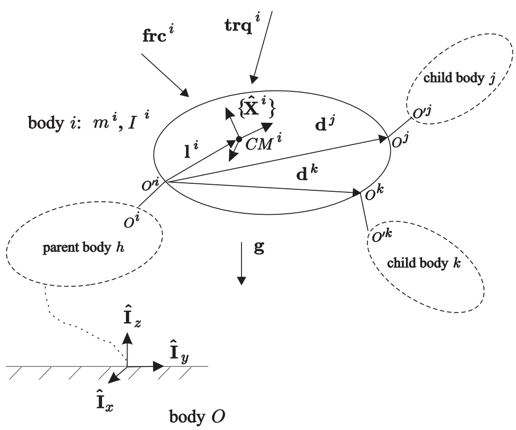


Figure 4.2: Body characterisation

Joints

Joints between bodies represent devices such as telescopic arms, hinges, universal joints, ball joints, etc. Relative motions which occur in these joints are described by relative generalised coordinates q, $\dot{q}$ and $\ddot{q}$. Consequently, the absolute configuration of the MBS must be computed in terms of this set of relative coordinates and their time derivatives. Let us note that each joint i is assumed to be massless and connects body i to its parent h at anchor reference points, O'^i, O^i respectively.

Forces and torques

Forces and torques acting on body i are split into three categories:

1. The *joint* forces/torques, which act on a body via the parent and child-joint connections. Their contribution to the equations of motion is denoted Q^i for joint i. A typical example is the vertical force between the key and the piece of cloth on the balance rail.
2. The *gravitational* force is considered separately in the formalism. This force is computed from the gravity vector $\mathbf{g}$ whose three components g are, for obvious reasons, provided in the inertial frame $\{\hat{\mathbf{I}}\}$: $\mathbf{g} = [\hat{\mathbf{I}}]^t g$ (Figure 4.2).
3. The *external* forces/torques: besides joint forces and gravity, all other forces and torques are considered as *external* to the MBS and gathered together, for each body i, into a resultant force vector $\mathbf{frc}^i$ and a resultant torque vector $\mathbf{trq}^i$ with respect to the body centre of mass. In many cases, the constitutive equations underlying external forces and torques rely on absolute kinematic quantities (position and velocity vectors, orientation matrices, ...) that Robotran generates symbolically. The interaction between the hammer and the string is a good illustration of an external force acting on a pair of contacting bodies.

Direct Dynamics

The *direct dynamics* of a multibody system is the computation of the generalised accelerations $\ddot{q}$ (joint accelerations) for a given configuration (q, $\dot{q}$) of the system to which forces and torques are applied. Direct dynamic equations are extensively used for simulation purposes, *i.e.* to predict the motion of the system ($q(t)$, $\dot{q}(t)$), starting from an initial configuration ($q(t=0)$, $\dot{q}(t=0)$), and time-integrating the accelerations $\ddot{q}(t)$.

Various multibody formalisms can be used to compute the joint accelerations $\ddot{q}$ (*e.g.* based on a virtual principle, the Lagrange equation or the standard Newton/Euler laws...). In our case, Robotran implements symbolically a Newton/Euler recursive scheme leading to an efficient and compact form of the well-known direct dynamics formulation:

$$M(q,\delta)\ddot{q} + c(q,\dot{q},\delta,frc,trq,g) = Q(q,\dot{q}) \tag{4.5}$$

In the previous equations:

M $[n*n]$ is the symmetric generalised mass matrix of the system,
c $[n*1]$ is the non-linear dynamic vector which contains the gyroscopic, centrifugal and gravity terms as well as the contribution of components of external resultant forces *textfrc* and torques *trq*,
q $[n*1]$ denotes the relative generalised coordinates,
δ $[10\,n*1]$ gathers together the dynamic parameters of the system (body masses m^i, centres of mass (the three components of vectors $\mathbf{l}^i$) and the inertia matrices (the six components of tensors $\mathbf{I}^i$)),
Q $[n*1]$ represents the generalised joint forces (torques).

The accelerations $\ddot{q}$ can be obtained by solving the linear system (4.5) with respect to $\ddot{q}$. For this purpose, rather than 'blindly' inverting the mass matrix $M(q,\delta)$, the Cholesky decomposition of M is achieved and followed by a backward/forward substitution.

4.2 Literature overview

Although the piano has been the topic of many acoustical studies in the past, one had to wait for the last decade before the scientific community started to tackle a complete model of its action with a real multibody approach.

Gillespie published in 1996 a model made of the five main bodies of the grand piano action: the key, the wippen, the escapement, the repetition lever and the hammer.[2] The bodies are rigid and linked with kinematic constraints. In 2004, Hirschkorn publishes his thesis in which the dynamic behaviour of the piano action is deeply analysed.[3] It is the first study in which every part of the mechanism is considered independently and with its own physical properties. Consequently, there is no need to adjust global parameters with no physical meaning in order to match the model with experimental results. Each body is characterised independently in order to create a design tool for piano makers. On the recommendation of Hirschkorn, Izadbakhsh (2006) introduces flexibility to the hammer shank using Rayleigh's method.[4] The articulation of the key, previously in pure rotation, is replaced by a combination of a rotation and translations, more in line with the real movement. The addition of flexibility influences only slightly the mechanism, but seems to increase the amplitude of the vibrations when the hammer strikes the string. In 2009, Vyasarayani integrates a vibrating string in the multibody model developed by Hirschkorn and Izadbakhsh. He observes an increase in the stick and slip between the hammer and the string and also a decrease in the vibrations in the hammer shank.[5] The same year, Mamou-Mani and Maniguet use the method developed by Hirschkorn in a comparison of historical piano actions which are not available anymore.[6] Their study compares Érard's pianos preceding his invention of the double escapement. The objective of this research is to identify the characteristics of an instrument which is presently lost, and to establish whether the underlying mechanism was (or not) precursory of the double escapement principle. More recently, Masoudi has worked on the action of an upright piano and proposed a micromechanical model of the felt based on the structural properties of its fibres.[7] Thorin used a different approach by modelling a grand piano action with non-smooth numerical method.[8] A great part of his work is

[2] R. B. Gillespie. 'Haptic Display of Systems with Changing Kinematic Constraints: The Virtual Piano Action'. PhD thesis. Stanford University, 1996.

[3] M. Hirschkorn. 'Dynamic Model of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2004.

[4] A. Izadbakhsh. 'Dynamics and Control of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2006.

[5] C. P. Vyasarayani. 'Transient Dynamics of Continuous Systems with Impact and Friction, with Applications to Musical Instruments'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2009.

[6] A. Mamou-Mani and T. Maniguet. 'Investigating the history of the piano action using scientific calculus: The case of an Érard grand piano from 1802'. In: 5[e] congrès international de musicologie - CIM. 2009, pp. 122–123.

[7] R. Masoudi. 'Micromechanics of Fiber Networks Including Nonlinear Hysteresis and its Application to Multibody Dynamic Modeling of Piano Mechanisms'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2012.

[8] A. Thorin. 'Non-smooth model of the grand piano action'. PhD thesis. Paris: École Polytechnique, Université Paris-Saclay, 2013.

dedicated to validating his model. In this respect, he considers that a model should be driven using displacement instead of force input.

4.3 Multibody model of the *Prellzungenmechanik*

In this section, a general overview of the multibody model of our *Prellzungenmechanik* is given. In the first place, the morphology of the components of the model is presented, followed by the hypotheses underlying the model.

The multibody model is composed of three bodies in motion: the key, the hammer and the pawl (Figure 4.3). The motion of these three bodies is characterised by the general coordinates of the model $q = \left(z_k, \theta_k, \theta_h, \theta_p\right)$. The hammer shank is modelled as a flexible beam as will be seen in Chapter 7.

The moving bodies of the action interact with other parts that are fixed to the inertial frame: the frame on which the key and the pawl are articulated, the catch (also called check) and the string. The case of the string is particular, as it is a separate model for which the transverse vibrational motion is considered in the frame of the hammer string interaction (see Chapter 6).

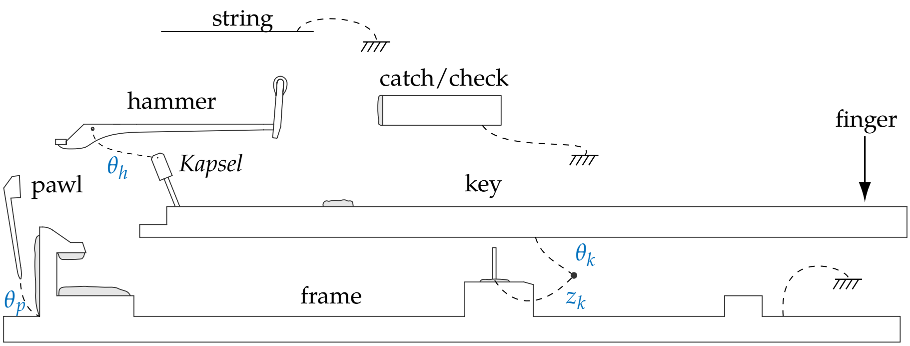


Figure 4.3: The rigid bodies of the model posses four degrees of freedom; three rotations and one translation. The string, the catch and the frame are rigidly fixed to the inertial frame.

As its name suggests it, a model is only able to approach a physical phenomenon, it is therefore a simplification of reality. This fact implies that some simplifying assumptions have been made in the representation of the system. In the case of our *Prellzungenmechanik*, these are the main assumptions that were taken:

- The model is two-dimensional and its movements restricted to the $(\hat{\mathbf{x}}, \hat{\mathbf{z}})$ plane. This means that the out-of-plane movements (in particular for the vibrations of the string) are neglected.
- The key and the pawl are rigid bodies. At first sight, this is not a strong assumption as such, but high-speed imaging analysis revealed noticeable vibrations of the metal *Kapsel* when the key is depressed with force. These vibrations were all the more visible when the hammer was caught by the check and the pawl repeatedly impacted the hammer.

- The joints are geometrically perfect, meaning no backlash is modelled. Given the low number of joints present in the model, let us consider them separately.

  The real key rotates around a balance rail and is fixed by a balance rail pin. In modern pianos, where the structure is similar, it has been observed that key lift-off can occur[9]. We have therefore modelled this movement as a combination of (1) a vertical displacement limited beneath by a cloth pad, and (2) a pure rotation.

  The hammer rotates in the U-shaped metal *Kapsel*. This configuration greatly reduces any possible backlash compared to the mounting found in *Prellzungenmechanik* equipped with wool filled bushings. Modelling the hammer pivot as a revolute joint is thus not a strong hypothesis.

  The pawl is connected to the frame via a piece a parchment that allows it to rotate. Here again, as the minimum quantity of parchment is used, no translational movements can be observed. The pawl is thus represented by a perfect revolute joint.
- Friction for the rotation of the hammer and the key have been neglected.
- The geometrical profiles for which contact detection is performed are treated as circles, lines, points or a combination of these elements. The interaction force between two bodies is computed as a resultant applied to a single equivalent contact point, common to the two profiles.

Further hypotheses, related to specific elements of the model (*e.g.* contact modelling, hammer flexibility, etc.) are presented in the *ad-hoc* sections.

4.4 Contact detection

Contact modelling requires to carry on two sequential steps. The first one is purely geometrical and consists in finding the contact location between bodies, which can be punctual or linear (rigid case) or areal (deformable case). As regards the latter case, we search for an equivalent contact point to which a contact force resultant will be applied. The second step, which is detailed in Chapter 5, is related to the computation of this contact force obtained from constitutive laws.

The working principle of the piano action is based on multiple intermittent percussive contacts which propagate motion through the different parts of the mechanism. Consequently, contact between bodies is of discontinuous nature and it must constantly be ascertained whether pairs of bodies are in contact or not. For the contact involved in piano actions, the geometrical contact problem is solved with sufficient precision by approximating the body surfaces via simple geometrical primitives: circles, lines, points or a combination of them (Figure 4.4). The 'point-to-point' case is straightforward since the material contact points involved are known in advance. For all other situations, one needs to find a geometrical contact point on a circle or a line: this can classically be achieved using either an analytical or an iterative procedure.

[9] Izadbakhsh, *op. cit.*

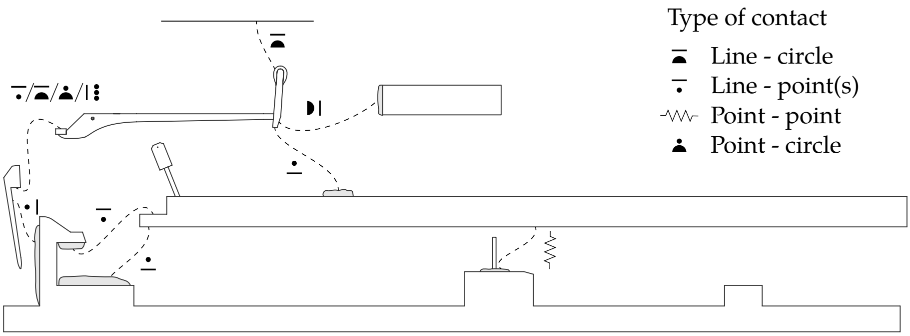


Figure 4.4: The contact geometries are represented with lines, circles, points or a combination of these elements.

Despite its rudimentary design, the interaction between the hammer beak and the pawl notch is the trickiest part of the model[10]. The contact being areal, the first step consists in finding the equivalent contact point (Figure 4.5). This may sound simple, but is in fact complex because we have to find a means to decide, on the basis of the past and current configuration of the action, whether we compute this point relative to the horizontal face of the pawl, its corner or its vertical face (Figure 4.5). Once the contact point is found, one needs to

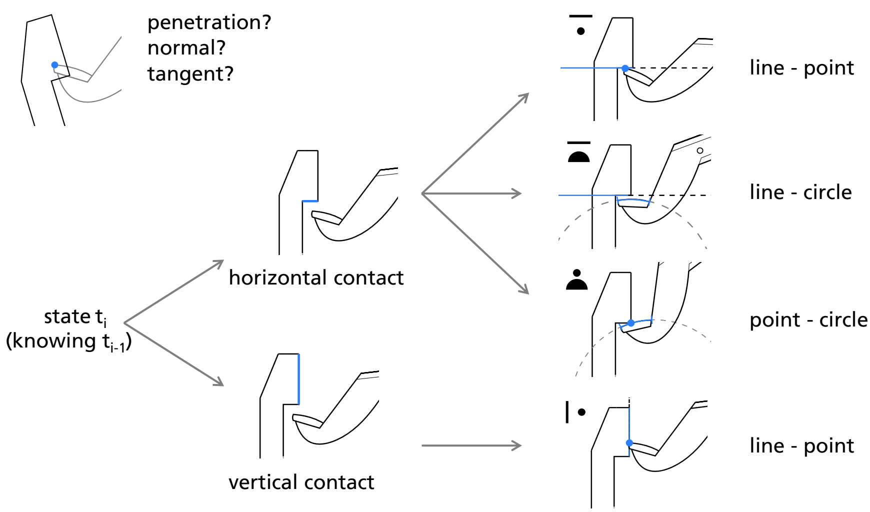


Figure 4.5: When the hammer beak and the pawl are in contact, different geometrical primitives can be used to approximate the contact geometry.

define a normal and a tangential direction to the pawl in order to compute the deformation depth and deformation speed of the hammer beak into the pawl.

[10] An in-depth explanation of the modelling principles may be found in B. Bokiau. 'Des manuscrits d'Henri Arnaut de Zwolle aux conceptions de Bartolomeo Cristofori et d'Andreas Stein. Approche historique et technique des mécaniques d'instruments à clavier et à cordes frappées'. MA thesis. Louvain-la-Neuve: Université catholique de Louvain, 2012, reproduced in Appendix A

Based on high-speed camera observations of the interaction between the hammer beak and the pawl, we have defined a first division; contact occurs either on the horizontal face of the pawl notch or on its vertical face (Figure 4.5). Next, we have defined four distinct contact configurations which follow a temporal sequence of functioning when the key is depressed. Referring to the last column of Figure 4.5 from top to down, these phases consist of a contact between (i) the left tip of the beak and the horizontal part of the pawl, (ii) the upper surface of the beak and the horizontal part of the pawl, (iii) the upper surface of the beak and the corner of the pawl, (iv) the left end of the beak and the vertical part of the pawl.

Situations exist for which it is impossible to determine which configuration has to be used at time $t = t_i$ without knowing the previous state $t = t_{i-1}$ of the two bodies. Even if this situation is exaggerated, it is for example impossible to know how to compute the penetration of the hammer beak in Figure 4.5, upper left corner. The most correct solution will arise from the sequence of motion time-history, which means that the algorithm will always first assess whether the configuration in t_{i-1} is still valid and, if it is not the case, test the other configurations.

For the horizontal contact, three situations can occur, according to the relative position of the beak with respect to the pawl (Figure 4.5). The first corresponds to the case when contact occurs on the tip of the beak (point) and the underside of the pawl (line). The second is when the equivalent contact point lies on the upper surface of the beak, which is represented by a circle of sufficient radius so that its curvature is very low. Finally, the third case is when contact occurs on the angle of the pawl notch (point) and the upper surface of the beak.

The vertical case is tackled with a somewhat different method that aims at approaching the complex behaviour of the hammer beak passing the corner of the pawl notch, as revealed by high-speed imaging. In a first version, the penetration of the beak was computed with the upper left corner of the beak as a reference point (the point near x_1 in Figure 4.6), leaving the rest of the beak as if it did not exist in terms of contact. This lead to erroneous results, in particular during the descending phase of the pawl where the lower part of the beak penetrated without any resistance in the pawl. In a novel version, multiple penetration depths (x_i) are computed between evenly distributed points on the lateral beak surface and the vertical surface of the pawl[11]. Once all non-zero penetrations have been obtained, an equivalent contact point and penetration depth (x) are computed.

4.5 Mass, inertia and geometry of the components

The components of the model have been measured with the help of a MYCRONA Signum HA in order to evaluate their dimensions precisely. The action has been disassembled, allowing to measure the mass, the centre of mass and the inertia of its components. The inertia has been evaluated via Euler's

[11] The vertical surface, which is 3.2 mm high in the treble hammer, is composed of 50 points.

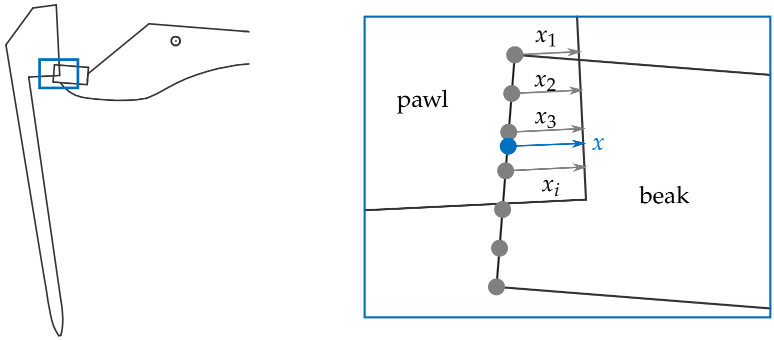


Figure 4.6: Left: the pawl and hammer in a vertical contact configuration. Right: zoom of the pawl/hammer contact. This contact is treated with N evenly distributed points along the vertical side of the hammer beak. The final penetration depth x is a mean of all the x_i penetrations.

equation of motion applied to a planar pendulum:

$$I^o\ddot{\theta} + mgd\sin\theta = 0 \tag{4.6}$$

with I^o the inertia of the body with respect to rotation axis, θ an $\ddot{\theta}$ its angular position and acceleration, m its mass, and d the distance between the centre of rotation and the centre of mass. For small movements the equation of motion can be linearised with the approximation $\sin\theta \simeq \theta$. The natural frequency of the system can be rewritten from Eq. (4.6) as $\nu = \frac{1}{2\pi}\sqrt{\frac{mgd}{I^o}}$. As it is easy to obtain the natural frequency of a pendulum experimentally (Figure 4.7), one can retrieve the value of I^o:

$$I^o = \frac{mgd}{(2\pi\nu)^2}, \tag{4.7}$$

and taking advantage of Steiner's theorem in 2D, one can compute the inertia with respect to the centre of mass of the body: $I^G = I^o - m\|d\|^2$.

In the case of the pawl, which was too difficult to disassemble without damaging the action and which is not subjected to a highly dynamic motion, we have determined these physical values with a CAD software.

4.6 Return spring of the pawls

Special care has been brought to the characterisation of the behaviour of the pawl springs. Indeed, in the Walter action, each register is equipped with a spring of different tension. The Stein version of the action, on the other hand, is equipped with the same spring for all the notes. The spring is different from all the Walter springs though.

The characteristics of the resisting springs have been measured using the linear actuator presented in Section 3.5 (Figure 4.8a). The result is a noisy

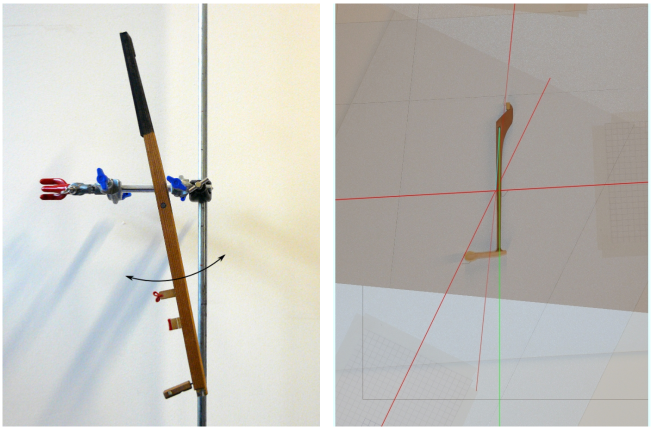
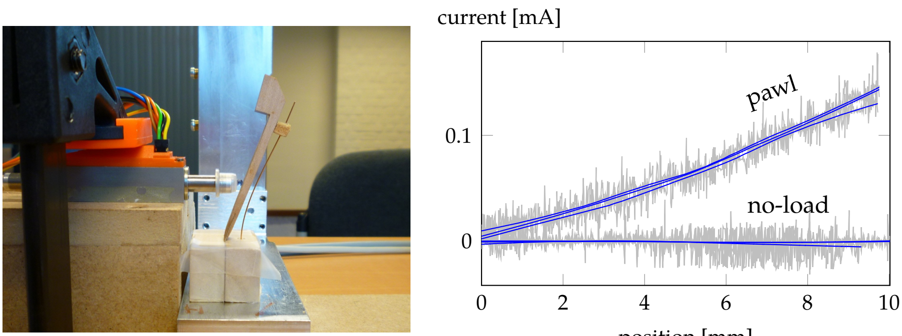


Figure 4.7: The inertia (left) and the centre of mass (right) of the parts have been measured experimentally.

curve, but with a very clear tendency that can be retrieved after using a moving average filter (Figure 4.8b).[12] The current needed for the displacement of the actuator rod under zero load has been measured and estimated to be negligible (Figure 4.8b). Each experiment has been performed three times and the precision of the displacement measurement is of 120 µm.



(a)

(b)

Figure 4.8: The smoothed current data for a zero load displacement of the actuator is negligible compared to the current needed for the displacement of the pawl (Walter bass in this case).

Knowing the gain of the actuator and the application point of the rod on the pawl, one obtains a torque-angular displacement relationship. The experimental curves were then interpolated using a third order polynomial, so as to obtain a torque law that reads:

$$\tau(\theta) = a\theta^3 + b\theta^2 + c\theta + d, \tag{4.8}$$

[12] The filtering is performed with the Matlab `smooth` function. The underlying method, '`rloess`', is based on a local regression using linear least squares and a second degree polynomial model.

where τ is the equivalent torque applied on the pawl, θ the angle of the pawl[13] a, b, c and d are the coefficients of the interpolation.

[13] $\theta = 0$ when the functional axis of the pawl is vertical. The functional axis has been defined in Section 2.2 as the imaginary straight line defined by the outer angle of the pawl notch and the pawl hinge.

Chapter 5

Constitutive laws

While today's soft components of the piano are built with various types of felt and leather, piano makers of the classical period were limited to the use of leather and cloth to soften the contact between the impacting bodies of their action. This chapter aims at obtaining constitutive laws that define the reaction forces between pairs of bodies that can be found in the *Prellzungenmechanik*.

Given the global structural similarity between the materials and the paucity of literature available regarding leather compression, the study of modern materials can serve as a starting point. Felt and leather have more or less the same type of microscopical structure; they are classified as non-woven fabrics, that is, complex '*web structures that are bonded mechanically, thermally or chemically together by entangling fibres or filaments*'.[1] Nonetheless, a distinction is made between fibre materials and fibrous materials.[2] In the former, the fibres can be distinguished as separate entities, which is the case for felt. In the latter, the fibres cannot be clearly differentiated separately from each other: this is the case for the leather.

This chapter is organised as follows: the first part is a literature review of the research concerning the compressional behaviour of the leather and the treatment of constitutive laws in previous piano models. Our personal experiments are then presented, followed by the development of a novel force-compression model. Finally, a simplified contact force model is presented, along with the law that models of the tangential force.

5.1 Literature overview

Physics of the leather

Leather has been the object of different studies, in particular concerning its treatment. Yu focussed his thesis on the mechanical behaviour of leather in

[1] R. Masoudi. 'Micromechanics of Fiber Networks Including Nonlinear Hysteresis and its Application to Multibody Dynamic Modeling of Piano Mechanisms'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2012.

[2] W. Stamm. 'Compressional Behavior of Felt'. MA thesis. Waterloo, Canada. Karlsruhe Germany: University of Waterloo. University of Karlsruhe, 2004; J. W. S. Hearle. *Structural Mechanics of Fibres, Yarns and Fabrics*. New York: Wiley Interscience, 1969.

bending and compression situations.[3] He performs compression experiments on circular leather pads at a quasi-static speed rate.[4] Based on the works of Matsudaira and Quin for fabrics, he develops a microstructural model that divides compression of felt in four steps.[5] From a microstructural point of view, leather is an assembly of tightly woven fibres and fibre bundles of different diameters, separated with voids. Both fibres and bundles are intermingled and adhere to each other. These adhesions may be seen as linkages that slip (causing friction) or break under mechanical stress of the leather. The four steps of deformation (Figure 5.1) of a leather pad under the effect of a compression probe are the following:

I. The first contact between the leather pad and the compression plate are due to the hair-like fibre ends protruding from the leather surface. If sufficient space is available, the protrusions perpendicular to the leather plane will buckle under the effect of compression, resulting in a roughly linear relationship between stress and thickness of the sample (a→b in Figure 5.1, curve (I) in Figure 5.2).
II. Once the protrusions have been bent and the probe has reached the leather surface, fibre bundles are pressed closer together, decreasing the size of the void that surrounds them. The linkage points between the bundled fibres may move somewhat at that point. Yu represents this non-linear process with a power-curve (b→c in Figure 5.1, curve (II) in Figure 5.2).
III. At a certain point, the void around the fibre bundles becomes critical. It is supposed that the fibres inside the bundles are then forced to rearrange their configuration, decreasing the inter-fibre void as well. This would again result in a non-linear relationship between stress and thickness, but with other coefficients than in the previous step (c→d in Figure 5.1, curve (III) in Figure 5.2).
IV. The last stage occurs when no void is left at all. The only way to further compress the pad is through direct deformation of the fibres. This stage follows a linear relation with regards to the felt thickness (d→e in Figure 5.1, curve (IV) in Figure 5.2).

Modelling of piano material

It is commonly admitted that Ghosh was the first to propose in 1932, a simple power law for the interaction between the hammer and the string in the form of

$$F_n(x) = k\,x^p, \tag{5.1}$$

where F_n is the normal force on the hammer, x its compression and k, p the fitting parameters.[6] The parameter k stands for an equivalent *stiffness* and p

[3] W. Yu. 'The mechanical properties of leather in relation to softness'. PhD thesis. University of Leicester, 1999.

[4] The load speed is of 0.05 mm/min, with a pre-load of 0.4 N.

[5] M. Matsudaira and H. Qin. 'Features and Mechanical Parameters of a Fabric's Compressional Property'. In: *The Journal of The Textile Institute* 86.3 (1995), pp. 476–486.

[6] M. Ghosh. 'Experimental Study of the Duration of Contact of an Elastic Hammer striking a Damped Pianoforte String'. In: *Indian Journal of Physics* 7 (1932), pp. 365–382.

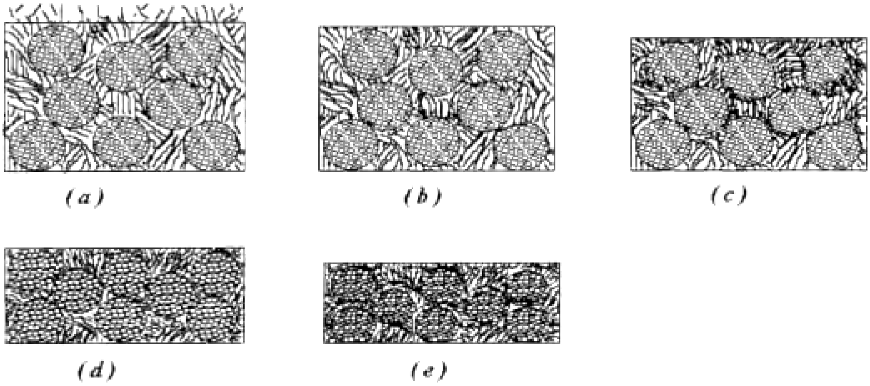


Figure 5.1: The compression of the leather can be divided in four steps: I. bending of the protruding fibres (a→b), II. decrease of the inter-bundle voids (b→c), III. decrease of the inter-fibre voids (c→d), IV. deformation of the fibres (d→e). Illustration taken from W. Yu, 'The mechanical properties of leather in relation to softness', p. 125.

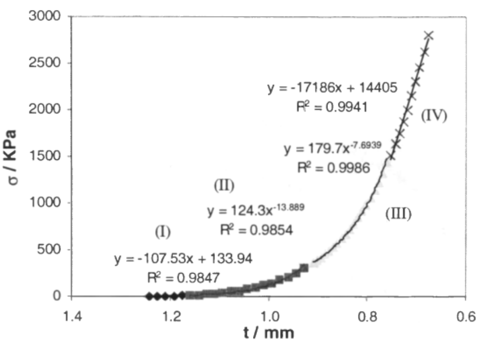


Figure 5.2: The four steps of leather compression can be observed in a stress–compression diagram. Yu interpolated the different phases of compression with distinct curves whose type directly translates the nature of the underlying physical phenomenon. Illustration taken from W. Yu, 'The mechanical properties of leather in relation to softness', p. 102.

depends on the geometry of the contact area.[7] Since then, many authors have further investigated this model and derived values for p experimentally, ranging $p \approx 2.2 - 4$.[8] However, a single power law like (5.1) is unable to catch the hysteresis due to decompression. This hysteresis effect has been observed thanks to dynamic compression measurements, summarised and analysed by Suzuki and Nakamura. [9]

Boutillon measured the compression of a hammer-head on real piano strings that were stiffened with hardwood wedges.[10] He developed a model on the basis of his observations. He observed that the hammer does not immediately fully recover its initial geometry, as it was prior to string contact. The resulting

[7] When two spheres impact each other in a perfect collision, $p = 3/2$, resulting in Hertz's law.

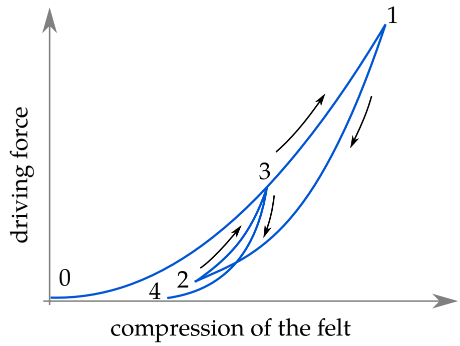
[8] D. E. Hall and A. Askenfelt. 'Piano string excitation V: Spectra for real hammers and strings'. In: *The Journal of the Acoustical Society of America* 83.4 (1988), pp. 1627–1638.

[9] H. Suzuki and I. Nakamura. 'Acoustics of pianos'. In: *Applied Acoustics* 30.2-3 (1990), pp. 147–205.

[10] X. Boutillon. 'Model for piano hammers: Experimental determination and digital simulation'. In: *The Journal of the Acoustical Society of America* 83 (Feb. 1988), pp. 746–754.

force compression law consequently does not form a closed loop where the unloading curve ends at a zero force and zero displacement point. He proposes a model where the two curves are separately fitted using (5.1). Because the latter law starts and comes back to the origin $(0,0)$, Boutillon considers an unloading curve where $F_n(x) = 0$ if F_n is smaller than a certain percentage of F_n^{max}, the maximal compression. The interest of his model consists in taking partial hysteresis into account; each new (de)compression curve is traced with an arbitrarily steeper slope than its predecessor so that dissipative characteristic of the curve is preserved (Figure 5.3). For example, referring to Figure 5.3, the first unloading curve (1 → 2) is steeper than the curve for initial loading (0 → 1). Similarly, the next loading curve (2 → 3) is steeper than the partial unloading (1 → 2) from where it originates and the final unloading curve (3 → 4) is even steeper than all the previous ones.

Figure 5.3: Boutillon's model for the compression of the hammer head of a grand piano takes partial unloading into account. Adapted from X. Boutillon, 'Model for piano hammers: Experimental determination and digital simulation', p. 751.



Different approaches, both experimental and theoretical, were proposed by Stulov. In a first model, he develops a static hammer felt model based on the deformation energy of two geometrically interpenetrating bodies.[11] Considering that this energy is focussed in the region of interaction, he deduces the force needed to cause this deformation. This leads to a static model with a single material parameter, E the Young's modulus of the felt material and two geometrical parameters: the radius of the string cross-section r and of the hammer head profile R:

$$F_n(x) = \frac{\sqrt{2}E}{R}\left(\frac{r\,R}{r+R}\right)^{1/2} x^{5/2}. \tag{5.2}$$

In fact, (5.2) represents a variant of the power law (5.1), with $k = \frac{\sqrt{2}E}{R}\left(\frac{r\,R}{r+R}\right)^{1/2}$ and $p = 2.5$.

Stulov developed two other models for which he insists on the importance of the memory effect present in hammer compression. The first model is based on the works of Rabotnov that tackles the subject of memory effects in materials.[12] He introduces a time-dependent operator that replaces the constant

[11] A. Stulov. 'A Simple Grand Piano Hammer Felt Model'. In: *Proceedings of the Estonian Academy of Sciences. Engineering* 1.2 (1995), pp. 172–182.

[12] A. Stulov. 'Hysteretic model of the grand piano hammer felt'. In: *The Journal of the Acoustical Society of America* 97.4 (1995), pp. 2577–2585; Y. N. Rabotnov. *Elements of hereditary solid mechanics*. Trans. by M. Konyaeva. Moscow: Mir Publishers, 1980. Chap. 17.

stiffness term k in (5.1)

$$k(t) = k_0\,(1 - R(t)*)\,, \tag{5.3}$$

where k_0 is the static felt stiffness, $R(t)$ is a relaxation function and $*$ denotes the convolution operator. He chooses a relaxation function of the form

$$R(t) = \frac{\epsilon}{\tau_0}\exp\left(-\frac{t}{\tau_0}\right), \tag{5.4}$$

where ϵ is a dimensionless hysteretic constant that quantifies the amount of hysteresis. The characteristic time scale associated with the felt is expressed by τ_0 a relaxation constant. Introducing both (5.3) and (5.4) in the terms of (5.1), one obtains

$$F_n\left(x\left(t\right)\right) = k_0\left(x^p(t) - \frac{\epsilon}{\tau_0}\int_0^t x^p(\xi)\exp\left(\frac{\xi - t}{\tau_0}\right)d\xi\right). \tag{5.5}$$

The four parameters of this model (k_0, p, ϵ, τ_0) were found through numerical fitting and through the comparison of numerical simulations with their experimental counterpart. The model is further compared with experimental data (Figure 5.4) obtained from a specially designed testing device in which the hammer impacts a rigid stop.[13]

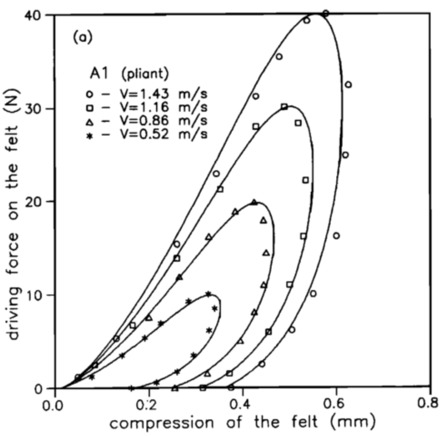


Figure 5.4: The four parameters of Stulov's model (5.5) can be tuned in order to catch the dynamic hysteretic effect measured in T. Yanagisawa and K. Nakamura, 'Dynamic compression characteristics of piano hammer'. These results display the force compression curve for an A1 pliant hammer at different impact velocities. Illustration taken from A. Stulov, 'Hysteretic model of the grand piano hammer felt', p. 2580.

In a later publication, Stulov observes that multiple sets of parameters can lead to seemingly identical responses of the hammer compression.[14] Starting from the equation of motion of the hammer in which the force is computed via (5.5), he eliminates the integral and suppresses the terms that can be neglected due to their small contribution. From there on, he deduces a simplified force law with only three parameters which reads:

$$\begin{aligned} F_n(x) &= k_0\left(\left(1 - \epsilon\right)x^p + \tau_0\,\dot{x}^p\right) \\ &= k'_0\left(x^p + \alpha\,\dot{x}^p\right) \end{aligned} \tag{5.6}$$

[13] A. Stulov and A. Mägi. 'Piano hammer testing device'. In: *Proceedings of the Estonian Academy of Sciences* 6 (2000), pp. 259–267.

[14] A. Stulov. 'Dynamic behavior and mechanical features of wool felt'. In: *Acta Mechanica* 169.1-4 (May 2004), pp. 13–21.

where $\dot{x}$ stands for $^{dx}/_{dt}$ and where the static stiffness is redefined as $k_0^{'} = k_0\,(1-\epsilon)$ and $\alpha = {}^{\tau_0}/_{(1-\epsilon)}$. His 'three-parameter felt model' gives the same type of results as his 'four-parameter felt model' (5.5), but it only allows a unique set of parameters (k'_0, p, α) for the right solution. A difference in behaviour with (5.5) can be observed at very high speeds, in the order of $\dot{x} = 10\,\mathrm{m/s}$. Unfortunately, the experimental equipment of the authors couldn't reach these velocities, making it impossible to ascertain which of the two models fits reality best. In practice, however, such high rates are never reached in piano actions.

In their latest publication, Stulov and Kartofelev tackled the problem of wave propagation in felt in order to formally characterise its properties.[15] They applied the same type of relaxation function as in (5.4) to the Young's modulus of felt and incorporated this memory affected modulus in the constitutive equation of the felt. One of their important conclusions is that felt is a strongly dissipative and dispersive medium, with a strong damping effect.

Giordano and Millis challenge the models of Stulov *et al.* as the observations on which they were based involve experiments for which the hammer impacts a rigidly held force sensor and not a vibrating string.[16] They call the rigid impact set-up a 'type I' measurement, as opposed to the 'type II' experiments in which the hammer impacts a real vibrating string. Type I measurements display the typical narrow hysteresis force-displacement loop, whereas type II measurements produce curves with much broader and somewhat more chaotic hysteresis in the form of multiple loops (Figure 5.5a). However, the method used to find such results can be questioned as they deduce the displacement from a double integration of the difference in acceleration between the hammer and the string. Confronted to this type of deformation, Stulov's law (5.6) confines the hammer force-displacement relation inside the type I hysteretic loop (Figure 5.5b). In their paper, Giordano and Millis develop a new model that captures the type II measurement semi-quantitatively (Figure 5.5c). Indeed, they use a power law (5.1) with a time–dependent stiffness that varies according to its compression history $W(t)$

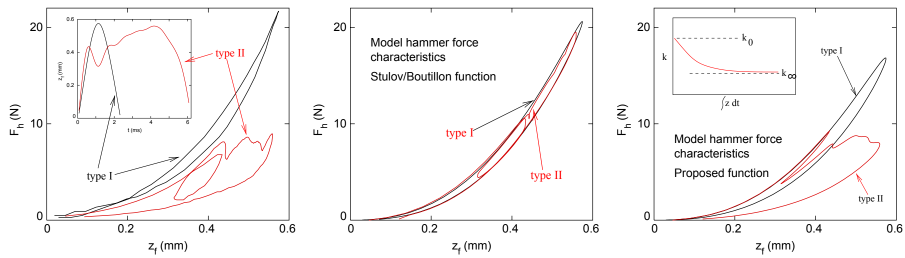
$$\begin{aligned} k(t) &= k_0 \left(1 + \frac{\beta}{1+\exp\left(\gamma\, W(t)\right)}\right), \\ W(t) &= \int_0^t x(\xi)\, d\xi. \end{aligned} \tag{5.7}$$

The dimensionless fitting parameters β and γ respectively influence the amplitude and rate of stiffness variation. The effective stiffness varies from $k(t) = k_0(1 + {}^{\beta}/_{2})$ to $k(t) = k_0$, resulting in a 'softening' of the hammer as it has been compressed (Figure 5.5c). Even if the authors claim this model fits the experimental results better than all the others, Giordano and Jiang abandon this

[15] D. Kartofelev and A. Stulov. 'Propagation of deformation waves in wool felt'. In: *Acta Mechanica* 225.11 (2014), pp. 3103–3113.

[16] N. Giordano and J. P. Millis. 'Using Physical Modeling to Learn About the Piano: New Insights into the Hammer-String Force'. In: *Proceedings of the International Congress on Acoustics*. Ed. by S. Furui, H. Kanai and I. Y. Kyoto, Japan, 2004.

approach in a later paper where they use Stulov's model, claiming that in the end, it is the best available even if it is not ideal.[17]



(a) (b) (c)

Figure 5.5: (a) Giordano and Millis' comparison of a hammer-string experimental force measurement for a rigid impact (type I) and a flexible string impact (type II). The type II curve displays an internal loop that reflects the bouncing of the hammer on the string. (b) Stulov's law applied to a vibrating string results in a force-compression curve that is nested inside the results obtained with the same model for an impact on a rigid stop. (c) Giordano and Millis' law displays larger hysteresis for type II contacts. Illustrations taken from N. Giodano and J. P. Millis, 'Using Physical Modeling to Learn About the Piano: New Insights into the Hammer-String Force', pp. 2114-2115.

Avanzini and Rochesso rewrote the general impact model of Hunt and Crossley.[18] Hunt and Crossley's law combines the elastic power function (5.1) and a dissipative viscous term. Their equation reads:

$$\begin{aligned} F_n(x, \dot{x}) &= k\, x^p + \lambda\, x^p \dot{x} \\ &= k\, x^p\, (1 + D\dot{x})\,, \end{aligned} \tag{5.8}$$

where λ is the force damping weight and $D = \lambda/k$ a convenient mathematical coefficient that accounts for the damping.

The Motion Research Laboratory of the University of Waterloo has extensively worked on multibody modelling of piano actions, and thus on contact dynamics of its components. They have based their models on the observation made by Stamm and later supported by Masoudi (Figure 5.6) that the nonlinear hysteresis is *independent* of deformation speed.[19] Probably due to the experimental complexity of measurements at high speed for such low masses, they provide results in which velocity and impact force vary simultaneously.

[17] N. Giordano and M. Jiang. 'Physical Modeling of the Piano'. In: *EURASIP Journal on Advances in Signal Processing* 7 (2004), pp. 926–933.

[18] F. Avanzini and D. Rocchesso. 'Physical modeling of impacts: theory and experiments on contact time and spectral centroid'. In: *Proceedings of the SMC Conference 2004*. Paris, 2004; K. H. Hunt and F. R. E. Crossley. 'Coefficient of Restitution Interpreted as Damping in Vibroimpact'. In: *Journal of Applied Mechanics* 42 (1975), pp. 440–445.

[19] Stamm, *op. cit.*; R. Masoudi, S. Birkett and A. Salehian. 'Dynamic simulation and vibration analysis of a mechanical piano key actuator'. In: *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 8th International Conference on Multibody Systems, Nonlinear Dynamics, and Control. (28th–31st Aug. 2011). Vol. 4. American Society of Mechanical Engineers. Washington, DC, USA, 2011, pp. 981–990.

In our opinion, these results do not allow to conclude that compression is speed-independent.

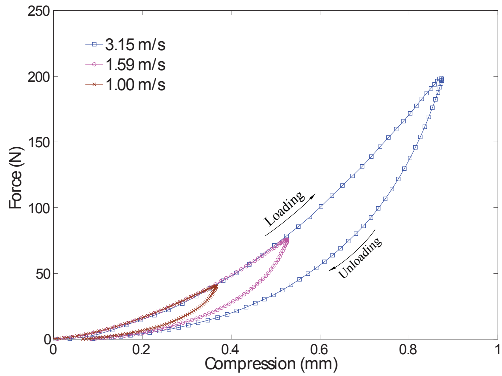


Figure 5.6: Force-compression curves for dynamic loading and unloading of a piano hammer on a rigid stop for distinct impact velocities. Both velocity and impact force vary from curve to curve. Illustration taken from R. Masoudi *et al.*, 'A Mechanistic Multibody Model For Simulating The Dynamics Of A Vertical Piano Action'.

Based on the works of Stamm, Hirschkorn also states in the frame of piano action that felt contact models should be speed-independent.[20] Hirschkorn adapted the power term of (5.8) to a cubic interpolation function that better suits the form of the measured curves:

$$F_n(x, \dot{x}) = f_{fit}\,(1 + D\dot{x})\,, \tag{5.9}$$

where $f_{fit} = ax^3 + bx^2 + cx$ is the cubic curve that interpolates the mean of the measured force-compression relations.[21] Aware that his model contains a speed dependent hysteresis, he computes D in such a way that it produces an adequate hysteresis at the average contact speed of each contact in his model. The drawback of this method is that the model deteriorates when it works under different speed (and thus dynamic) conditions.

Masoudi developed three micromechanical models in his thesis that are based on the micro-scale deformation of the felt as a non-woven fibre assembly.[22] He firstly adapts a deformation mechanism initially designed for small strain to large deformations of a three-dimensional web. These deformations are characterised by the elongation of the fibres. The second model is based on the rate theory of flexible granular solids. In this model, deformation is mainly caused by bending and torsion of fibres. As mentioned in a later paper, unsatisfactory results were obtained for compression of felt with various volume fractions.[23] The last micromechanical model uses the general deformation theory of fibre networks with fibre bending at the micro level and a binomial distribution of fibre contacts. Masoudi also proposed a simplified model.[24] Experimental compression curves were mathematically interpolated with a function

[20] Stamm, *op. cit.*; M. Hirschkorn. 'Dynamic Model of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2004.

[21] *Ibid.*

[22] Masoudi, *op. cit.*

[23] R. Masoudi and S. Birkett. 'Experimental Validation of a Mechanistic Multibody Model of a Vertical Piano Action'. In: *Journal of Computational and Nonlinear Dynamics* 10.6 (2015), p. 061004.

[24] R. Masoudi, S. Birkett and J. McPhee. 'A Mechanistic Multibody Model for Simulating the Dynamics of a Vertical Piano Action'. In: *Journal of Computational and Nonlinear Dynamics* 9.3 (2014), pp. 031014–1.

of the type $F(x) = ax\, e^{bx} + cx$. In all cases, the transition from compression to decompression is ensured via a mathematical model in the form of

$$F_n(x) = \begin{cases} F_l(x) & \text{if } \dot{x} > 0 \text{ (compression)} \\ F_l(x) + \delta_{lu} \tanh(\alpha \dot{x}) & \text{if } \dot{x} < 0 \text{ (decompression)}, \end{cases} \quad (5.10)$$

with $\delta_{lu}(x) = F_l(x) - F_u(x)$ the difference between the reference loading (F_l) and unloading (F_u) curve. The reference curves are the compression results for an excessive loading of the material. A transition speed factor α is used to assure a smooth transition between the curves and to take partial loadings into account.

The precision of the non-simplified micromechanical models also has a computational cost; Masoudi reports that their simulation time is $4 \sim 6$ times higher than with his simplified mathematical model.

Discussion

On the basis of our own experiences and results available in the literature, we consider the following elements to be important for a macro-model of the leather parts of our piano actions:

1. Compression curves follow a non-linear behaviour.
2. Compression and decompression are not alike; a complex hysteretic phenomenon leading to a loss of energy is always present.
3. A complex behaviour occurs when the felt is partially (un)loaded; that is, when the sample is reloaded before it has been completely unloaded.
4. The effect of compression speed seems to be of a great influence on the response of fibrous assemblies. Many researchers have observed this effect, although it is strongly contested by the research team at Waterloo University.
5. A strong memory effect can be observed and is believed to have considerable influence on the partial loadings.

Although Masoudi's simplified model is based on the assumption that felt compression is speed-independent, a hypothesis we strongly put in doubt in the frame of piano modelling, it remains a model which is attractive for its elegant simplicity.

Masoudi insisted on the fact that the overall, potentially more complex, behaviour of the hammer when it is submitted to successive partial loadings is restrained inside a loop defined by the highest achieved loading and its corresponding complete unloading.[25] For example, looking at Figure 5.10, if the maximal compression load applied to the hammer prior to unloading is 30 N, then its behaviour will be completely contained inside the hysteresis loop culminating at 30 N.

These observations have been contradicted by the findings of many previously cited authors, but the complete multibody models of piano actions developed by Masoudi seem to approach reality convincingly. For this reason,

[25] *Ibid.*

and because we lack the specialised material to perform high velocity compressions of such lightweight samples, we will depart from the same hypotheses to build our force-compression model.

There are, nonetheless, some elements of Masoudi's model that should definitely be enhanced. For the sake of clarity, let us recall his simplified model (5.10) on which we will base our own model:

$$F_n(x) = \begin{cases} F_l(x) & \text{if } \dot{x} > 0 \\ F_l(x) + \delta_{lu} \tanh(\alpha \dot{x}) & \text{if } \dot{x} < 0 \,, \end{cases} \tag{5.11}$$

with $\delta_{lu}(x) = F_l(x) - F_u(x)$ the difference between the reference loading (F_l) and unloading (F_u) curve. The reference curves are the compression results for an excessive loading of the material. The transition speed factor α assures a smooth transition between the curves.

A model for partial loading is thus proposed, where the unloading curve is defined as a portion of the loading and unloading curve, transitioned thanks to a speed-dependent hyperbolic tangent function. This model indeed provides a smooth transition from loading to unloading, but it has three drawbacks we propose to address; (1) the transition is speed-dependent, which is somewhat inconsistent with the initial postulate, (2) the quasi-static hysteresis is not (well) captured (if $\dot{x} \to 0 \Rightarrow F_n(x) \to F_l(x)$) and (3) the curve becomes discontinuous if the material is loaded again after a partial unloading.

5.2 Experimental set-up

Compression tests for the hammers have been performed with an Instron 5566 UTM loading machine, equipped with a 100 N cell. Care has been taken to perform these tests in the most realistic configuration; for instance, the hammers have been compressed on real strings that were installed in an undeformable configuration, and not on a plate for which the contact surface with the hammer would be completely incoherent with respect to the studied situation (Figure 5.7).

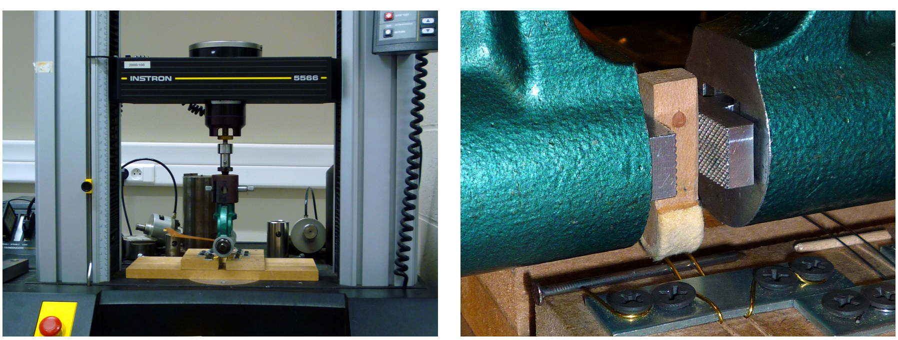


Figure 5.7: The compression experiments were performed with the hammers compressing rigidified strings.

A simple test-bed has been designed so that each hammer is pressed against the string assembly that would be found in the real piano (double strings for the bass and medium hammer, three for the treble hammer). Also, the exact same strings have been used for this montage, allowing consistency in the use of materials and string diameters. Since the subject of this experiment is deliberately restricted to the behaviour of the hammer, the vibration and bending of the strings has been prevented. This has been done by rigidifying the montage in several ways: the strings have been stretched over a small length (a few centimetres), at the highest possible tension. The tension has further been increased with the introduction of nails between the support and the tensioned strings. Finally, bending was almost annihilated thanks to the application of the hammer as close as possible to a supporting point of the strings.

The Instron loading machine is conceived for slow displacement, and is thus not suitable for dynamic testing of the felt. Although the loading machine can reach speeds up to 500 mm/min, in cyclic compressions at the highest available rates, it has been observed that the internal dynamics of the moving masses of the machine strongly disturbed the measurements. For this reason, we were unable to obtain experimental data related to the velocity effects of compression.

5.3 Leather force model

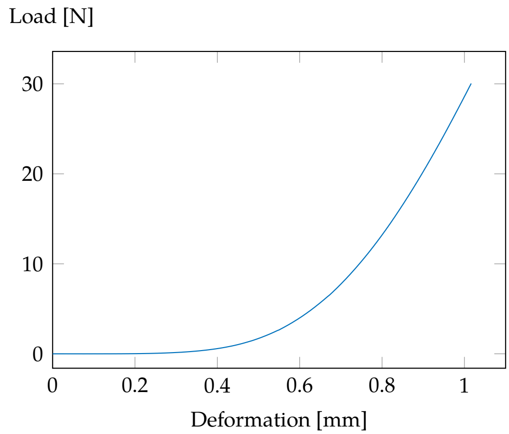
The five general observations made in Section 5.1 are discussed in detail in the following sections; whenever possible, each assumption is confronted with experimental data and their incidence on the model is presented. In this way, the different constitutive elements are explained in the order of growing complexity.

Quasi-static loading

The relation between compression and deformation of the leather is clearly non-linear as can be seen on a motion driven compression limited to 30 N and performed at a quasi-static speed of 1 mm/min (Figure 5.8). Although it may in the first instance seem to look like a simple power law, the four phases defined in Section 5.1 can be retraced, the boundaries between each stage being more or less easily definable. In particular, the linear evolution of the force with respect to deformation at the start and the end of the compression are clearly observable. The protrusions of the felt leathers made it difficult to define a clear origin for the deformation, hence the length of the almost horizontal line at the beginning of the experiment. The curve between the linear segments corresponds to phases II and III of Section 5.1, but the latter phases could not be clearly distinguished one from another.

Different mathematical functions were tried out as interpolants for the data, but the linear parts at the extremities and the general shape of the central part disturbed this process. Among these functions, the one proposed by Masoudi $F(x) = ax\, e^{bx} + cx$ was discarded as it resulted in significant negative force values over the linear part of the beginning curve. As a result, it has been chosen

Figure 5.8: The quasi-static force-compression curve resulting from a compression experiment of the hammer with its corresponding strings follows a non-linear curve that comprises the four phases defined in Section 5.1.

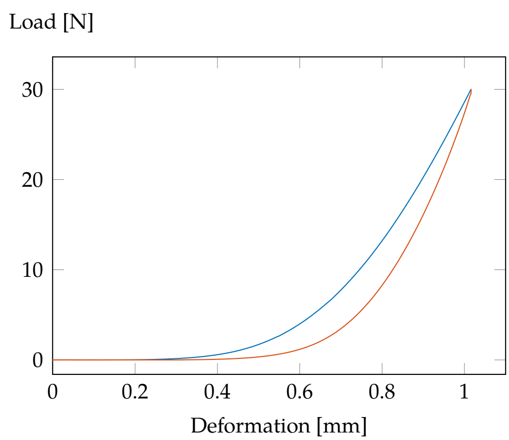


to interpolate the curve with a limited number of splines. In some cases, this also led to a negative compression force, but in a far more limited measure than with all the interpolating functions envisaged. Given their physical nonsense, these values were consistently put to 0 without causing strong discontinuities.

Quasi-static unloading

Looking at the unloading of the curve (achieved at the same rate as in the previous experiment) provides a good illustration of the difference between loading and unloading that gives rise to hysteresis (Figure 5.9). The upper curve corresponds to the loading of the hammer on the rigidified set of strings, while the lower curve is the unloading characteristic: the resisting force of the hammer is greater when it is loaded than when it is unloaded. The area defined by the two curves is the energy lost during the full loading cycle. Let us also note that the form of the unloading curve is also slightly different; the linear part in the highest deformations is almost absent. This is another reason for the choice of spline-interpolation instead of a unique mathematical formula.

Figure 5.9: When the hammer felt is loaded and unloaded, the force deformation curves display hysteresis, that is, dissipation of energy. The area defined by the two curves is the total amount of lost energy.



As in Boutillon and Masoudi's works,[26] our model will be based on two separate reference curves for compression and decompression respectively, resulting in the following formulation:

$$F_n(x) = \begin{cases} F_{load}(x) & \text{if } \dot{x} > 0 \\ F_{unload}(x) & \text{if } \dot{x} < 0\,. \end{cases} \tag{5.12}$$

Modelling a complete cycle

As previous authors did, we have experimentally applied multiple complete loading cycles on the piano hammers pressed on the corresponding strings (here illustrated with the bass hammer at a rate of 1 mm/min in Figure 5.10). Successive loading cycles with increasing maximal force were applied to the hammer and then compared. The results for the compression of leather hammers show that:

1. All the force-compression curves are more or less nested in the characteristic of the maximal applied force (in this case, 50 N), as already pointed out in literature.
2. All unloading curves have approximately the same shape with different x-contraction.
3. Contrary to Masoudi's model, the unloading curves tend towards the envelope lower curve, rather than the envelope upper curve (comparison between Figure 5.10 and Figure 5.11.)
4. The loading curves of the successive loadings do not perfectly follow the same path at each new compression; a memory effect due to the previous loadings is clearly present, but this effect is rather weak.

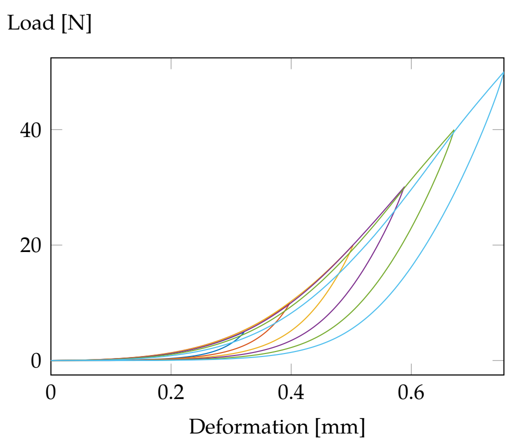


Figure 5.10: The multiple loading cycles that have been applied to the piano hammers and their corresponding strings show a series of hystereses, characterising the dissipated energy.

Given these observations, we have taken advantage of this network of curves obtained experimentally in order to construct our model. For the loading case, a general upper loading curve (ULC) has been defined as the envelope of all

[26] Boutillon, *op. cit.*; Masoudi, *op. cit.*

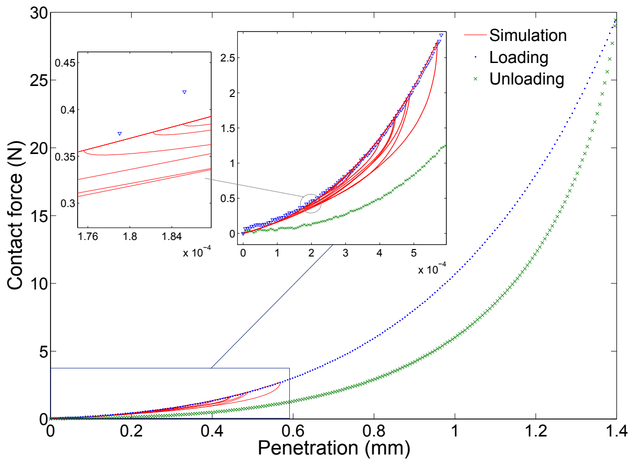


Figure 5.11: Masoudi provides an illustration in which he confronts his model with experimental measurements; most of his simulation curves (red) are very close to the reference loading curve. R. Masoudi *et al.*, 'A Mechanistic Multibody Model For Simulating The Dynamics Of A Vertical Piano Action'.

the loading curves. Every compression that starts from 0 N follows this curve. This means the small memory effect (point 4. above) has been neglected.

For our modelling purpose, the following general situation must be considered. It consists in defining the unloading curves starting from the locally highest applied load (x_l^{max}, F_l^{max}) on the basis of the two experimental unloading curves $F_u^a(x)$ and $F_u^b(x)$ which surround this point, respectively left and right of x_l^{max}(Figure 5.12). The maximal points for each curve are noted (x_a^{max}, F_a^{max}) and (x_b^{max}, F_b^{max}).

The newly defined unloading curve consists of two parts; the first, $F_u^1(x)$, is defined in the interval $0 \leq x \leq x_a^{max}$ as a weighted average of the neighbouring curves:

$$F_u^1(x) = F_b(x) + r\left(F_a(x) - F_b\left(x\right)\right), \tag{5.13}$$

where $r = {}^{b}/_{h}$, with $b = F_b^{max} - F_l^{max}$ and $h = F_b^{max} - F_a^{max}$: these parameters are illustrated in Figure 5.12.

For the second part of the curve, $F_u^2(x)$ defined over the range $x_a^{max} < x \leq x_l^{max}$, only one reference curve is available, making it impossible to define a weighted average. We therefore use a second order polynomial obeying to two constraints: (1) the slope of the first and second curve are equal at the transition point $x = x_a^{max}$: $\frac{dF_u^2(x_a^{max})}{dx} = \frac{dF_u^1(x_a^{max})}{dx}$, (2) obviously, the curve contains the locally highest applied load: $F_u^2(x_l^{max}) = F_l^{max}$.

A special case arises when the locally maximal load (x_l^{max}, F_l^{max}) is at the left of the first experimental unloading curve, because $F_u^a(x)$ does not exist. In this particular case, the loading curve is used as a reference for the left curve. A slight variant of the previous approach is thus used in this case; the curve is still defined in two parts $F_u^1(x)$ and $F_u^2(x)$. $F_u^1(x)$ is defined over the range $0 \leq x \leq x_{sep}$, where x_{sep} is arbitrarily defined as a portion of x_l^{max} (typically $x_{sep} = 0.7 \ldots 0.9\, x_l^{max}$). The mean factor of (5.13) for this relation becomes $r = 1 - {}^{a}/_{b}$, with a the maximal applied deformation x_l^{max} and b the deformation on the first experimental unloading curve corresponding to the maximal applied

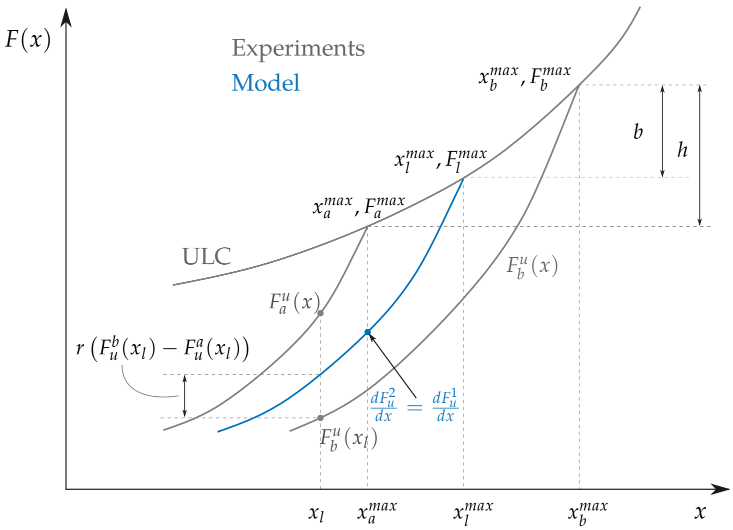


Figure 5.12: The unloading curve starting from the ULC is piecewise defined via a mean average of experimental data and a second order polynomial function.

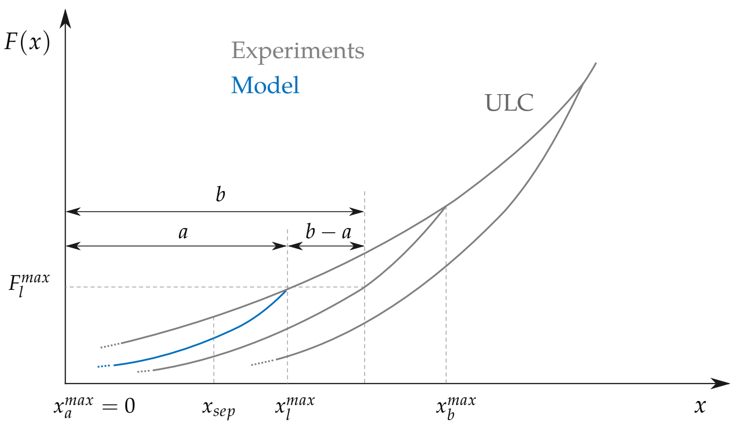


Figure 5.13: The unloading curve needs to be defined in a specific way when its maximal loading point is located between the origin of the curve and the first experimentally obtained unloading curve.

load F_l^{max} (Figure 5.13). The second part of the curve, $F_u^2(x)$, is defined in the same way as previously.

Partial loading and unloading

At this point, our model completely characterises the behaviour for a complete load-cycle. However, in many cases the interpenetration between two bodies can switch from loading to unloading, without loosing contact. The cycles that are performed in this case are incomplete, this is called partial loading. In the case of the hammer-string contact, partial reloading can occur when the contact duration is longer than the time for the wave of the vibrating string to reflect (in particular, this frequently happens with bass strings).[27] Moreover, this model has been developed with the idea to apply to any other pair of interacting body, as for example the key rail that limits the movement of the key. In these kind of contacts, partial reloading is inevitable.

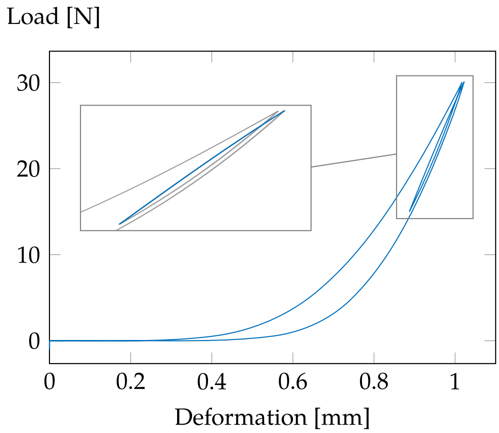


Figure 5.14: When the hammer is partially unloaded before it is being loaded again, the compression force slowly returns to the upper loading curve.

In order to study what happens between incomplete partial compressions, the hammer has been submitted to a complete loading reaching 30 N, a partial unloading limited to 15 N, followed by a second loading at 30 N and finishing by a complete unloading. The illustrated results were obtained with the bass hammer at a compression rate of 1 mm/min (Figure 5.14). Defining the reference loading curve $F_l(x)$ as the first compression and the reference unloading curve $F_u(x)$ as the last decompression, it can be noticed concerning the second compression (starting from 15 N in Figure 5.14), that:

1. The force-deformation characteristic follows a smooth transition that leads it approximately to its point of maximal force and deformation;
2. The curve followed by the second compression has a negative concavity;
3. The end-point for the second compression (which is limited to 30 N) is shifted to the right; this means a higher compression is needed in order to obtain the same resisting force. This is most probably due to a memory effect.

In our model, the curve for partial reloading F_{pl} is defined with a second degree polynomial defined by three conditions that impose that:

1. the curve contains the local minimal load point (x_l^{min}, F_l^{min}) which is the last point of the previous unloading curve from which the reloading curve departs;
2. the curve contains the local maximal load point (x_l^{max}, F_l^{max}) which is the last point on the ULC from which the previous loading curve departs;
3. the slope of the curve at the maximal loading point (x_l^{max}, F_l^{max}) is equal to the curve of the ULC at that point: $\frac{dF_{pl}(x_l^{max})}{dx} = \frac{dF_{ULC}(x_l^{max})}{dx}$.

[27] S. Birkett. 'Experimental investigation of the piano hammer-string interaction'. In: *The Journal of the Acoustical Society of America* 133.4 (2013), pp. 2467–2478.

It can happen that the newly defined curve rises above the ULC of the force-compression envelope. If this happens, the partial reloading curve is redefined as the ULC.

Partial unloading

A more complex aspect consists in defining an unloading curve that starts right after an incomplete partial reloading, or put more simply, when unloading starts from a point which lies in the middle of the experimental force-compression envelope. In short, if this happens we apply a shift in the x direction to the experimental curves, so that the local maximal point of loading (x_l^{max}, F_l^{max}) coincides with a point on the ULC. From there on, a new (translated) curve can be defined.

5.4 Simplified constitutive laws

Constitutive laws for other pairs of contact than the hammers and the string have been modelled with a simplified approach. In these cases, contact forces have been represented with an enhanced Kelvin-Voigt model, in which the stiffness is a third order polynomial. The normal force then reads:

$$F_n(x) = \left(ax^3 + bx^2 + cx\right) - D\dot{x} \tag{5.14}$$

The polynomial function has been fitted with compression experiments. In line with the experiments performed for the hammer string interaction, care has been taken that the parts of the action were in a configuration in which they are normally working. Also, the interpolation function has been chosen so that it passes through the origin. The damping term D has been identified numerically so as to fit with the experimentally measured behaviour of the action.

5.5 Tangential forces

The tangential component F_t of the force is modelled with the Coulomb friction, using Cull and Tucker's formula which takes both static and dynamic coefficients of friction into account.[28] The tangential force is computed as:

$$F_t = \mu F_n \tag{5.15}$$

with

$$\mu = A\left(\tanh(\dot{x}_t/v_t) + \frac{B_1\dot{x}_t/v_t}{1 + B_2(\dot{x}_t/v_t)^4}\right) \tag{5.16}$$

with μ the friction coefficient, $\dot{x}_t$ the relative tangential velocity, v_t the relative threshold velocity, A the dynamic coefficient of friction, B_1 and B_2 coefficients adjusted in order to obtain the right force peak corresponding to the static

[28] S. J. Cull and R. W. Tucker. 'On the Modeling of Coulomb Friction'. In: *Journal of Physics A : Mathematical and General* 32 (1999), pp. 2103–2113.

coefficient of friction. The parameters A, B_1, B_2 have first been chosen on the basis of their similarity with the materials used in a grand piano action. We have thus taken the parameters from Hirschkorn's work, and adapted some of them with experimental measurements in order to make them fit with our particular action.[29]

[29] Hirschkorn, *op. cit.*

Chapter 6

Vibrating string

Acoustics is probably the most studied field of research concerning the piano. In this respect, different sub-parts of the piano have been studied separately or in combination. These studies deal with the hammer-string interaction, the string vibration, the coupling of the string with the soundboard, the soundboard vibration and the emission of sound in an acoustical room. It goes without saying that the hammer-string interaction is the only element that is useful for us. In a logical way, these studies have evolved toward a greater precision and complexity of the methods that were used both experimentally or numerically.

In the first versions of our model, the hammer string interaction was modelled as a soft hammer that impacted a solid stop. The addition of a vibrating string to our model was not motivated by the desire to study acoustical phenomena, but for strictly dynamic purposes. As will be seen, technicians and scientists insist on the high influence of contact duration when the hammer hits the rightly assorted string. Behind this simple observation lie considerable consequences and complex interactions that can influence the behaviour of the whole action, in particular when played with force.

6.1 Equation of the vibrating string

The one-dimensional equation of the vibrating string developed by d'Alembert is still at the heart of today's most modern string models.[1] Considering the transversal movement (x, z plane) of a non-stiff string with zero diameter that is pinned at its two ends, the French encyclopaedist derived its equation of motion through the following differential relation:

$$\mu \frac{\partial^2 z}{\partial t^2} = T \frac{\partial^2 z}{\partial x^2} \tag{6.1}$$

where T is the tension and μ the linear density of the string. This equation follows Newton's force law, where the left part is the term related to mass and

[1] J. L. R. d'Alembert. 'Recherches sur la courbe que forme une corde tendüe mise en vibration'. In: *Histoire de l'Académie des Sciences et des Belles-Lettres de Berlin, année 1747*. .3. Berlin, 1749, pp. 214–249.

acceleration, the term on the right related to internal forces. In this case, the sole force term is related to the tension in the string. The equation can be rewritten conveniently so as to let the wave propagation speed appear explicitly $c = \sqrt{T/\mu}$. In practice, this equation is sufficient for strings with small length and with reasonable flexibility.

In piano strings, however, at least a second element has to be considered: the bending stiffness of the string that gives it beam-like characteristics.[2] Relating to basic beam theory, the restoring force of a bending beam is added to the right side of (6.1)

$$\mu \frac{\partial^2 z}{\partial t^2} = T \frac{\partial^2 z}{\partial x^2} - EI \frac{\partial^4 z}{\partial x^4} \tag{6.2}$$

where E is the Young's modulus and I the cross-sectional inertia of the string. The inharmonicities that are characteristic of the modern piano are due to string stiffness.[3] Generally speaking, the influence of the stiffness term is of less importance than the bending stiffness contribution.

A last enhancement that is proposed for the transverse behaviour of the string is the inclusion of damping effects. Chaigne and Askenfelt observed the effect of velocity damping caused by the friction with air ($-d_1 \frac{\partial z}{\partial t}$) and of the internal damping due to material imperfections ($d_2 \frac{\partial^3 z}{\partial t^3}$).[4] Bensa *et al.* further extended this second term, taking frequency dependent damping into account ($d_2 \frac{\partial^3 z}{\partial x^2 \partial t}$): the higher the frequency, the more damped the mode will be.[5] The damping terms taken into account, (6.2) becomes

$$\mu \frac{\partial^2 z}{\partial t^2} = T \frac{\partial^2 z}{\partial x^2} - EI \frac{\partial^4 z}{\partial x^4} - d_1 \frac{\partial z}{\partial t} + d_2 \frac{\partial^3 z}{\partial x^2 \partial t} \tag{6.3}$$

where d_1 and d_2 are the damping factors.

In the case of our model, the damping terms have been neglected, in the first instance because of the difficulty to find suitable parameters, secondly because the motion of the string is computed during such a short time that damping effects can be neglected.[6] The equation thus reduces to (6.2).

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[2] J. W. S. Rayleigh. *The Theory of Sound*. Vol. 1. London: MacMillan and Co, 1894, pp. 298-301.

[3] Ancient *pianoforte* suffer less from inharmonicity than their modern counterparts since their stringing is thinner. For a string with pinned ends, the inharmonicity is expressed in the solution as $f_n = n f_1^0 \sqrt{1 + Bn^2}$, where n is the n-th harmonic, f_1^0 the fundamental frequency of the same string without stiffness and $B = \frac{EI}{TL^2}$.

[4] A. Chaigne and A. Askenfelt. 'Numerical simulations of piano strings. I. A physical model for a struck string using finite difference methods'. In: *The Journal of the Acoustical Society of America* 95.2 (1994), p. 1112; A. Chaigne and A. Askenfelt. 'Numerical simulations of piano strings. II. Comparisons with measurements and systematic exploration of some hammer-string parameters'. In: *The Journal of the Acoustical Society of America* 95.3 (1994), pp. 1631–1640.

[5] J. Bensa et al. 'The simulation of piano string vibration: From physical models to finite difference schemes and digital waveguides.' In: *The Journal of the Acoustical Society of America* 114.2 (2003), pp. 1095–1107.

[6] The total duration of the hammer-string contact and a short supplementary delay, so that the string would still be vibrating if a second hammer impact should occur immediately after the first. The total duration of these events is generally less than 10 ms.

6.2 Finite difference model

The equation governing the string dynamics is solved in space using a finite difference method. The simplest way to do so consists in discretising the string of length L in N intervals of equal width Δx (Figure 6.1). For the i-th element of the grid, the central finite difference for the second and fourth derivatives with second-order accuracy yield:

$$\frac{\partial^2 z\,(x_i)}{\partial x^2} = \frac{z_{i-1} - 2z_i + z_{i+1}}{\Delta x^2} + \mathcal{O}(\Delta x^2) \tag{6.4}$$

$$\frac{\partial^4 z\,(x_i)}{\partial x^4} = \frac{z_{i-2} - 4z_{i-1} + 6z_i - 4z_{i+1} + z_{i+2}}{\Delta x^4} + \mathcal{O}(\Delta x^2) \tag{6.5}$$

$$\tag{6.6}$$

The string being pinned at its ends, the boundary conditions imply zero displacement and zero velocity:

$$z(0,t) = z(L,t) = 0 \tag{6.7}$$

$$\frac{\partial z(0,t)}{\partial t} = \frac{\partial z(L,t)}{\partial t} = 0 \tag{6.8}$$

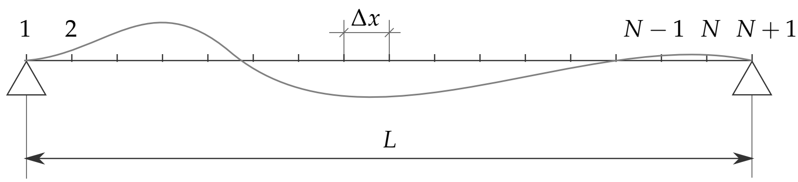

Figure 6.1: The string is discretised in N segments of length Δx.

The interaction with the hammer of the multibody model is considered through a distributed force applied on the two knots of the grid. The hammer head being modelled as a circle, the force is distributed on the two knots that surround the projection of the centre of the circle on the string (Figure 6.2, right). The force itself is computed with the constitutive law defined in Section 5.3. The penetration depth between the hammer and the string e is taken as the difference between the circle radius r and the vertical distance h_{cs} between the circle centre and the height of the string at the point that is horizontally the closest to the circle centre (Figure 6.2, left). The resulting force F_n computed with the penetration depth e is distributed in two forces (F_l and F_r), in proportion to the distance between the hammer centre and the neighbouring knots (Figure 6.2, right).

Since each note in the piano has two or three strings, the resulting force F_n computed previously is divided by n the number of strings. The final equation, in which the space derivatives have to be replaced with their finite difference equivalents of (6.5) and (6.6) becomes:

$$\mu \frac{\partial^2 z}{\partial t^2} - T\frac{\partial^2 z}{\partial x^2} + EI\frac{\partial^4 z}{\partial x^4} = \frac{F_j(t)}{n\Delta x}\delta(x-j) \tag{6.9}$$

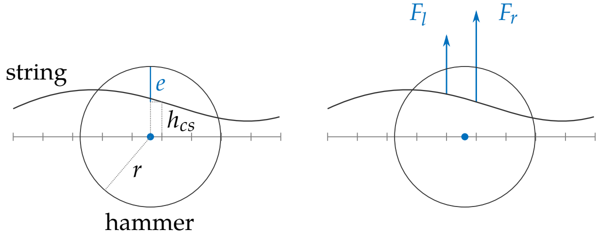

Figure 6.2: (left) The penetration between the hammer and the string is computed with respect to the point that lies the closest to the hammer centre. (right) The hammer-string force is distributed on two knots of the grid.

where δ is the Dirac delta operator and j the indices of the knots where an impact force is to be applied.

6.3 Physical characteristics of ancient strings reproductions

The strings used in our experimental work bench have been tested in order to provide the data needed for the string equation of (6.9). Given the specific nature of the strings (strings specially manufactured for ancient *pianofortes*), it is interesting to compare our findings with those in literature.

The manufacturing of historical piano wiring has been studied by Stephen Birkett and Paul Poletti.[7] Their study intended to find a proper way to reproduce the essential steps of ancient metallurgical techniques, while keeping in mind the available modern technology and the constraints that would make the product economically viable.

Birkett made and extensive report of the mechanical properties of his wires and other reproductions available on the market.[8] Based on various writings of the 19th century, he gives general recommendations regarding the characteristics an ideal *pianoforte* string should have. One of them is that tension of the strings should be such that their deformations remain in the elastic region, that is, the region in which deformation is totally reversible. According to 19th century sources,[9] tone quality of strings could be altered if the strings entered plasticity. Stephen Birkett posits that this loss of quality is due to metallurgical changes that occur with plastic deformations. He thus considers it as an advantage that the strings break without displaying too much plastic deformation. He also observes that historical wires display very few, or no creep at all

[7] S. Birkett and P. Poletti. 'Reproduction of Authentic Historical Soft Iron Wire'. In: *Instruments à claviers – expressivité et flexibilité sonore. Keyboad Instruments – Flexibility of Sound and Expression*. Actes des Rencontres Internationales harmoniques, Lausanne 2006 Proceedings of the harmoniques International Congress, Lausanne 2006. (Lausanne). Ed. by T. Steiner. Vol. 44. 2. Bern: Peter Lang, 2004, pp. 259–272.

[8] S. Birkett. 'The physical characteristics of historical iron music wire and a report on its replication as a viable modern product'. In: *Cordes et claviers au temps de Mozart. Bowed and Keyboard Instruments in the Age of Mozart*. Actes des Rencontres Internationales harmoniques, Lausanne 2006 Proceedings of the harmoniques International Congress, Lausanne 2006. (Lausanne). Ed. by T. Steiner. Bern: Peter Lang, 2010, pp. 327–346.

[9] C. Dieudonné and J. L. Schiedmayer. *Kurze Anleitung zu einer richtigen Kenntniss und Behandlung der Forte-Pianos in Beziehung auf das Spielen, Stimmen und Erhalten derselben, besonders derer, welche in der Werkstätte von Dieudonné und Schiedmayer in Stuttgart verfertigt werden*. Stuttgart, 1824.

before reaching their breaking stress. In other words, their behaviour can be compared to brittle materials.

Tensile tests have been performed on the three types of strings of our test bench in order to obtain the adequate Young's modulus for the string equation. The tests have been performed with a Zwick Z50 kN testing machine which provides a resolution of 1 µm for extension data. A gauge length of 100 mm was defined and the displacement of the machine head was performed at a rate of 0.1 mm/min. A pre-load of 10 N, 25 N and 50 N has been applied respectively to the treble, medium and bass strings prior to the measurements in order to ensure that the string was well strung. Note that the wires for medium and treble are made of iron, the bass wire of brass.

The aspect of the curves coincide with those of Stephen Birkett for the historical wires with the disadvantageous property that the region of elasticity is followed by a steady and an unclear transition to plasticity before reaching failure.[10] As will be seen hereafter, the measured values are also in line with Birkett's results.

The most common way to define a materials' Young's modulus consists in measuring the slope in the linear part of elasticity, when $\sigma < \sigma_{lin}$ (dotted lines of Figure 6.3). This standard Young's modulus will be noted E_{lin}. After examination of the results, the linear strain ϵ_{lin} was defined as $\epsilon = 0.2\%$. However, for both the medium and bass string, the strain applied due to the string tension is outside the linear zone. This does not necessarily mean that we are out of the region of elastic deformation, but simply that the local Young's modulus varies with strain. We therefore define a local Young's modulus E_w, which corresponds to the slope of the curve at the working stress level of the strings (dashed lines of Figure 6.3). Without surprise, the Young's moduli are lower at that point of the curve than in the linear part.

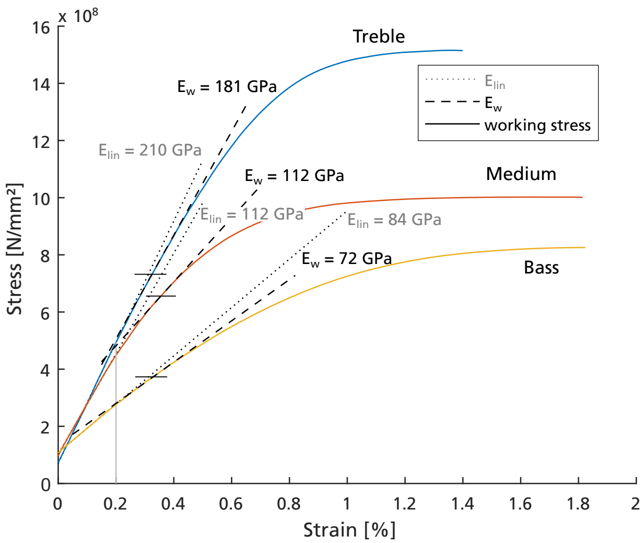

Figure 6.3: Tensile tests for treble, medium and bass strings. The Young's modulus for $\sigma_{lin} = 0.2\%$ are indicated in grey dotted lines, whereas the Young's modulus under working stress are drawn in black dashed lines.

[10] As each of our samples broke outside the gauges, it was impossible to measure the fracture stress σ_f without further investigation of the string rupture.

Remaining data that are required for the string model are summarised for each type of string in Table 6.1.

note	L [mm]	l_s [mm]	D [mm]	n	μ [g/m]	E_0 [GPa]	E_w [GPa]	T [N]	f [Hz]
C	1607	117	0.75	2	3.71	84.15	72.22	163.87	65.405
c^1	560	44	0.56	2	1.87	176.23	111.91	161.42	261.62
f^3	111	7.5	0.38	3	0.879	210.31	181.37	82.99	1396.91

Table 6.1: Measured data for the bass, medium and treble strings.

Chapter 7

Vibrating hammer shank

Among the elements of the piano action, it is suspected that the flexibility of the hammer shank plays an important role in the overall behaviour of the action. The vibration of the shanks built for this project has been measured for different kinds of experiments. In the multibody model, the flexibility of the hammer shank has been modelled using the finite segment method (FSM) and confronted to experimental results.

This chapter is divided in three parts: the first is a literature overview, the second displays experimental observations and the last presents the finite segment model of our hammer. The first part of the state of the art explores the literature in which the effect of hammer shank flexibility has been highlighted. The literature review continues with an overview of the existing mechanical models for deformable beams, finishing with the contributions in which a flexible hammer is integrated in a piano model.

7.1 Literature overview

In the literature, the study of shank flexibility is often associated with the complete hammer-string interaction. For this reason, we have decided to mention only those contributions in which hammer shank flexibility is considered as a central part of the research. This state of the art is divided in two parts. The first is related to experimental studies, the second is focussed on the treatment of flexible shanks with multibody formulation. The latter part tackles the modelling methods for flexible beams in general, followed by the developments specifically related to hammer shanks.

Experimental observations

The main interest to study the flexibility of the hammer shank was motivated by the belief that its deformation contributes to the timbre of the piano.

Suzuki observed and modelled the movement and interaction from hammer shank to string.[1]. His experiments revealed the rubbing and the vibratory

[1]H. Suzuki. *Vibration Analysis of Hammer-Shank System*. CBS Technology Center, 1985. His model is described in the next Section.

motion of the hammer on the strings that find their origin in the shank flexing. Shank deflections up to 0.75 mm were measured and believed to influence the vibration of the string audibly.

Approximately at the same time, in a broader study related to the piano, Askenfelt and Jansson observed the vibrating behaviour of several hammer shanks of grand piano actions.[2] They noted that the hammer exhibited several resonances that can be excited differently. The lowest mode, found at a frequency of *ca* 50 Hz behaves like a beam with a lumped mass at its tip. Higher order modes behave in a more complex manner. Starting from the observation that the vibrating motion of the hammer prior to string contact can be influenced by the pianist's touch, they suggest that the modes of the hammer could also influence the sound of the piano. However, a formal and quantified link between hammer mode excitations and timbre variations could not yet be established.

Giordano and Winans observed that for loud dynamics, the force-deformation curve of the hammer impacting the string displayed a strange inverted hysteresis-like relationship.[3] They suspected that the hysteretic aspect of this curve was attributable to hammer deformation and not properties of the materials.

In his study concerning the hammer-string interaction in a modern upright piano, Birkett based his observation on very precise high-imaging procedures.[4] Observing the deformation of the shank, he deduces the contribution of shank flexibility in the overall hammer string contact via a linear relationship between force and shank deformation. He observes that shank flexion represents a rather small contribution to the force that is transmitted to the strings. Finally, he observes a displacement along the strings of the contact location of about 0.2 mm due to flexing at the highest impact velocities.

In a set of studies focussed on high-speed comparison of Stein and Walter-type *Prellzungenmechaniken*, Birkett points out how the vibrations of the hammer head can lead to a dysfunction of the catch.[5] Under strong initial accelerations, the hammer is subjected to such deformations that it already intercepts the catch in its rising phase (whereas it should only be caught in its descending phase). It is concluded that under high dynamics, the check design in Walter pianos will inevitably cause the hammer to scuff the check before it frees itself and continues its trajectory towards the strings.

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[2] A. Askenfelt and J. E. V. 'From touch to string vibrations. II: The motion of the key and hammer'. In: *The Journal of the Acoustical Society of America* 90.5 (1991), pp. 2383–2393.

[3] N. Giordano and J. Winans. 'Piano hammers and their force compression characteristics: does a power law make sense?' In: *The Journal of the Acoustical Society of America* 107.4 (2000), pp. 2248–2255.

[4] S. Birkett. 'Experimental investigation of the piano hammer-string interaction'. In: *The Journal of the Acoustical Society of America* 133.4 (2013), pp. 2467–2478.

[5] S. Birkett. 'Observing the 18th-century Prellzungenmechanik through high-speed imaging. Pianissimo and forte response compared'. In: *Cordes et claviers au temps de Mozart. Bowed and Keyboard Instruments in the Age of Mozart*. Actes des Rencontres Internationales harmoniques, Lausanne 2006 Proceedings of the harmoniques International Congress, Lausanne 2006. (Lausanne). Ed. by T. Steiner. Bern: Peter Lang, 2010.

Modelling

In terms of modelling, a hammer shank can be associated to a flexible beam. The different beam modelling methods that are commonly used in the frame of multibody dynamics are briefly summarised, followed by an overview of the previous research in which flexible hammer shanks are modelled.

Flexible beams Historically speaking, multibody dynamics is based on the assumption that bodies are intrinsically not flexible, but rigid. It is therefore not surprising that flexibility has to be approached with a different formulation than the one which rules the dynamics of the rigid bodies. Different formalisms can be used, depending on the nature of the deformable bodies (shape, amplitude of deformation, composition of materials, etc.) and of the envisaged study (frequency analysis, stress strain evolution, etc.). The specific case of beams that one finds in many applications is particularly attractive thanks to their relative simplicity. Two types of approaches can be envisaged for this application: the first takes advantage of the relative simplicity of the beam geometry that makes it possible to formulate the problem analytically and to solve it straightforwardly. Nonetheless, this is limited to simple situations. When dealing with more complex geometries and motions (*e.g.* dynamics loading, multiples adjacent bodies), a second approach has to be used. This second approach consists in discretising the beam via a series of elements (*e.g.* finite elements or finite segments) and in studying the relative displacements and rotation within or between these elements via suitable generalised coordinates.

Different degrees of precision can be achieved with analytical beam models. The simplest model is governed by the so-called classical beam theory, or Euler-Bernouilli theory that is valid for slender beams under small deformations. The hypothesis of small deformations implies that the cross-sections of the beam remain planar and perpendicular to the centroidal axis. In consequence, shear stress is neglected. An improvement of this model consists in taking the inertial effect of the rotating beam into account, this is called the Rayleigh beam theory. Finally, the Timoshenko model is the most complete as it comprises the shear deformation of the beam. These analytical models are governed by partial differential equations (PDE) that have to be converted to ordinary differential equations (ODE), for example using the Rayleigh Ritz approach. The solution is approximated using shape functions issuing from a modal analysis pre-process or using well-suited mathematical interpolants (polynomials, splines, etc.). The more shape functions are used, the more precise the model will be, but the more costly the numerical treatment analysis will be.

The second approach, in which the beam is discretised, can be solved with the finite elements method (FEM). The great advantage of FEM is their ability to subdivide a potentially complex geometry into smaller and simpler parts, the so-called finite elements. The problem is locally formulated in each subpart before assembling all the equations in one system of equations that governs the entire system. For transient problems, the PDE's of each subdomain is approximated by an ODE in which rotations and displacements of the nodes represent the variables. Refinement of the model is obtained by increasing the number of elements that define the geometry and/or the type of interpolation functions.

The finite segments method (FSM) falls in the same category as it amounts to discretising the beam. It is nonetheless much simpler than FEM in practice but is limited to simple beam geometries. However, despite the simplicity of the approach, FSM is able to capture high dynamical effects (*e.g.* geometric stiffening phenomenon[6]) and can be implemented in a rigid multibody program in a very versatile way. In short, a beam is subdivided in small beams linked with joints that dispose of degrees of freedom in the desired directions of deformation. Each joint is governed by a constitutive equation, namely a lumped image of the deformation laws of continuum beam. Since the finite segment method has been chosen for our application, its principles will be the subject of Section 7.3.

Applications to piano models Suzuki modelled a hammer shank using a lumped-element model, decomposing the hammer shank in 13 parts.[7] Apart from the experimental observations mentioned in the previous Section, his model showed that for a given impact speed, stiffer hammers led to higher peak forces and broader force time-patterns.

Izadbakhsh added hammer shank flexibility to an existing multibody model of a grand piano action developed by Hirschkorn.[8] Considering the shank as a long narrow beam, he modelled it using the Rayleigh approach. Based on the impact of the hammer on a rigid stop, he concluded that the flexibility of the shank does not significantly influence the motion of the other components of the action. However, his model with flexible shank highlights the consequence of hammer deflection on the hammer-string interaction: the velocity of the hammer head increased significantly, causing more *scuffing*[9] during hammer-string contact.

Vyasarayani refined Izadbakhsh's work by adding a vibrating string to his model.[10] The string deformation causes a diminution of shank vibration and an increase in hammer scuffing during string contact. Masoudi also included a flexible hammer shank in his multibody model of an upright piano action.[11] He concluded that hammer shank compliance mainly influences the post-imp-

[6] R. E. Valembois, P. Fisette and J.-c. Samin. 'Comparison of Various Techniques for Modelling Flexible Beams in Multibody Dynamics'. In: *Nonlinear Dynamics* 12.4 (1997), pp. 367–397.

[7] Suzuki, *op. cit.*; H. Suzuki. 'Model analysis of a hammer-string interaction'. In: *The Journal of the Acoustical Society of America* 82.4 (1987), pp. 1145–1151.

[8] A. Izadbakhsh. 'Dynamics and Control of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2006; M. Hirschkorn. 'Dynamic Model of a Piano Action Mechanism'. MA thesis. Waterloo, Ontario, Canada: University of Waterloo, 2004.

[9] Scuffing is the longitudinal motion of the hammer during hammer-string contact.

[10] C. P. Vyasarayani. 'Transient Dynamics of Continuous Systems with Impact and Friction, with Applications to Musical Instruments'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2009.

[11] R. Masoudi. 'Micromechanics of Fiber Networks Including Nonlinear Hysteresis and its Application to Multibody Dynamic Modeling of Piano Mechanisms'. PhD thesis. Waterloo, Ontario, Canada: University of Waterloo, 2012.

act behaviour of the action, and more precisely the rest position of the hammer when it is caught by the check.

Chabassier and Duruflé modelled a flexible hammer shank as a Timoshenko beam and coupled it with a full model of a vibrating string, a soundboard and sound radiation in free space.[12] Different pianistic touches were approximated by varying jack force acting on the hammer shank without resorting to any dynamical multibody model. The results show that the subsequent changes in hammer vibration cause different timbre spectra that were not due to a possible shock excitation on the structure, nor from a changing impact point, nor hammer scuffing on the string since none of these features were modelled.

7.2 Experimental observations

It has been seen in the previous section that hammer shank flexibility seems to play an important role in the dynamics of the *Prellzungenmechanik* and the tone of the grand piano. At first sight, *Prellzungenmechanik* hammer shanks seem less inclined to flexing given the lower mass of their hammer heads and their high cross section inertia that seems to have been developed to prevent any bending. Even though Stephen Birkett published some results concerning the vibrational behaviour of *Prellzungenmechaniken*, the non-uniformity of the late 18$^{\text{th}}$ century *pianofortes* incited us to perform the same kinds of experiments on our actions.[13]

A visual inspection of the high-speed imaging videos reveals vibrations of the hammer shank when the key is depressed with a moderate force.[14] A marker fixed on the upper part of the hammer serves as a reference point for the hammer movement (Figure 7.1). Since the tracked point is taken on the extremity of the hammer, it is not aligned with the hammer shank. The measured deformations are therefore amplified as a result of the hammer height. They nonetheless provide an interesting visualisation of the phenomenon of hammer bending. The results are displayed on a recorded image in order to give the reader a good idea of the amplitude of the vibrations (Figure 7.1).

Different dynamics have been applied to the key-front in order to evaluate the varying amplitude of the effect. The results are displayed for a sonorous *mf* and an aggressive *ff* (respectively left and right of Figure 7.2). Vibrations seem to be the strongest after the string impact (blue line on Figure 7.2). The amplitude of the vibrations is clearly more important for the *ff* stroke, but due to its higher impact and rebound velocity, the hammer performs less cycles. The vibrational behaviour of the hammer after string impact is of less importance for our study, but it is noteworthy to observe the hammer deformation before string impact (red line on Figure 7.2). In case of the *mf* dynamics, the hammer rise follows the geometric combination of two circular movements (the hammer rotating on a the rotating key). No particular effect of flexibility can

[12] J. Chabassier and M. Duruflé. 'Energy based simulation of a Timoshenko beam in non-forced rotation. Application to the flexible piano hammer shank'. In: *Journal of Sound and Vibration* 333.26 (2014), pp. 7198–7215.

[13] Birkett, *op. cit.*

[14] Photography was performed at 15 kHz with a resolution of 256×256 pixels. Motion has been tracked using the circle detection method described in Section 3.4.

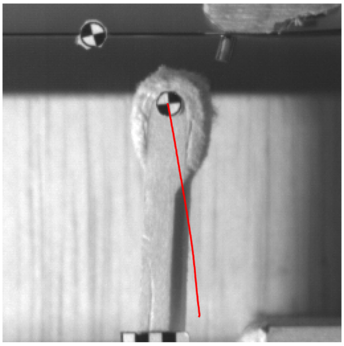


Figure 7.1: The movement of the treble hammer has been tracked with a marker on the upper part of the hammer core. In the selected frame, the hammer is a few millimetres away from the string and rising following the red path.

be clearly observed. With the louder strike, the hammer follows an inverted 'S'-shaped trajectory which can only come from the hammer flexing.

When the hammer shank bends, a potentially important amount of energy can be accumulated during a short period of time, before being released somewhat later. If this storage and release of energy happens during a critical phase of motion, it could influence the behaviour of the action.

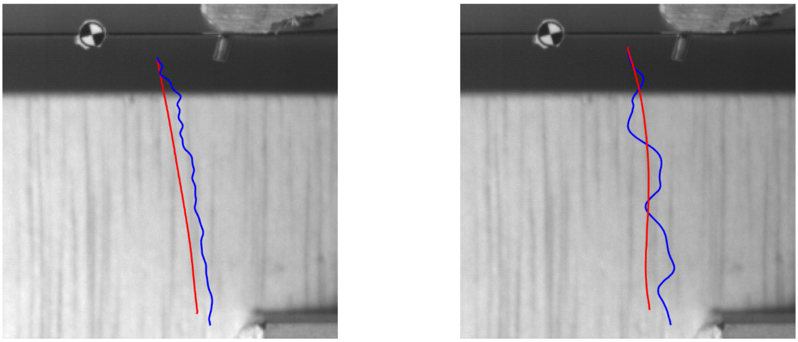


Figure 7.2: (left) For a strong *mf*, the hammer vibration is more present after the string impact (blue line) than during hammer-rise (red). (right) For stronger *ff* impacts, the effect on hammer rise (red) is much more obvious as the hammer follows an inverted 'S' shape. Post-impact vibrations (blue) are expectedly much more important than for the *mf* impulse.

The chaotic nature of the hammer vibration was also studied. In this, we tried to answer whether the realised experiments were repeatable. We therefore used the actuator device described in Section 3.5 to reproduce the *mf* impulse that served for the previous investigations. Three different experiments that were recorded in a row (every 6 minutes) are compared. The first two gives an almost perfect overlap of oscillations (red and blue continuous lines in Figure 7.3). The third one (red dashed line in Figure 7.3) coincides with the two previous ones until the first complete oscillation that occurs after string impact. The small differences between experiments (1, 2) and (3) must be due to small perturbations in the experimental set-up (initial position of the actuator's rod, of the actuator itself, of a component of the action, etc.). In any event, the fact that two results of a seemingly chaotic phenomenon are so to speak identical means that the phenomenon can be reasonably well captured which is rather reassuring with the view of modelling.

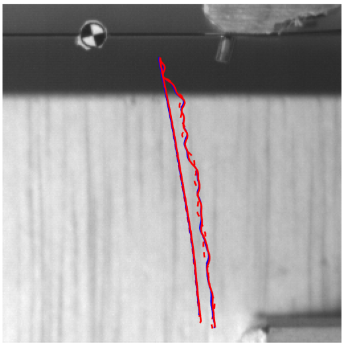


Figure 7.3: Here the key has been depressed three times with the same input. For two of the trials, the hammer follows the same trajectories and displays the same vibrations (blue and red continuous line). In one of the experiments, the motion is slightly different (dashed red line).

The relative motion of the hammer tip with respect to the non-vibrating part of the hammer was investigated. This was done by using a different set-up of the camera, where a larger part of the action is visible.[15] As we have seen in Section 3.3, capturing a larger part of the action causes a significant drop in recorded frames and in the pixel/mm resolution of the results. A mobile reference frame $\{\hat{\mathbf{X}}_{rel}\}$ is defined with the help of two targets glued on a part of the hammer shank where vibrations are supposed to be insignificant (Figure 7.4). The motion of the hammer tip is then tracked with respect to this frame which enables us to experimentally capture the relative local deformation $(\Delta x_{rel}, \Delta z_{rel})$ of the hammer shank with respect to its rigid tip articulated on the *Kapsel*.

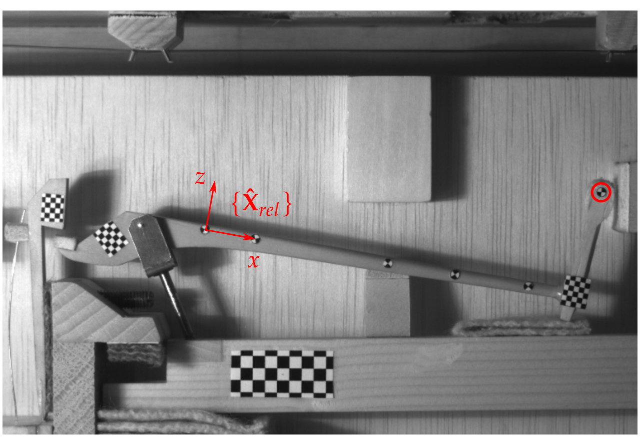


Figure 7.4: The relative local movement $(\Delta x_{rel}, \Delta z_{rel})$ of the hammer tip with respect to the rigid part of the shank provides an image of the hammer deformation.

[15]The recordings were performed at 3800 fps, with a resolution of 768 × 512 pixels.

Interestingly, this type of analysis enables to confirm the importance of hammer distortion before string impact. In the experimental results that are discussed hereafter, the key is depressed with the hand, applying a *fortissimo* touch. The time history of the absolute vertical position provides a reference point for the stroke progress (Figure 7.5, bottom). In particular, it divides the results in pre- and post string impact at *ca* 19 ms.

Remarkably, the largest amplitude of relative vertical displacement occurs before the impact and not during hammer-string contact (Figure 7.5, middle). The maximal hammer deflection thus takes place during the initial phase of hammer acceleration, that is, at the first instants when the hammer beak enters in contact with the pawl and is put in rotation. The hammer motion then restores to its initial configuration, before being lightly deformed again. A second restoration phase occurs before the string impact, where the shank is brutally deformed (20 ms). The two negative oscillations prior to string contact, present both for the relative horizontal (Δx_{rel}) and vertical displacement (Δz_{rel}) are at the base of the already observed inverted 'S'-shaped curve. Here it is easy to observe how important this deformation is. What follows are the oscillations that were already clearly observed in Figure 7.2

Another advantage of the larger view-range is that we can also capture the initial and final phases of the hammer-tip trajectory (right plot in Figure 7.5). The trajectory of the hammer starts at the left side of the graph (coordinate $(0; 0)$). The loop performed at the very beginning may seem intriguing, but it is due to the so-called *Schnabelluft* discussed in Section 2.1. Indeed, during the first moments of key depression, the hammer follows the movement of the key without rotating. It thus moves to the right. Logically, it should also make a rising movement, but here it is going downwards because the hammer is free to rotate around its pivot, and the acceleration to which it is subjected pushes it downwards in the cloth stop.

7.3 Finite segment model

In our application, the different hammer shanks can be considered as one-dimensional, slender, tapered beams. It has therefore been chosen to model their flexibility using the 'finite segment', or 'lumped parameter' approach developed by Huston.[16] With this method, a beam is divided in multiple flexible members, connected one to another with joints whose constitutive law represents (a portion of) the flexibility of its two neighbouring bodies (Figure 7.6). This method enables to take extensional, torsional and bending flexibility into account despite the use of rigid bodies. In the case of a piano hammer shank, the main flexibility effect is clearly due to bending in the vertical plane.

FSM has the advantage to be very easily implementable in a multibody framework. From a numerical point of view, the potentially small masses of the segments and the high stiffness of the joints may lead to a stiff system, for which one must pay attention to select the suitable time integration scheme.

[16] R. L. Huston and Y. Wang. 'Flexibility effects in multibody system dynamics'. In: *Computer-Aided Analysis of Rigid and Flexible Mechanical Systems*. Ed. by M. F. O. S. Pereira and J. A. C. Ambrósio. Vol. 268. Springer Science+Business Media, B.V., 1994, pp. 351–376.

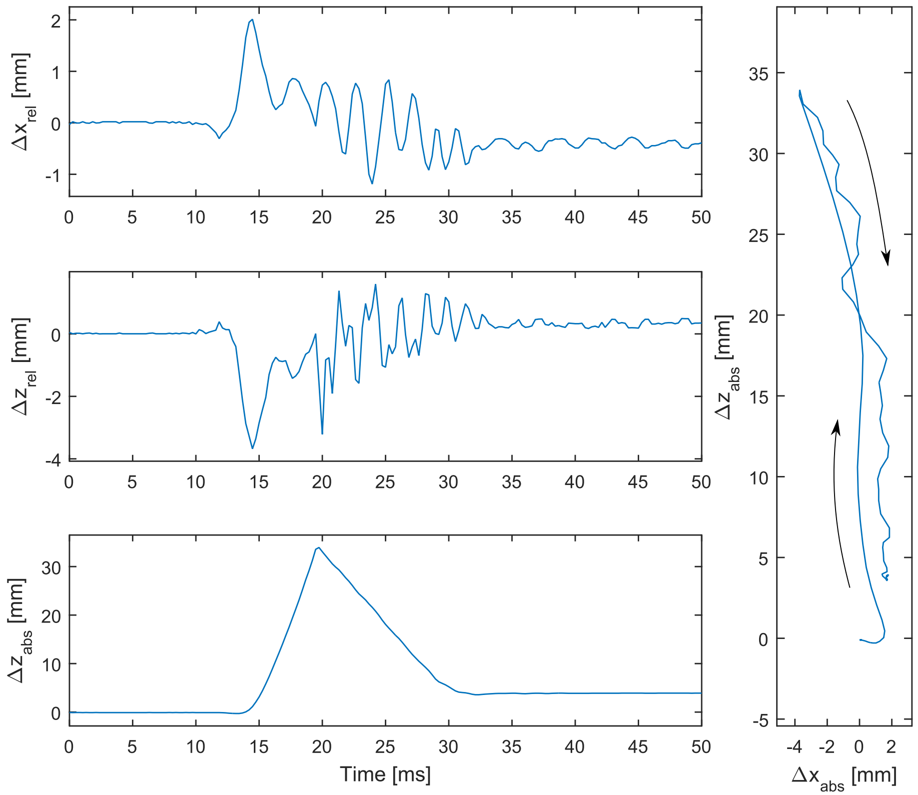


Figure 7.5: Time history of the relative horizontal and vertical displacement of the hammer tip (top and middle), absolute vertical displacement of the hammer (bottom) and the absolute (x, z) displacement of the hammer (right). The key stroke corresponds to *fortissimo* dynamics applied to the Stein-treble version of the action.

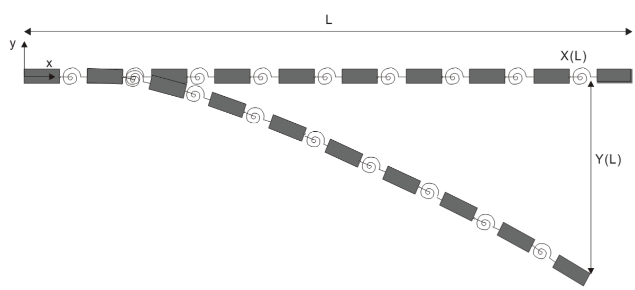


Figure 7.6: With the finite segment method, a beam is divided in small segments linked with joint forces that account for its flexibility. Image taken from Samin *et al.*, *Symbolic Modeling of Multibody Systems*, p. 436.

Finite segments applied to a bending beam

Considering the segments obey linear elasticity, the stiffness coefficients that define the joints' relation between inter-segment rotation and their moment are defined with principles of structural analysis. Two different cases are envisaged: first the equivalent stiffness between two bending elements and second the stiffness at the border of the extreme segments, for which only one of the two segments bends.

Let us therefore define θ the inter-segment rotation and k_θ its corresponding rotational stiffness, leading to the generic joint equation

$$\tau = -k_\theta \theta \tag{7.1}$$

that accounts for local beam flexibility. In order to simplify the notation, we will consider two elements with subscripts $i = 1, 2$. At the segment level, we define the subscripts $j = l, r, c$ that respectively stand for the left end, the right end and the centre of mass of the segment (Figure 7.7). Let E be the Young's modulus of the beam's material (here considered uniform for all segments), I_{ij} the cross section moment of inertia of the i^{th} segment with respect to the beam centroid axis. Let L_{ij} be the distance between the centre of mass and the left or right end for the i^{th} segment flexibility.

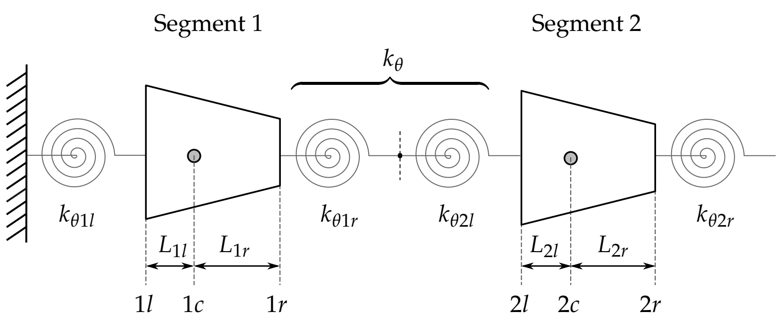


Figure 7.7: Segment 1 is clamped at its left side. Segments 1 and 2 are connected with an equivalent rotational spring.

The equivalent bending stiffness between two segments is composed of two springs in series that independently represent the contribution of each segment. According to Huston, the contribution of each element in terms of stiffness can be written

$$k_{\theta 1r} = \frac{E\left(I_{1r} - I_{1c}\right)}{L_{1r} \ln\left({}^{I_{1r}}/{}_{I_{1c}}\right)} \tag{7.2}$$

$$k_{\theta 2l} = \frac{E\left(I_{2l} - I_{2c}\right)}{L_{2l} \ln\left({}^{I_{2l}}/{}_{I_{2c}}\right)} \tag{7.3}$$

Combining (7.2) and (7.3), the equivalent spring modulus k_θ for the two spring segments in series becomes

$$\begin{aligned} k_\theta &= \frac{k_{\theta 1r}\, k_{\theta 2l}}{k_{\theta 1r} + k_{\theta 2l}} && (7.4) \\ &= \frac{E\left(I_{1r} - I_{1c}\right)\left(I_{2l} - I_{2c}\right)}{L_{2l}\left(I_{1r} - I_{1c}\right)\ln\left({}^{I_{2l}}/{}_{I_{2c}}\right) + L_{1r}\left(I_{2l} - I_{2c}\right)\ln\left({}^{I_{1r}}/{}_{I_{1c}}\right)} && (7.5) \end{aligned}$$

The equivalent stiffness of a segment that is clamped on a supporting body follows the same reasoning, except that only the stiffness of one element has to be taken into account. For instance, let us consider the case where the left side of segment 1 is clamped (Figure 7.7), the equivalent stiffness modulus $k_\theta = k_{\theta 1l}$ is then simply computed as

$$k_\theta = \frac{E\left(I_{1l} - I_{1c}\right)}{L_{1l}\ln\left(I_{1l}/I_{1c}\right)} \tag{7.6}$$

Finally, to take structural damping into account, a damping term can be added to (7.1), that becomes, assuming a linear law:

$$\tau = -k_\theta\theta - D\,\dot{\theta} \tag{7.7}$$

where the damping factor (D) will be fitted experimentally in our case, as will be seen later.

Application to the hammer shank

The finite segment method requires to divide the beam in small segments that are considered as normal rigid bodies in the multibody formalism (Figure 7.8). Physical properties like mass, inertia, centre of mass and the exact dimensions of each segment thus need to be known. Given the very small size of the segments and the will to establish a non-destructive method of characterisation, it was chosen to extract this data from CAD models of the hammers. The latter have thus been accurately redrawn and the appropriate mass density has been applied to each of its components. The resulting mass, centre of mass and inertia for the entire hammer produced by the CAD software have been compared with measurements of the real hammers (Table 7.1 and 7.2). Since both types of data for full hammers are in good agreement, the sliced CAD data can be considered as relevant for our purpose.

	mass [g]	c.o.m. (x; z) [mm]	inertia [kg m2]
measured	2.40	(55.2; 3.6)	5.99E-6
CAD	2.398	(54.0; 3.4)	5.93E-6
CAD error	0.083 %	(2.17 %; 5.56 %)	1.00 %

Table 7.1: Measured data and CAD values for the treble hammer are very close

	mass [g]	c.o.m. (x; z) [mm]	inertia [kg m2]
measured	3.34	(61.8; 5.2)	6.66E-6
CAD	3.328	(66.1; 8.2)	7.00E-6
CAD error	0.36 %	(2.17 %; 6.96 %)	5.11 %

Table 7.2: Measured data and CAD values for the bass hammer are very close

Both treble and bass hammers have been divided in seven segments connected by six joints that model the bending stiffness of the hammers (Figure 7.8). With this number of segments, the first two bending modes are captured with sufficient accuracy, as it has been shown by a model analysis of cantilever beams modelled via FSM.[17] The length of the segments has been deliberately decreased as they approach the hammer head where the beam section is smaller. Segments 1 and 7 have been considered as rigid; the first because of its thickness, the second because it is rigidified by the hammer head glued to it. The equivalent stiffness of joints 1 and 6 thus follow (7.6), while joints 2–5 are governed by (7.5).

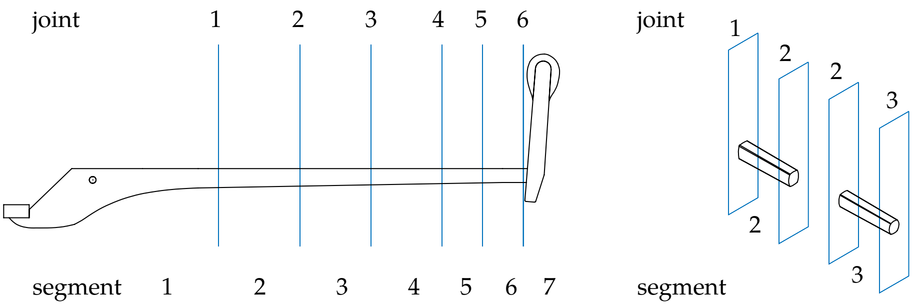


Figure 7.8: The hammer shanks have been divided in such manner that flexibility is represented with six joints. On the right, cross-sectional views of segment 2 and 3.

7.4 Experimental validation

As mentioned above, the damping factor D in (7.7) is difficult to compute or to measure directly. Also, the Young's Modulus E cannot be determined with precision from literature. Indeed, though it is known that the shank is made out of pearwood, a variety of parameters of the wood used to craft the shank can influence its Young's Modulus: orientation of the wood fibres, humidity of the component, density of the fibres, etc. In order to evaluate E and D, the motion of the vibrating hammer has been measured and compared with simulations.[18] The frequency of oscillation is supposed to inform us about the stiffness of the system (and thus the Young's modulus E which is directly proportional to it), while the decay enables us to approximate the damping factor D.

For this high-speed camera-based experiment, the hammer has been clamped at the position of joint 1 (Figure 7.8). The hammer shank is bent manually by pushing horizontally on its head and thereafter suddenly releasing it (Figure 7.9). Since the finger cannot let go the hammer instantly, the first oscillations have been neglected for the comparison with simulation data. The experiment has been reproduced on a FSM multibody model with the same configuration.

As an illustrative example, the experimentally measured horizontal motion of the oscillating treble hammer is compared with the same experiment

[17] Valembois, Fisette and Samin, *op. cit.*

[18] Photography was performed at 6 kHz with a resolution of 512×512 pixels. Motion has been tracked using the chequerboard detection method described in Section 3.4.

Figure 7.9: The Young's Modulus and damping factor of the constitutive laws of the bending hammer have been obtained via high-speed imaging by oscillating the hammer. From left to right, three snapshots of the experiment with the treble hammer, approximately for the most positive, most negative, and zero bending.

reproduced in the model (Figure 7.10). A high-pass filter is applied to the experimental signal .[19] The filter was mainly used for the bass hammer which displayed a residual oscillation at low frequency (*ca* 15 Hz). The Young's modulus was calibrated to fit with the oscillation frequency (*ca* 146 Hz for the treble hammer, *ca* 125 Hz for the bass hammer) and the damping term modified so that the decrease in amplitude would match the experiment.

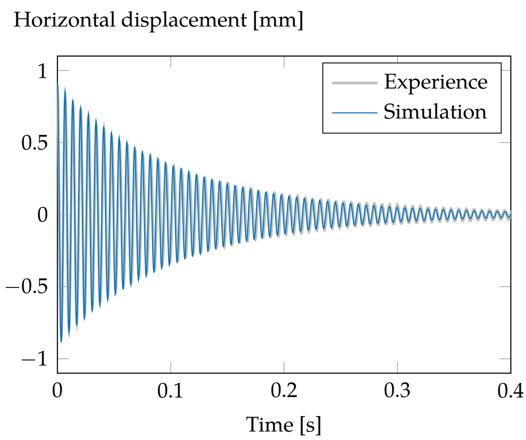


Figure 7.10: The transverse displacement of the hammer head when it is oscillating displays a clear natural frequency that can be precisely captured with the model.

The simulations were finally rerun with the obtained parameters, but with different initial conditions that corresponded to similar experiments. The obtained results were very similar.

Note that the Young's modulus obtained for the treble and bass hammers were surprisingly different, though both hammers are made of pearwood. This difference can probably be explained by the lack of precision of the shank profiles redrawn in the CAD software. Indeed, the equivalent stiffness of a beam is almost[20] directly proportional to the product of the Young Modulus

[19] A third order Butterworth IIR filter with a cut-off frequency of 20 Hz.
[20] Neglecting the logarithmic term $\ln\left(I_{ij}/I_{ic}\right)$.

and the cross section moment of inertia (see (7.5) and (7.6)), and not to the Young's Modulus alone. The moment of inertia being a quadratic physical value of the cross-sectional dimensions, it comes that minor errors in the shape and dimensions can lead to compounded errors and thus to considerable differences of the inertial contribution to the stiffness. These errors are thus counterbalanced via our experimental identification with a corrective factor in the last unknown element of the stiffness: the Young's modulus.

Chapter 8

Validation and observations

The validation of the model was performed by comparing the high-speed imaging results with the simulation results. The model that was chosen for validation is the action equipped with the Stein pawl and the treble hammer. Two different kinds of inputs are presented; the first corresponds to a *forte* impulse, the second to a *piano*. The movement of the experimental action was driven with the linear actuator presented in Section 3.5, so that the experiment could be reproduced. In particular, the motion of the whole action has been recorded, followed by a recording focussed on the hammer-string interaction.[1]

The simulations were performed using a motion-driven input at the key.[2] Force-driven simulations are left as future work. For both inputs, the motion of the three main components are inspected in parallel: the (driven) key, the hammer and the string. Next, the behaviour of the vibrating hammer is inspected more closely.

Although the general coordinates of the model are angular rotations of the bodies, the results are given in terms of the (x, z) coordinates that correspond to the targets placed on the experimental action (Figure 8.1). The same trackers have been integrated in the multibody model action. This representation enables to observe the effect of the composite motion of the bodies that is due to the flexibility.

8.1 *Forte* touch

The key stroke that is used for this validation experiment corresponds to *forte* dynamics. To be more precise, the key has been played with a modern touch, defined as a struck touch by Goebl.[3] As opposed to the *pressed* touch, where the finger is already on the key at the moment of depression, the *struck* touch corresponds to a strike of the key starting at a certain distance above the keyboard.

[1]The whole action was filmed at a resolution of 768×521 pixels and at a rate of 3800 Hz. The hammer-string interaction was recorded at a resolution of 256×256 pixels and a frame rate of 15 kHz.

[2]That is, a consistent set of key position, velocity and acceleration time histories.

[3]W. Goebl, R. Bresin and A. Galembo. 'Touch and temporal behavior of grand piano actions'. In: *The Journal of the Acoustical Society of America* 118.2 (2005), pp. 1154–1165.

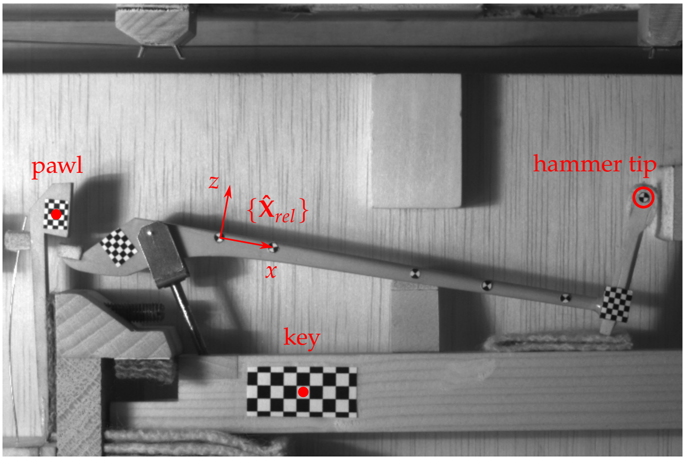


Figure 8.1: The targets placed on the real action for motion tracking purposes have been defined at the same place on the multibody action.

A general overview of the movement of the action shows the time history of the vertical motion of the key and the hammer, and the horizontal motion of the pawl (Figure 8.2). The key depression starts at approximately 20 ms and is fully depressed at 65 ms where it oscillates on the upper cloth rail (Figure 8.2, top). It is kept depressed until 800 ms where it is released. The movement of the hammer closely follows the experiment, except for the release of the key. This is due to the complex friction mechanism that occurs between the leather hammer and the leather pad of the catch. In our model, the hammer is immediately released and bounces on the little stop of the key, whereas in the real action, the release of the hammer is more progressive. Note that the impact of the hammer with the string occurs before the key has reached its full depth. The timing of the string impact and rebound of the hammer also closely follows the experiments.

Regarding the pawl, larger discrepancies can be observed between the simulation results and the experiments. The overall picture is that the experimental pawl produces more rebounds at a higher frequency than the modelled one. In the present case, this is not of great importance, as the rebounds roughly located in the range 50–120 ms occur when the hammer has already escaped. The only influence that will be felt by the hammer is during its return, because in this configuration, the oscillations of the pawl are limited by the hammer beak and not the pawl stop. A more interesting part of the pawl behaviour occurs during the working key-dip, that is, between 25–37 ms as illustrated in the zoomed window of Figure 8.2, bottom. An interesting behaviour that could not be captured with the model is the initial backward movement of the pawl (first negative values of the grey curve) before it is pulled forward by the beak. In the model, the pawl is simply pulled forward, before escapement occurs and it is free to move backwards again.

The motion of the hammer is inspected in more detail with the study of its

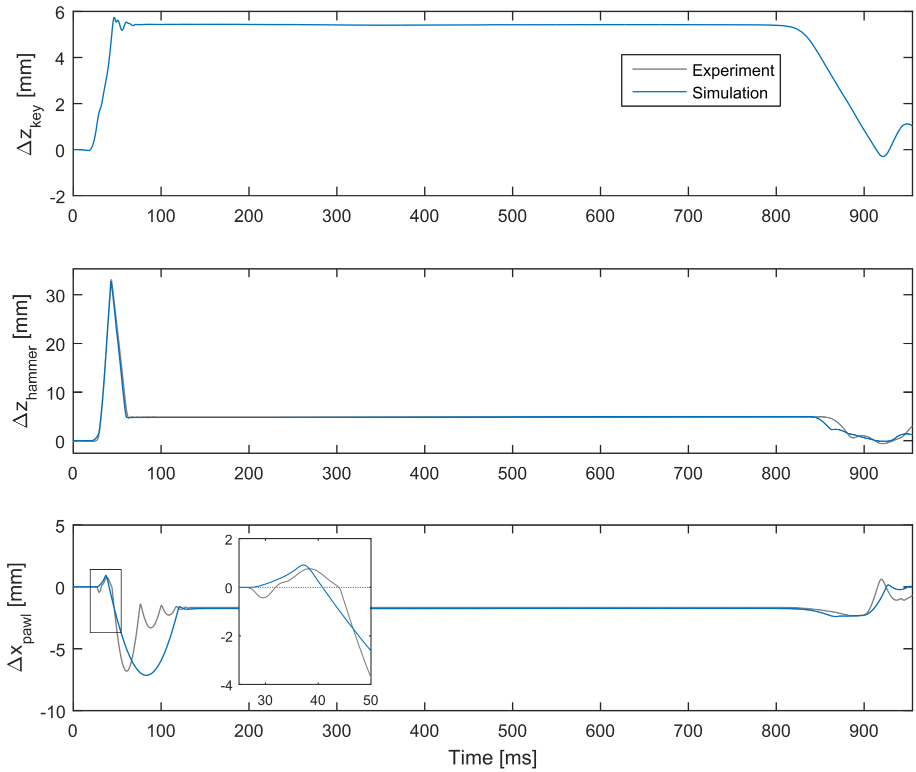


Figure 8.2: Comparison of the experimental and simulated results for the time history of the vertical displacement of the key (top), the vertical displacement of the hammer (middle) and the horizontal displacement of the pawl (bottom). The key stroke corresponds to *forte* dynamics applied to the Stein-treble version of the action.

movement during the first 120 ms of the simulation (Figure 8.3). The horizontal and vertical deformations of the hammer with respect to the rigid part of the hammer shank are studied (Figure 8.3, top and middle respectively). The absolute time history is also provided in order to easily identify the different phases of motion (Figure 8.3, bottom). Finally, the (x, z) trajectory is shown (Figure 8.3, left). The relative displacements are of very low amplitude and thus difficult to track. Because it is not always possible to distinguish what should be considered as noise in the curve, we have decided to display the experimental results in their non-smoothed version. It is, however, possible to retrieve the tendency of movement, in particular in phases where its amplitude is greater.

Let us focus on the relative vertical displacement of the hammer (Figure 8.3, middle). Deformation of the hammer shank starts both in the model and the experiment at the first contact with the pawl (27 ms). The inertia of the hammer that resists its rotational motion inflicted by the pawl causes the shank to bend downwards. In the experiment, this corresponds to one large oscillation that recovers at 37 ms, whereas the model displays two of theses oscillations

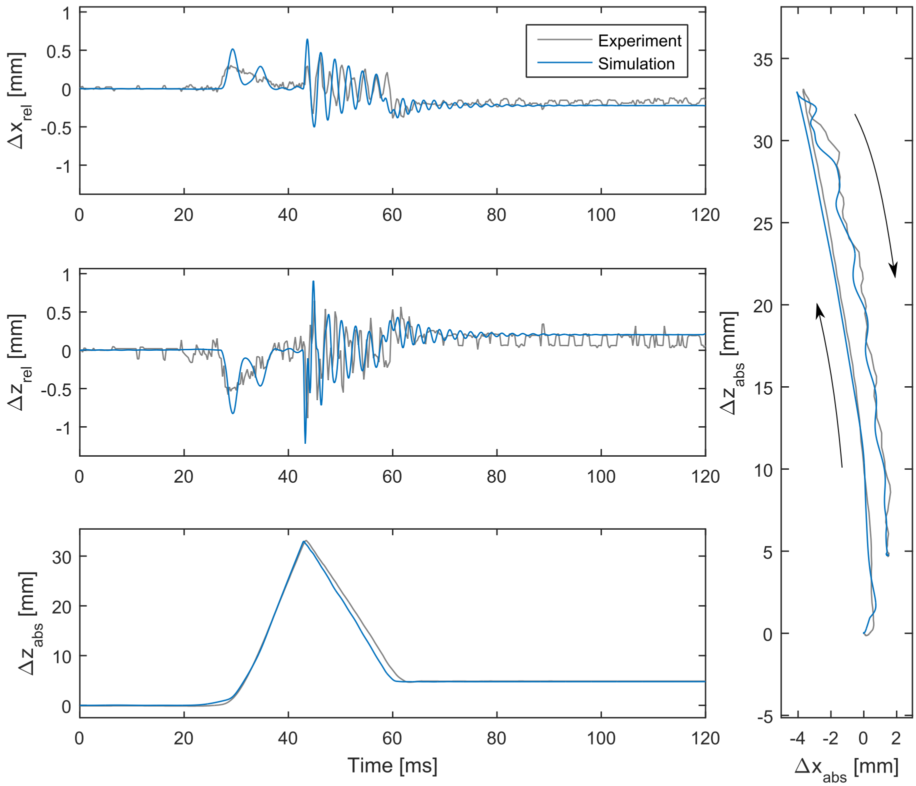


Figure 8.3: Comparison of the experimental and simulated results for the time history of relative horizontal and vertical displacement of the hammer tip (top and middle), the absolute vertical displacement of the hammer (bottom) and the absolute (x, z) displacement of the hammer (right). The key stroke corresponds to *forte* dynamics applied to the Stein-treble version of the action.

in the same time. This first moment of deformation corresponds to the initial acceleration of the hammer. Put in perspective with the force profile between the pawl and the hammer, it is clear that the first oscillations of the model are due to the non-constant forces of the pawl. Comparing high-speed imaging and videos of the model, it is clear that the beak-pawl contact of the model is more chaotic than reality. It has been tried to obtain smoother contact forces, but without success.

The moments before and right after escapement display no significant hammer deformation (37–43 ms), neither in the model, nor in the experiments. The hammer impact occurs around 43 ms with a slight shift of 0.5 ms between simulation and experiment. The impact with the string causes a strong downwards deformation, followed by a few oscillations during the free return of the hammer (43–60 ms). Amplitude and frequency of deformation are in conformity with the experiments, though a slight shift in terms of frequency. The impact duration has been evaluated for the experiments at 0.8 ms, though it was not possible to define the exact moment of contact and the subsequent loss of contact. In simulation, the contact between the hammer and the string lasts for 0.664 ms. At 60 ms, the hammer is getting caught by the check and is deformed with a positive concavity. Here again, the movement in the experimental data is definitely noisy.

The observations made in the previous paragraph can be transposed to the (x, z) diagram of the hammer tip motion (Figure 8.3, right). It does enlighten the reason why the hammer of the model rises earlier than in experiments around 20–27 ms. As was already observed for the real action in Section 7.2, the acceleration of the key causes the hammer to slightly deform the support on which it rests before it starts rising. The complexity to model this double woven piece of cloth did not allow us to incorporate this very soft deformation phase in the model. Consequently, as can be seen in the (x, z) diagram, the model hammer does not perform the small loop at the beginning of key movement. Instead, it immediately rises towards the strings as is confirmed in the time history graph.

8.2 *Piano* touch

The second keystroke that is analysed consists in a pressed *piano* touch, meaning the finger is already on the key upon its depression. The same types of results as for the *forte* touch are displayed. Following the time history of the three main components of the action gives us some more information about the validity of the model (Figure 8.4). The first obvious observation is that all the components move slower than for the *forte* touch.

Looking at the hammer motion for the experimental data during its return, one notices that its slope suddenly changes and becomes less steep than in the model (Figure 8.4). It was thought that the origin of this change was due to a lack of friction caused by the pawl (that could be due to too low a friction coefficient or too low a stiffness of the spring). In fact, it is caused by the hammer that *almost* escapes before reaching the strings (Figure 8.6, top), but in fact stays in contact with the pawl until right after the string impact (Figure 8.6, middle). The hammer beak then deforms up to a point where the pawl escapes and is propelled backwards like a catapult (Figure 8.6, bottom). In the meantime, this beak deformation has absorbed part of the kinetic energy of the hammer, thus slowing it down. As with the *forte* dynamics, the let-off of the hammer is followed by vibrations of the beak leather.

Contrary to the *forte* impulse, the motion of the pawl in the experimental action does not display any initial backward movement (Figure 8.4). Instead, it is pushed forward and undergoes three oscillations revealing a stick-slip transition. As can be seen in the detailed view, the model also follows these three stick-slip phases, but slipping is more important than sticking and the pawl goes a little more backward. Besides the limitations in terms of the flexible modelling of the leather beak, this might be one of the reasons why the hammer escapes earlier in the model (line *a* on zoomed part in Figure 8.4, bottom) than in reality (line *b*). Comparing the behaviour of the pawl right after let-off shows the importance of the 'catapult effect' mentioned earlier; after the escapement of the experimental action (line *b* in Figure 8.4, bottom), the slope

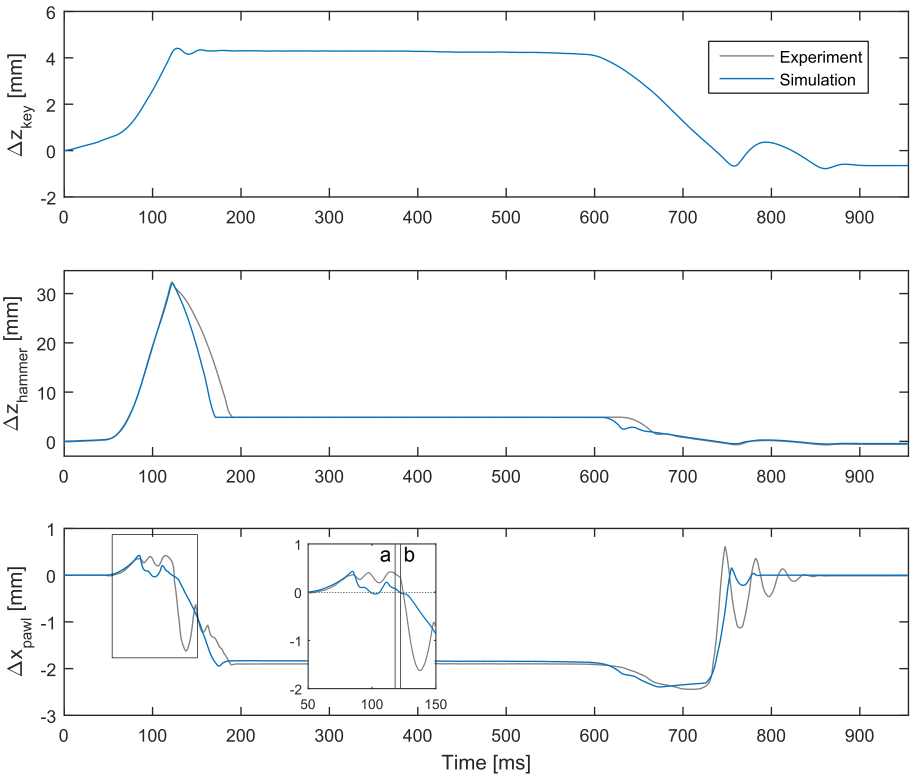


Figure 8.4: Comparison of the experimental and simulated results for the time history of the vertical displacement of the key (top), the vertical displacement of the hammer (middle) and the horizontal displacement of the pawl (bottom). The key stroke corresponds to *piano* dynamics applied to the Stein-treble version of the action.

of the pawl movement becomes very steep, indicating a great velocity due to its propulsion by the beak deformation. In the model, where the pawl is not propelled by beak deformation, the pawl is simply pushed away slowly by the movement of the descending beak.

Hammer vibrations at lower dynamics are clearly of less amplitude than with the *forte* impulse (Figure 8.5, right). In fact, the amplitudes of deformation are of such a low magnitude (approximately 5 times less than in the *forte* case), that the tracking algorithm had difficulties measuring them with the available frame resolution. As can be observed, the data for the horizontal motion is almost unexploitable, while only a slight tendency can be extracted from vertical data.

Focussing on the relative vertical motion of the hammer tip for the model (Figure 8.5, middle), one can distinguish the four phases observed in the previous Section. Between 45–100 ms, the hammer bends downwards due to its initial acceleration. Then, a few moments before impacting the strings, it recovers, followed by small oscillations (100–120 ms). The string impact at 125 ms causes strong vibrations, starting with the downward bending of the shank

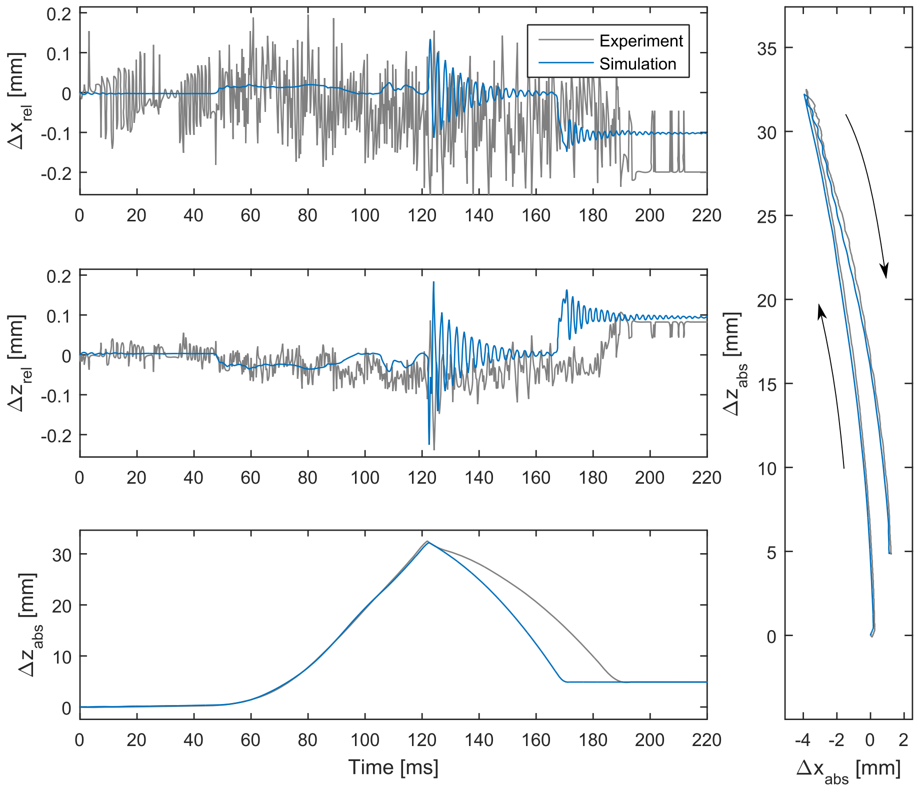


Figure 8.5: Comparison of the experimental and simulated results for the time history of relative horizontal and vertical displacement of the hammer tip (top and middle), the absolute vertical displacement of the hammer (bottom) and the absolute (x, z) displacement of the hammer (right). The key stroke corresponds to *piano* dynamics applied to the Stein-treble version of the action.

and followed by a strong decrease in amplitudes, until the hammer is caught by the check (170 ms). At this point, the hammer bends upwards with some vibrations before stabilising. The time-shift with the experimental data for the 'catch deformation' has to be put in parallel with the hammer movement (Figure 8.5, bottom) where it is clear that the hammer gets caught later (190 ms) in the experiments, due to its lower velocity. Putting aside the time-shift, the amplitudes of deformation seem to follow the same tendency when comparing experimental and simulated results.

A comparison of the hammer-string contact times is even more difficult than for the *forte* stroke as the deformation of both hammer leather and string cannot be totally ascertained with a visual inspection. Experimental string contact lasts for about 1.5–2 ms, whereas the model hammer is in contact with the string during 1.4 ms.

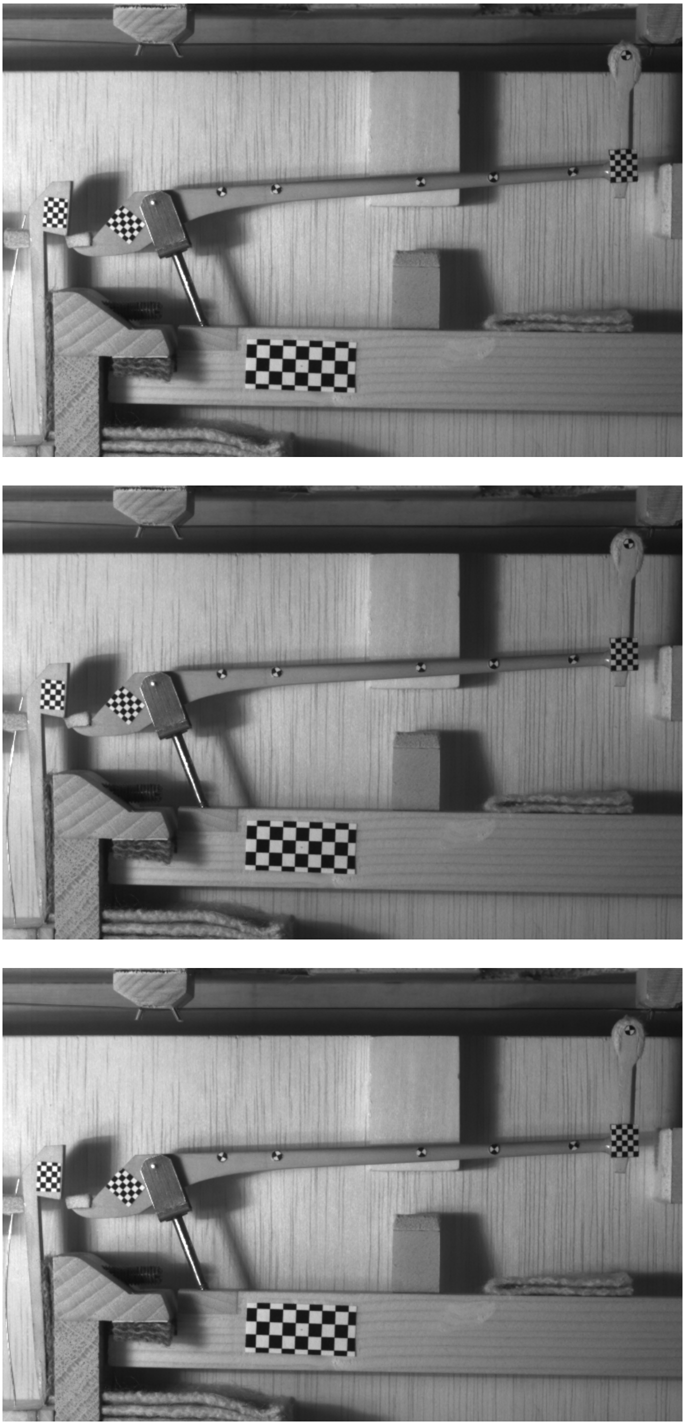


Figure 8.6: (top) The hammer impacts the string at t_i; (middle) at $t_i + 4.47$ ms the hammer rebounds from the string but has still not escaped, notice the deformation of the beak leather; (bottom) at $t_i + 11$ ms the hammer has escaped but is still near the strings. The pawl has been pushed far backwards with the springiness of the leather.

Conclusion

The objective of this work consisted in studying the behaviour of 18^{th} century piano actions. The main innovation consisted in transposing modern methods used in engineering to the field of organology. Quite a few studies using multibody dynamics have focussed their attention on the modern grand piano action, with the ultimate goal to provide a tool that would help piano manufacturers to take decisions in their design process. Our approach was different and rather intended to look back in time so as to provide supplementary arguments to explain the characteristics and the evolution of piano actions: the so-called *Prellzungenmechaniken*. The contributions of this thesis can be split in two parts; the first concerns the development of the multibody model in itself together with well-targeted experiments. The second part focusses on what the model and the associated experimentations tell us about the Stein and Walter action.

Multibody model

A complete multibody model of two *Prellzungenmechaniken* has been conceived. As far as we know, this is the first time a *Prellzungenmechanik* has been modelled with a multibody formalism. In order to achieve this model, several elements have been developed and analysed separately. These findings form in itself separate contributions.

The multibody model is characterised by a great number of intermittent contacts between the action's components. This implies the need to firstly perform contact detection and then to apply constitutive laws that reproduce the behaviour of the bodies in contact. Concerning the issue of defining contact locations, most of the bodies could be easily and correctly represented by simple geometric shapes. In contrast, the beak-pawl contact being a key issue of the analysis, it has been handled through a combination of different shapes according to the relative position of the contacting bodies and to the sequence of their successive states.

As regards the constitutive laws for the contacting bodies, we have carried out compression experiments for each of the contacting pairs, considering that all contacts refer more to smooth contacts than to impact mechanics. From these measurements, we developed a model for the behaviour of the compression of leather and cloth that takes the following characteristics into account; the hysteretic nature of the compression cycle, the fact that their force-displacement characteristic is limited by upper and lower bounds relative to a maximal load and the potentially complex phenomena that occur under the effects of partial loading. The models that we encountered in literature did not propose this continuous transition from loading to unloading under incomplete loadings. This original contact law has been applied to the hammer-string contact. The other pairs of contacts have been treated with a simplified law, here again based on compression tests of the bodies in question.

When observing *Prellzungenmechaniken* with high-speed imaging, it becomes obvious that the vibrations of the hammer shank are not negligible once the action is used at *mezzo forte* dynamics or higher. For this reason, the hammer shank deformation was modelled using the finite segments method. An equally important element is the behaviour of the string during the contact duration with the hammer. This element has been represented using a finite difference model. The combination of the hammer shank dynamics, the dynamic response of the string and realistic constitutive laws were crucial to obtain a coherent response of the hammer on the strings.

Once the model was assembled, it has been validated along with data resulting from experiments performed on our test bench. Besides a real model of a Stein and a Walter action, the test bench contains strings for each register of the piano (bass, medium, treble). It is equipped with a force sensor on the key and an actuator which reproduces the motion of the finger. High-speed movies of the action were performed in order to compare the simulations with reality. From our validation process, the model globally follows the same behaviour as the real actions. However, the contact model of the pawl should be more refined, as will be explained hereafter.

Stein and Walter's *Prellzungenmechaniken*

With our modern engineering eyes, a strict comparison between Stein and Walter's actions could easily lead to the conclusion that the latter enhanced the former's invention. Stein would be the revolutionary inventor of a technology, the *Prellzungenmechanik*, and Walter the 'researcher' who brought it to its perfection. This work could provide at least two important arguments that would encourage this vision.

Let us first note the profile of Anton Walter; a few years ago, Rita Steblin discovered that Anton Walter followed classes at the Royal Imperial Engineering Academy of Vienna. This unexpected discovery was made thanks to testimonies of professors who taught at the Academy. One of them, Friedrich Wilhelm Gerlach, mentions that Walter '[aspired] to conduct even more intensive and painstaking investigations, and that he [strived] to determine the relationship between the components of the musical instruments with regard to sound and motion.' Clearly, Walter was experimenting with his *pianoforte* actions. We found that the content of the courses taught at the Academy, especially those by Gerlach, can only confirm that Walter had the ability to scientifically analyse his *Prellzungenmechanik*. The approach that he applied in his theoretical research must have been very close to what modern mechanical engineers use as the base of their science: vectorial decomposition of forces, torques and displacements. Anton Walter thus had every skill in his possession to enhance the design of Stein's action.

This leads us to the second argument which happens to be based on a rational analysis of the interacting forces of the *Prellzungenmechanik*. Departing from Paul Poletti's analogy of the hammer-pawl interaction with a ratchet and pawl system, we have studied the influence of the pawl design on the ability of the *Prellzungenmechanik* to support strong key blows. Indeed, experiments show that Stein actions, when they are played upon with great force, have the tendency to (incorrectly) escape *after* the string impact. Under the same conditions, Walter actions will rather escape too early. This early escapement may also be seen as a malfunction, but it is probably rather a safety precaution that prevents the hammer from blocking against the strings as it can happen when escapement occurs too late. In this respect, Paul Poletti defined what he calls 'slipper' and 'grabber' pawls. As the name implies, grabber pawls grab the hammer and thus delay its escapement, as opposed to the slipper pawls which help the hammer to escape. Simulation results from our multibody models confirmed that the Walter action behaves as slipper action throughout its key-depression. The Stein-type action we modelled (a Walter action modified to work with a Stein pawl) started as a grabber and finished up as a slipper action. Unfortunately, the results for strokes corresponding to higher dynamics were not totally convincing. In fact, the model did not show the change of behaviour which occurs between soft and loud dynamics and that we observed in the high-speed videos. However, the results did highlight the importance of the friction force between the hammer and the pawl in the behaviour of the pawl. Indeed, up to here, the contribution of the friction force was overlooked by the importance of the normal contact force.

These two findings (Walter's scientific education and the ability to respond to forceful key strokes thanks to a design modification) may thus lead us to conclude that Walter engineered an instrument that surpassed Stein's initial design. As a matter of fact, the transition to this wrong conclusion is made at the point where 'louder' or 'stronger' would necessarily mean 'better'. Walter did build instruments that resisted a more violent playing style than the Stein instruments, but both makers evidently supported different schools of piano playing, as pointed out by Schönfeld. In sum, it would be preferable to talk about a modification of Stein's action, rather than an enhancement, as Stein's actions had other advantages that were not present with Walter's. However, it is true that, in the end, the somewhat heavier playing style supported by Walter seems to have got the best of the purely classical and light aesthetics. This happened to the detriment of Stein's action design which was more or less abandoned at the beginning of the 19^{th} century.

Besides these considerations, our multibody model was used to study the dynamic behaviour of the *Prellzungenmechanik*. As such, the influence of the escapement regulation on the timing in the action and the string impact force have shown that an ideal position in terms of control and power of the sound can be obtained when it is regulated properly. It is also shown that the displacement ratio between the key depression and the hammer travel can be sensitively higher than the ones found with a quasi-static analysis. We believe that the higher displacement ratios are due to the effect of hammer flexing under dynamic conditions. Finally, it is suggested that the debated function of the slap-rail is to prevent the extreme backward motion of the pawl that can happen under very strong key blows. Contrary to what has been suggested in literature, we observed that strong kickbacks could also happen when the action is well regulated.

Perspectives

As we have seen throughout this work, a multibody model is a useful tool for studying elements that are difficult or even impossible to measure. However, for highly dynamic simulations, the model was less convincing. The following developments are proposed to improve the model. The most important point that would benefit from enhancements is the leather beak contact model. At the light of its observed behaviour with the help of high-speed imaging, various improvements can be proposed. Quite clearly, there is a big difference in the behaviour of the beak leather according to the angle at which the latter is in contact with the pawl. In this respect, both the law for the normal force and the tangential (friction) force needs to be adapted according to the relative position of the two bodies. The left end of the beak leather is also a part of the model which is more complex than it appears. Because of its (very small) free end, this part of the beak behaves like a bending spring; when the hammer escapes under a forceful key depression, the recovery of the beak-end appears to be responsible for pushing the pawl away violently. For high dynamics, the hammer shank displayed oscillations of too high amplitude. We therefore believe that structural damping should probably be modelled with a more complex law.

The model the has been proposed can be exploited in many different ways. In particular, it would be interesting to impose increasing dynamics to the key in order to observe the transitional behaviour of the action. This would allow for a better understanding of the consequences of the grabber and slipper nature of the actions. With this same principle, the evolution in timing of the hammer oscillations should be monitored. It would for example be interesting to know whether it is possible that the hammer recovers from its deformation at the moment it impacts the string.

The issue of the slap-rail also deserves a more thorough analysis so as to understand its origin. Both the model and further experimentation are required for this matter. Since the data for the medium and the bass hammers are available, it could be interesting to compare their behaviour with those of the treble hammer that was modelled in this work. High-speed imaging footage revealed that not only the hammer shank, but also the *Kapsel* vibrated significantly under hard blows. A flexible *Kapsel* could thus be integrated in the model. The current model comprises a model for the vibrating string. For the moment, its sole purpose is to evaluate the mechanical response of the strings. It would be beneficial to couple the multibody model with a complete model of a bridge and a soundboard so as to obtain sound.

A real-time multibody model of a *Prellzungenmechanik* has been achieved during this thesis. It has not been further developed as we aimed for precision and not speed of execution. Nonetheless, it provided promising results in terms of the precision of the results and of the real-time factor on an ordinary computer. Therefore, it could be used in an electrically actuated key so as to provide a haptic interface for which the touch characteristics could be easily modified. This would allow to perform subjective studies related to the feel an action provides. As a first approach to this subjective feeling, it could be interesting to evaluate the feel an action provides by analysing its local stiffness. Typically, this local stiffness would be the ratio between the torque at the balance pin of the key and its relative displacement. This ratio might provide a first step to quantify the influence of different regulations on the response of the action.

Appendices

Appendix A

The hammer-pawl contact

Malgré la simplicité apparente du système d'échappement de la mécanique, sa modélisation n'est pas aussi intuitive que son fonctionnement. En effet, nous avons dû découper les phases de mouvements possibles en cinq configurations géométriques différentes. Le problème principal vient du fait que la languette de cuir du marteau doit franchir un angle droit pour échapper (l'angle droit est indiqué par une croix bleue à l'origine du repère $\{\hat{\mathbf{X}}^{échap}\}$ sur la Figure A.1). La nature hybride de ce cas vient du fait que les diverses configurations font appel tant au contact droite-cercle, qu'au contact droite-point. La recherche du cas géométrique dans lequel se situent les pièces se fait par tests successifs, comme dans un arbre logique.

Dans un premier temps, nous définissons des surfaces par rapport au repère de l'échappement qui indiquent si le point de contact sur ce dernier se fera sur sa partie horizontale, verticale ou si nous pouvons d'ores et déjà nous assurer qu'il n'y aura pas de contact avec le marteau. Ces aires, que nous avons nommées zone 'horizontale', 'verticale' et 'morte', sont illustrées à la Figure A.1. Le quadrant supérieur gauche est une zone qui peut être à la fois 'horizontale' ou 'verticale', nous expliquons la raison plus loin, mais pour l'heure, nous pouvons considérer qu'il s'agit d'une zone 'horizontale'.

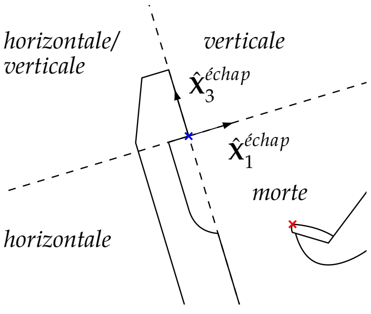
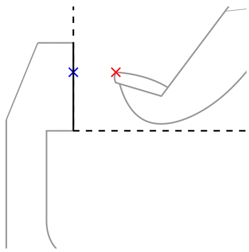
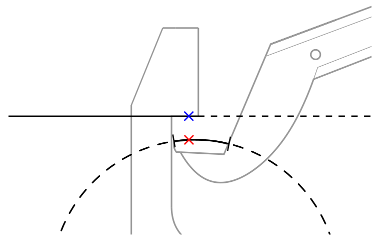


Figure A.1: Définition des quatre zones géométriques par rapport au repère de l'échappement. Le point d'extrémité de la languette du marteau (PEL) est indiqué par une croix rouge le coin de l'échappement par une croix bleue. Dans le cas illustré, les corps se trouvent en configuration 'morte'.

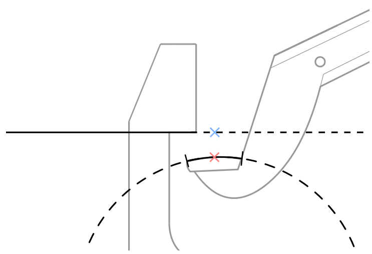
La position du point sur l'extrémité de la languette du marteau (dénommé PEL ci-après) définit dans quelle configuration se trouve le système. Trois cas de figure sont envisageables, dans lesquels nous appliquons des hypothèses plus ou moins fortes, basées sur des observations tirées des films réalisés avec



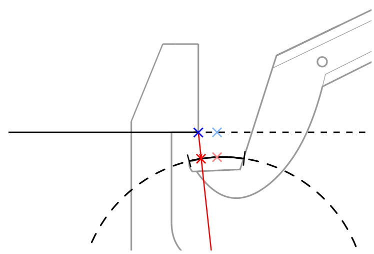
(a) Zone verticale



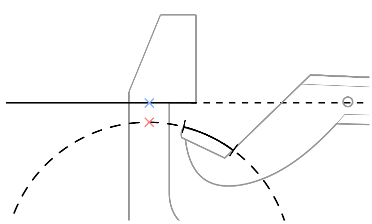
(b) Zone horizontale : droite - cercle



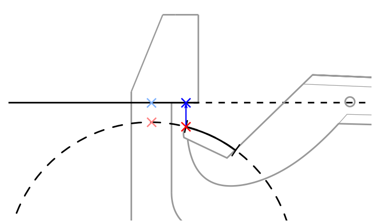
(c) Zone horizontale : point de contact non physique (cas 1)



(d) Zone horizontale : rectification des points de contact (cas 1)



(e) Zone horizontale : point de contact non physique (cas 2)



(f) Zone horizontale : rectification des points de contact (cas 2)

Figure A.2: Différentes configurations possibles pour effectuer la recherche du point potentiel de contact entre le marteau et l'échappement. Les croix indiquent les points potentiels de contact (bleu pour l'échappement, rouge pour le marteau). Les traits continus indiquent les segments sur lesquels sont définis les corps et les segments colorés indiquent les normales utilisées pour projeter un point de contact prédéfini sur l'autre corps.

caméra rapide. Afin d'expliquer les différentes possibilités, nous représentons les deux pièces de sorte qu'elles ne se touchent pas[1], la marche à suivre lorsqu'elles s'interpénètrent nécessite une astuce supplémentaire qui est expliquée par après.

1. le PEL est dans la zone 'morte': il ne faut rien calculer car les corps ne sont pas en contact et n'exercent donc aucune force mutuelle (Figure A.1).
2. le PEL est dans la zone 'verticale' : nous assimilons la surface de contact de la languette du marteau par le PEL et l'échappement est assimilé à une droite verticale. Le contact est donc de type 'droite-point' (Figure A.2a).
3. le point fixe est dans la zone 'horizontale' : trois sous-cas sont possibles en raison du contact entre un arc de cercle et une droite. Pour ce cas précis, la localisation du point de contact sur les deux profils (droite et cercle) se fait via une méthode numérique itérative. Les points déterminés sont tels que leurs vecteurs tangents aux profils en ces points ($\hat{\mathbf{t}}_a$, $\hat{\mathbf{t}}_b$) sont parallèles, que les corps soient interpénétrés ou non. Les cas se distinguent par la position du point de contact sur l'arc de cercle (localisé soit sur une de ces extrémités soit entre les deux).

   a) Le point de contact trouvé se situe sur l'arc de cercle (entre ses deux extrémités) et sur la demi-droite qui représente le bord horizontal de l'échappement (l'arc et la demi-droite sont représentés en traits continus sur la Figure A.2b). Dans ce cas, on a affaire à un cas normal de contact de type droite-cercle. Si l'un de ces deux points de contacts se trouve en dehors des bornes qui délimitent ces segments, on est dans un des cas suivants.
   b) Le point de contact se situe sur l'arc de cercle (entre ses extrémités) mais en dehors de la demi-droite qui représente le bord horizontal de l'échappement (les croix claires à la Figure A.2c). Ce cas de figure se présente lorsque le marteau passe le coin de l'échappement. En réalité, lors de cette phase de transition, le point de contact sur l'échappement reste invariablement sur le coin (c'est-à-dire la limite de la demi-droite), tandis que celui sur la languette du marteau varie, jusqu'à atteindre son extrémité gauche (Figure A.2d).

      Afin de tenir compte de cette modification, il faut rejeter la solution obtenue par la méthode itérative et la remplacer par le point du contact au coin de l'échappement. Son point de contact équivalent sur le marteau s'obtient alors en le projetant sur l'arc de cercle suivant une direction radiale (la droite de projection est illustrée en rouge à Figure A.2d). Cette droite correspond à la normale de contact $\hat{\mathbf{n}}$ pour cette configuration.
   c) Le point de contact se situe à gauche de l'arc de cercle et sur la demi-droite (Figure A.2f). Il faut dans ce cas ramener le point de contact au point de l'arc de cercle le plus proche, c'est-à-dire à son extrémité gauche. Le point de contact correspondant sur l'échappement se

[1]On pourrait s'interroger sur l'intérêt de trouver un point potentiel de contact dans le cas où les corps ne se touchent pas, mais il faut garder à l'esprit qu'on ne peut savoir mathématiquement si deux corps sont en contact tant qu'on ne connait pas les points où ce contact pourrait avoir lieu.

trouve par projection orthogonale de ce point sur la demi-droite. Comme dans le cas précédent, la normale et la tangente du point isolé (qui se trouve cette fois sur le cercle) sont obtenues grâce à celles de la demi-droite.

Étant donné que notre modèle tient compte de la déformation des matériaux grâce à l'interpénétration géométrique de corps indéformables, les zones qui délimitent les différentes configurations ne sont pas aussi clairement définies lorsqu'il y a réellement contact (et donc interpénétration). Nous illustrons cela à la Figure A.3 : le point fixe sur le marteau se trouve dans la zone que nous avons proposé de considérer comme 'horizontale', pourtant, il est évident que le contact se se trouve au niveau de la partie verticale de l'échappement.

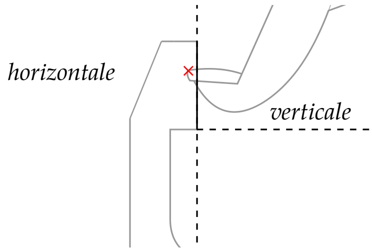
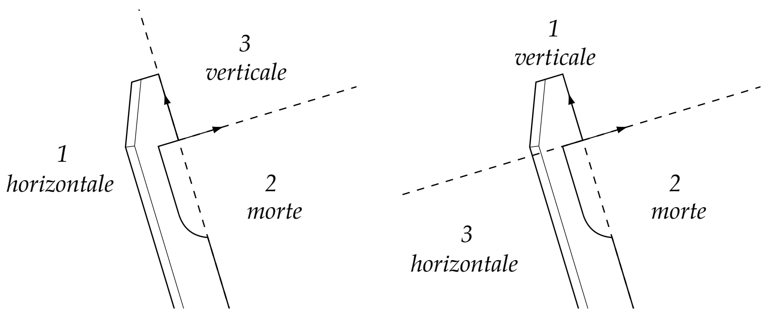


Figure A.3: Illustration de la problématique du découpage en zones.

Pour cette raison, il est important de donner deux cartes de zones qui varient en fonction de la configuration au pas de temps de calcul précédent. Il suffit pour cela de suivre une séquence de tests concernant la localisation du point fixe sur la languette du marteau, comme expliqué ci-après. Au début de la simulation le PEL est situé sous le flanc horizontal de l'échappement, correspondant à notre configuration 'horizontale'. L'ordre dans lequel sont vérifiées ces conditions définit les deux cartographies. La Figure A.4 illustre les deux cas possibles avec l'ordre des tests ($1 \Rightarrow 2 \Rightarrow 3$):

Cartographie 1: Figure A.4a. Si on part d'une configuration horizontale: la première vérification consiste à voir si on est toujours à gauche du repère de l'échappement. Le cas échéant, on maintient la configuration horizontale, dans le cas contraire on regarde si on est dans la zone 'morte' (sous le repère de l'échappement). Une réponse négative à ce dernier test signifie qu'on se trouve en région 'verticale'.

Cartographie 2: Figure A.4b. Si on se trouve préalablement dans la zone 'verticale', on teste si le PEL se situe dans la moitié supérieure du quadrant (cas 'vertical'), puis inférieur droit ('zone morte'), si ces tests sont tous deux négatifs, c'est qu'il est revenu en configuration 'horizontale'.



(a) t_{i-1} : horizontal (b) t_{i-1} : vertical

Figure A.4: La cartographies des deux cas de contact et accompagnée de leur ordre de vérification ($1 \Rightarrow 2 \Rightarrow 3$).

Appendix B

Multibody System Dynamics

Multibody Syst Dyn
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Multibody dynamics as a tool for historical research

Study of an 18th century piano action of Johann Andreas Stein

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Abstract Ancient musical instruments can tell us much about the way composers of the past centuries wrote their music. Indeed, the sound and playing characteristics of historical instruments are often very different from those of the instruments we are used to. For example, in the case of the Viennese piano actions used by Mozart and his contemporaries, the so-called "escapement height" largely conditions the response of the instrument to the pianist's touch. In this contribution, we aim to define how the Viennese action behaves when the escapement height, usually tuned by piano technicians, is changed.

To do this, a multibody model containing the frame, the key, the hammer, the pawl, and the string has been developed. This paper describes how the model has been carried out; a special focus is put on the detection of the intermittent contacts between bodies, which may look easy in the real action, but is rather complex to model. The model is compared with high-speed imaging data and a parametric study of the escapement height is performed by adjusting the rest position of the pawl. The high sensitivity of this regulation is revealed as a shift of 1 mm of the pawl seems to induce a displacement of the escapement height of 20 mm. It is also shown that a strong but linear decrease of the maximal force between the hammer and the string appears when the escapement height increases.

Keywords Piano action dynamics · Ancient musical instruments · Johann Andreas Stein · Action tuning

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Fig. 1 The Viennese action of Johann Andreas Stein was used by Mozart and his contemporaries. A virtual 3D representation of the action is used to visualize the simulation results

1 Introduction

While all modern grand pianos roughly contain the same action models, their predecessors display a remarkable variation in shapes and sizes. Nowadays, a professional pianist would probably play one of Mozart's sonatas on a Steinway grand piano, trying to approach the spirit the musical master has put in his piece of music. One thing he might not be aware of is the huge difference which lies in the piano he is used to play, and the one Mozart composed his music with. Such differences can be crucial when interpreting 18th century music with 21st century instruments: some dynamical expressions were impossible, or sometimes easier to produce, touch and weight of the keys were different, tone quality had other standards than today, etc. For these reasons, it is interesting to look back at the capabilities of older, historical instruments. In engineering terms, these "machines" would probably look obsolete, but in the eyes of a historian or musician defending historically informed performances,[1] they are of the highest importance. The action studied in this article has been conceived by Johann Andreas Stein, a famous piano builder, contemporary of Mozart (Fig. 1).

One of the reasons why a multibody model may be interesting in studying historical piano actions is the fact that their dynamic behavior is largely unknown. Even specialists are often limited in their analysis, on the one hand, because of the complex and very fast interaction between parts of the action, and on the other hand, because of small but crucial differences between the different existing models. As we shall see below, some studies have already highlighted differences between two piano actions which were famous for having been appreciated by Mozart. The present paper aims at highlighting the influence of technicians' settings applied to one of these actions on its behavior.

The paper is organized as follows. Section 2 summarizes the previous contributions in modeling piano actions. The modeling procedure and measurements performed on the parts of the model are illustrated in Sect. 3. It sums up the different bodies of the model and the way contact interaction is computed. Then, a comparison between the model and high-speed camera images is developed in Sect. 4. Finally, Sect. 5 explores the simulation results which correspond to one of the important regulations technicians apply on the action.

2 State of the art

Although the piano has been the topic of many acoustical studies in the past, one had to wait for the last decade before the scientific community started to tackle a complete model of its action with a real multibody approach.

[1]The practice of "historically informed performances" consists in playing music while being aware of the historical background of its composition and performance. This usually implies that the piece of music is played on instruments contemporary of the music itself.

Gillespie published in 1996 a model made of the five main bodies of the grand piano action: the key, the wippen, the escapement, the repetition lever, and the hammer [1]. The bodies are rigid and linked with kinematic constraints. In 2004, Hirschkorn published his thesis [2] in which the dynamic behavior of the piano action is deeply analyzed. It is the first study in which every part of the mechanism is considered independently and with its own physical properties. Consequently, there is no need to adjust global parameters with no physical meaning in order to match the model with experimental results. Each body is characterized independently in order to create a design tool for piano makers. On the recommendation of Hirschkorn, Izadbakhsh [3] introduces flexibility to the hammer shank using Rayleigh's method [3]. The articulation of the key, previously in pure rotation, is replaced by a combination of a rotation and translations, more in line with the real movement. The addition of flexibility influences the mechanism only slightly, but seems to increase the amplitude of the vibrations when the hammer strikes the string. In 2009, Vyasarayani [4] integrated a vibrating string in the multibody model developed by Hirschkorn and Izadbakhsh. He observed an increase in the stick and slip between the hammer and the string and also a decrease in the vibrations in the hammer shank. In the same year, Mamou-Mani and Maniguet [5] used the method developed by Hirschkorn in a comparison of historical piano actions which are not available anymore. Their study compares Érard's pianos preceding his invention of the double escapement. The objective of this research is to identify the characteristics of an instrument which is presently unknown, and to establish whether the underlying mechanism was (or not) precursory of the double escapement principle. More recently, Masoudi has worked on the action of an upright piano and proposed a micromechanical model of the felt based on the structural properties of its fibers [6]. Thorin used a different approach by modeling a grand piano action with non-smooth numerical method [7]. A great part of his work is dedicated to validating his model. In this respect, he considers that a model should be driven using displacement instead of force input.

Research on piano actions contemporary to Mozart has been led by Stephen Birkett [8]. His work compares two similar, yet different actions supposedly used during Mozart's time. The analysis is based on high-speed imaging results of existing reconstructions of the action, but does not yet contain a multibody model of the studied actions. This kind of study enables pointing out important characteristics of the action, but does not allow easily modifying some of its properties in order to compare their importance on the overall behavior.

3 Multibody model

The action we have modeled is a reproduction taken from an original 1788 Johann Andreas Stein piano, located at the Germanisches Nationalmuseum (inventory number MIR1097). The reproduction, currently kept at the Musical Instruments Museum (MIM) in Belgium, represents the highest note of the instrument (F6). The original action also contains a string damper, which we have neglected in the model since it does not significantly participate in the overall motion.

The multibody model of the action is composed of five different bodies: the frame, the key, the pawl, the hammer, and the string (Fig. 2). The model is bi-dimensional, and each body possesses one relative degree of freedom in rotation, which is represented by discontinuous lines. In total, the system thus has three degrees of freedom. Some sub-parts of the bodies are of prime importance and deserve special attention; the *Kapsel* is a wooden fork in which the hammer is hinged so that it can rotate, the pawl is kept upright with the help

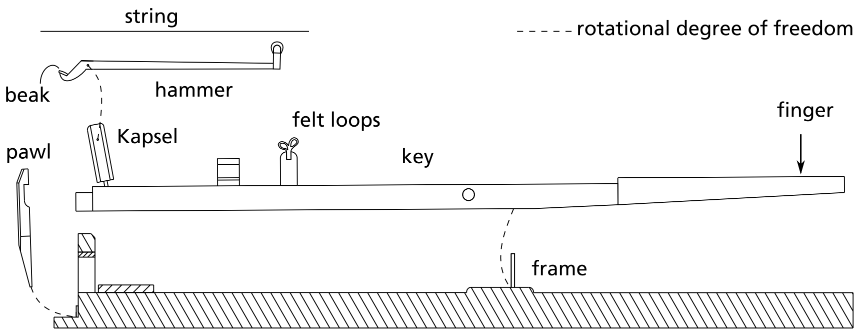

Fig. 2 The model is in 2D and comprises the frame, the key, the hammer, the pawl, and the string

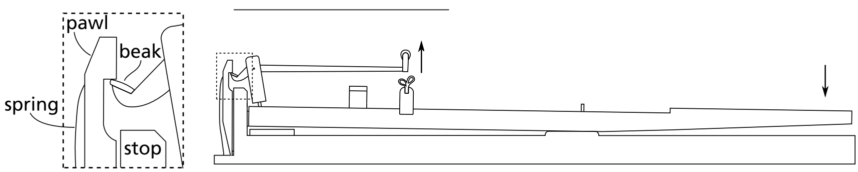

Fig. 3 The rotation of the hammer is caused by the depression of the key and the contact between the hammer beak and the pawl

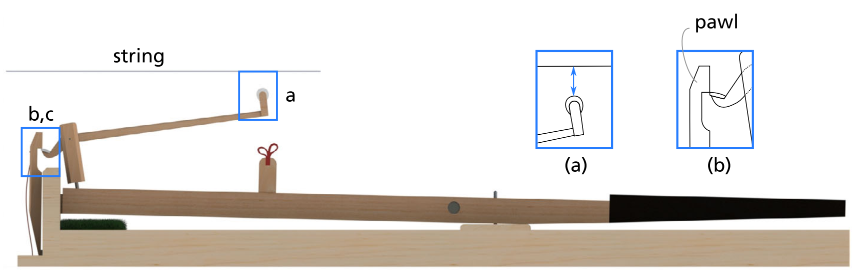

Fig. 4 The hammer escapes when the hammer beak passes the angled corner of the pawl (**b**). The distance between the hammer and the string at that moment is called the "escapement height" (**a**)

of a spring (left side, visible in Fig. 3) and a stop (right side). The hammer beak is a small leather tongue glued on top of the left end of the hammer.

All in all, the functioning of this action is very simple (Fig. 3). When the key is depressed by a pianist's finger, the key turns clockwise, taking with it the hammer which is hinged to the *Kapsel*. The beak of the hammer then comes in contact with the pawl (Fig. 3, dashed rectangle), causing the hammer to turn anticlockwise with respect to the key. This accelerates the hammer's motion and projects it towards the string while the finger keeps pressing the key down. A few millimeters before the hammer hits the string, the leather patch fixed at the beak passes the corner of the pawl (Fig. 3, dashed rectangle). This releases the hammer, allows it to hit the string and freely rebound right after the impact. The hammer then falls down on the felt loops attached to the key which absorb its energy in order to prevent it from bouncing back on the string.

One crucial aspect in the functioning of the action is the so-called “escapement height”. Referring to the working process described above, the escapement height is a purely geometrical value characterized by the vertical distance between the hammer and the string (Fig. 4(a)) at the precise moment when the hammer beak escapes from the pawl by passing its angled corner (Fig. 4(b)). In practice, piano technicians adapt the escapement height through successive quasi-static configurations in order to obtain the desired response and touch of a key. The regulation of this key parameter and the precise consequences on the behavior of the action are described in Sect. 5.

3.1 Multibody formulation

The generalized joint accelerations $\ddot{q}$ of the multibody system to which forces and torques are applied are computed via the following dynamic model:

$$M(q,\delta)\ddot{q} + c(q,\dot{q},\delta,f,t,g) = Q(q,\dot{q}) \tag{1}$$

where M is the generalized mass matrix of the system, c the nonlinear dynamic vector (it contains the gyroscopic and centrifugal effects, the external resultant forces f and torques t, and the gravity g), Q the generalized forces and torques applied in the joints, q the relative generalized coordinates, and δ the dynamic parameters of the system (body masses, positions of the center of masses and body inertia tensors). The equations of motion (Eq. (1)) are symbolically generated with ROBOTRAN [9] on the basis of the Newton–Euler recursive scheme and are fully implemented in C language and time integrated with efficient numerical libraries.

3.2 Body characteristics

The components of the model have been scanned in 3D in order to evaluate their dimensions. The action has been disassembled, allowing to measure the mass, the center of mass and the inertia of its components. The inertia has been evaluated via Euler's equation of motion applied to a planar pendulum:

$$I^o\ddot{\theta} + mgd\sin\theta = 0 \tag{2}$$

with I^o being the inertia of the body with respect to rotation axis, θ and $\ddot{\theta}$ its angular position and acceleration, m its mass, and d the distance between the center of rotation and the center of mass. For small movements the equation of motion can be linearized with the approximation $\sin\theta \simeq \theta$. The natural frequency of the system can be rewritten from Eq. (2) as $\nu = \frac{1}{2\pi}\sqrt{\frac{mgd}{I^o}}$. As it is easy to obtain the natural frequency of a pendulum experimentally (Fig. 5), one can retrieve the value of I^o:

$$I^o = \frac{mgd}{(2\pi\nu)^2}, \tag{3}$$

and taking advantage of Steiner's theorem in 2D, one can compute the inertia with respect to the center of mass of the body: $I^G = I^o - m\|d\|^2$.

In the case of the pawl, which was too difficult to disassemble without damaging the action and which is not subjected to a highly dynamic motion, we have determined these physical values with a CAD software.

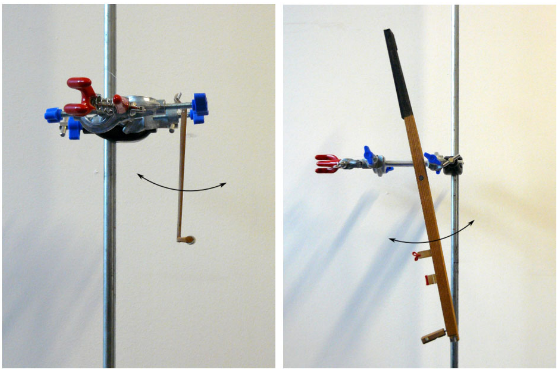

Fig. 5 The inertias of the hammer (*left*) and the key (*right*) have been measured experimentally

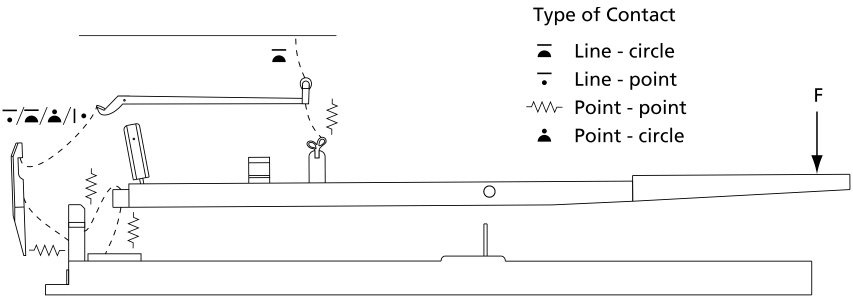

Fig. 6 The contact geometries are approximated with *lines*, *circles*, *points* or a combination of these elements

3.3 Geometrical contact model

Contact modeling requires to carry on two sequential steps. The first one is purely geometrical and consists in finding the contact location between bodies, which can be punctual or linear (rigid case) or areal (flexible case). As regards the latter case, we search for an equivalent contact point to which a contact force resultant will be applied. The second step, which is detailed in Sect. 3.4, is related to the computation of the contact forces issuing from constitutive laws.

The working principle of the piano action is based on multiple percussive contacts which propagate motion through the different parts of the mechanism. Consequently, contact between bodies is of discontinuous nature and thus it should always be ascertained whether pairs of bodies are in contact. In our case, the geometrical contact problem is solved by approximating the body surfaces via simple geometrical primitives: circles, lines, points or a combination of them (Fig. 6). The "point-to-point" case is straightforward since the material contact points involved are known in advance. For all other situations, one needs to find a geometrical contact point on a circle or a line: this can classically be achieved using either an analytical or iterative procedure.

Despite its rudimentary design, the interaction between the hammer beak and the pawl notch (Fig. 3, left) is the trickiest part of the model. The contact being areal, the first step consists in finding the equivalent contact point (Fig. 7). This may sound simple, but is, in

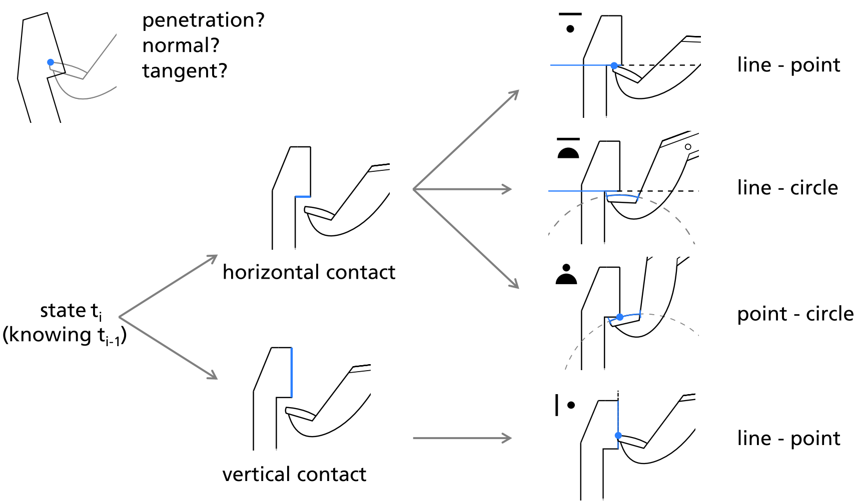

Fig. 7 When the hammer beak and the pawl are in contact, different geometrical primitives can be used to approximate the contact geometry

fact, complex because we have to find a means to choose whether we compute this point relative to the horizontal face of the pawl, its corner or its vertical face.

Once the contact point is found, one needs to define a normal and a tangential direction to the pawl in order to compute the deformation depth and deformation speed of the hammer beak into the pawl.

Based on high-speed camera observations of the interaction between the hammer beak and the pawl, we have defined a first division; contact occurs either on the horizontal face of the pawl notch or on its vertical face (Fig. 7). Next, we have defined four distinct contact configurations which follow a temporal sequence of functioning when the key is depressed. Reading the last column of Fig. 7 from top to down, these phases consist of a contact between (i) the left end of the beak and the horizontal part of the pawl, (ii) the upper surface of the beak and the horizontal part of the pawl, (iii) the upper surface of the beak and the corner of the pawl, and (iv) the left end of the beak and the vertical part of the pawl.

In some cases, it would be impossible to determine which configuration has to be used at $t = t_i$ without knowing the previous state $t = t_{i-1}$ of the two bodies. Even if this representation is exaggerated, it is, for example, impossible to know how to compute the penetration of the hammer beak in Fig. 7, upper left corner. The most correct solution will arise from the sequence of motion, which means the algorithm will always first assess whether the configuration in t_{i-1} is still valid and if it is not the case, test the other configurations.

3.4 Force and torque laws

The interacting parts of the action are mainly composed of wood, leather and felt. Although Masoudi [6] has made substantial efforts to find a suitable law for these scarcely studied materials, we have chosen, for the sake of effectiveness and simplicity, to use the same laws as in Hirschkorn [2]. Force and torque are computed using a derivative of Hunt and Crosley's law [10], changing the power function into a third order polynomial fit. The hysteresis is taken into account thanks to the damping factor D, which has been calibrated to fit the

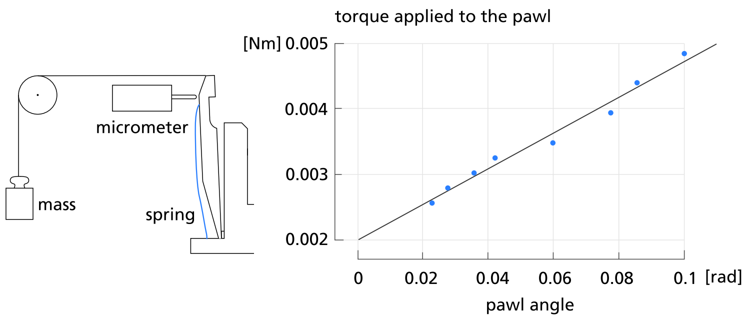

Fig. 8 Considering the importance of the pawl in the action, the characteristics of its spring have been measured using a weight and a displacement sensor

curves at a typical speed for a compression and decompression cycle when the action is used under normal playing conditions. The expression of the normal force is given by

$$f_n = f_{\text{fit}}(x)(1 + D\dot{x}_n) \tag{4}$$

with $f_{\text{fit}} = ax^3 + bx^2 + cx$, x being the deformation of the bodies, D the damping factor, and $\dot{x}_n$ the relative normal velocity of the bodies. The tangential component of the force is modeled with the Coulomb friction, using Cull and Tucker's [11] formula which takes both static and dynamic coefficients of friction into account:

$$\mu = A\left(\tanh\left(\frac{\dot{x}_t}{v_t}\right) + \frac{B_1\dot{x}_t/v_t}{1 + B_2(\dot{x}_t/v_t)^4}\right) \tag{5}$$

with μ being the friction coefficient, $\dot{x}_t$ the relative tangential velocity, v_t the relative threshold velocity, A the dynamic coefficient of friction, B_1 and B_2 coefficients adjusted in order to obtain the right force peak corresponding to the static coefficient of friction. The parameters of the contact model have first been chosen on the basis of their similarity with the materials used in a grand piano action. We have thus taken the parameters from [2], and adapted some of them with experimental measurements in order to make them fit with our particular action.

Torque due to friction in the joints is computed with a law of the same form as in Eq. (5), but applied to a rotational movement. Torque due to the rotational spring at the back of the pawl is of the form

$$\tau = k_\theta(\theta - \theta_0) \tag{6}$$

with k_θ being the equivalent angular stiffness of the pawl return spring, θ the instantaneous, and θ_0 the neutral angle of the pawl. As the resistance of the rotation of the pawl is of high importance for the response of the action, we have evaluated k_θ and θ_0 experimentally by submitting the pawl to various loads and by measuring its resulting inclination with a micrometer (Fig. 8).

4 Comparison with experimental data

The multibody model presented in the previous section has been compared with the real action in motion. The experimental set-up allows reproducing its behavior easily in the model;

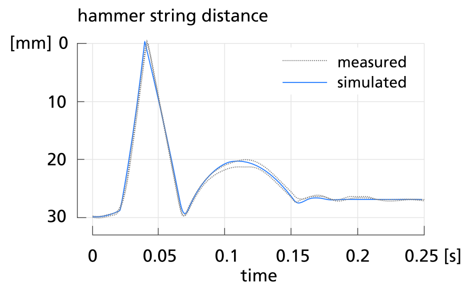

Fig. 9 The evolution of the hammer–string distance of the model is compared with high-speed imaging data of the action submitted to a falling mass of 100 g

for instance, via a suspended mass of 100 g which is flush with the key surface and let off by cutting the wire which supports it. The vertical position of the hammer is then recorded with the help of high speed camera. The free fall of the mass is easily reproduced in the model, and the latter is virtually calibrated in order to match the initial and final positions of the action (Fig. 9).

For the few remaining unknown parameters, such as the stiffness and the damping of the loops, coefficients for Eq. (4) and the friction coefficient between the hammer beak and the pawl, they have been chosen, within a suitable range, by comparing the simulated and the real action, according to the two following criteria. The first criterion is the difference between the measured and the simulated distance between the hammer and the string. The second criterion is the dynamic escapement height of the hammer, which precisely occurs at 2.2 mm of the string when the real action is depressed with the 100 g mass. The result of this identification process gives us a mean discrepancy of 0.014 mm between experimental data and the model (Fig. 9).

5 Simulation results

In this section, we perform simulations similar to the regulations piano technicians apply to these actions. The aim is, on the one hand, to quantify the precision required to regulate the action, and on the other hand, to evaluate its influence on the playing characteristics of the instrument. For all the simulation results shown in this section, the input is a free falling mass of 100 g which is flush with the key surface. This means the key is kept depressed after the string has been hit.

5.1 Regulation sensitivity of the escapement height

As mentioned previously, the escapement height strongly influences the way the action behaves, and consequently, the sense of touch felt by the pianist. When the escapement height is small, it means the hammer escapes near the string. In this case, the hammer is in free flight during a limited portion of its travel towards the string. According to our technician colleagues of the Musical Instruments Museum Brussels, actions set up with a small escapement height are felt by pianists as being “stiff”, but seem to ensure a good control of the action response. A drawback of such a regulation is that the hammer can get jammed against the string, particularly if the key is hit with much force. Increasing the escapement height gives the feeling of a smoother action, but goes together with a loss of precision; it will, for example, be much more complex to produce a controlled *piano* sound because the

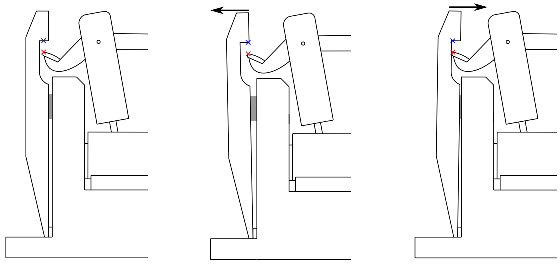

Fig. 10 The escapement height is regulated by changing the width of the pawl stop (*grey rectangle*). Compared to the reference case (**a**), the rest position of the pawl moves to the left when plies of paper are added (**b**), and to the right when they are removed (**c**)

portion of stroke during which the hammer is in free flight is much larger. Another drawback is the fact that the sound loses power.

The multibody model allows us to illustrate these behaviors and to confirm the observations made by the technicians when regulating them. In practice, technicians adjust the escapement height in two different ways. The most common one is the horizontal displacement of the stop which defines the rest position of the pawl (grey rectangle in Fig. 10). The second one consists in slightly changing the stiffness of the spring which keeps the pawl in position by bending it.[2] In this work, we will only consider the first type of regulation.

In our particular action, the rest position of the pawl is changed by adding or removing thin pieces of paper behind the stop.[3] A geometrical escapement height of 2–3 mm is ideal because it is supposed to offer a compromise between hammer speed at the impact of the string, sensation of free flight of the hammer and precision of the touch of the action. Referring to a normal setting (Fig. 10a), adding some paper to the stop will move the rest position of the pawl to the left (Fig. 10b). On the other hand, suppressing some paper will shift the pawl to the right (Fig. 10c).

Let us define Δx as the displacement of the stop, with $\Delta x > 0$ meaning a displacement of the pawl to the right. With respect to a reference regulation for which the hammer escapes dynamically[4] at 2.2 mm (Fig. 11), simulations confirm that a shift of the stop to the right ($\Delta x > 0$) causes a decrease of the escapement height, whereas a shift to the left ($\Delta x < 0$) causes an increase of this value. More interestingly, one notes the steep slope of this quasi-linear relationship between escapement height and the initial position of the pawl. Indeed, the relationship of $1/20$ means that adding a sheet of paper of 0.1 mm width changes the escapement position with 2 mm. Knowing that a homogeneous touch of the piano throughout its entire range can only be assured if the escapement height is regulated with a precision in the order of 1 mm, one can understand how meticulous the technician proceeds in his work. It is also remarkable to note how limited the range of action the technician disposes of; outside of the pictured bounds, the model shows that the action does not work anymore, that is, if the pawl stop is shifted more than 1.25 mm to left or 0.2 mm to the right. When $\Delta x < 1.25$ mm, the pawl notch is simply too far from the hammer beak for both bodies to be in contact. Letting the pawl lean too much to the right prevents the hammer from escaping.

[2]Note that changing the spring preload not only changes its behavior during the motion of the action, but also changes the rest position of pawl, just like the first type of regulation.

[3]In later Viennese actions, the stop is an adjustable screw, which makes its regulation easier. Nonetheless, fine regulation can still be performed with pieces of paper.

[4]Let us recall that the key is depressed with a 100 g mass, causing a movement that cannot be considered as quasi-static anymore.

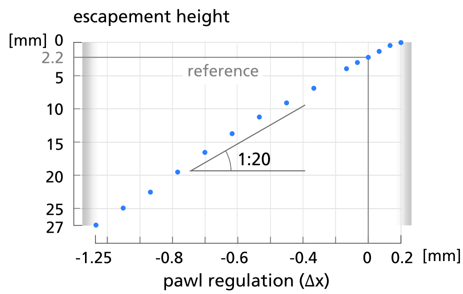

Fig. 11 The relationship between the pawl stop and the dynamic escapement height is quasi-linear. Negative displacement values indicate a shift of the stop to the left. The *grey zones* indicate when the action is not working anymore

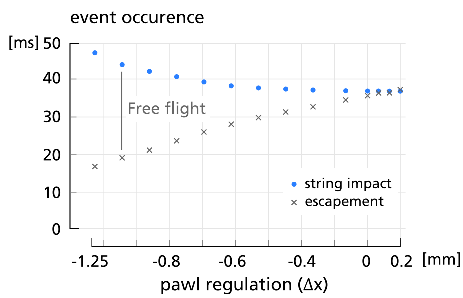

Fig. 12 The moment at which the hammer escapes and at which it hits the string is conditioned by the regulation of the pawl. The free flight of the hammer is the period between those two events, when the hammer flies independently of the action of the pianos

5.2 Event timing of the action

In order to have a more precise idea of what happens when the escapement height varies, it is interesting to observe the timing of two events during a key stroke for each regulation. Figure 12 has to be read bottom-up, starting at $t = 0$ s where the key is hit. The first marker shows the moment at which the hammer escapes; the more the pawl is shifted to the left, the earlier the hammer escapes. This is also in agreement with the increase in escapement height (Fig. 11); escaping earlier means the action escapes further from the string. Conversely, it is fairly logical that the escapement is delayed as the pawl is moved more to the right.

The upper markers indicate the moment at which the hammer hits the string. Going from left to right, this event appears asymptotically sooner when the pawl is moved to the right. This is a first hint indicating the sense of control the action confers to the pianist; the earlier the hammer escapes, the later the sound will be produced. Another important factor is the so-called "free flight" during which the hammer moves towards the strings, without the pianist being able to control it anymore. The free flight of the hammer happens between the escapement and the impact of the string. Intuitively, it seems logical that being unable to control the hammer over a long period of time gives rise to a less controllable action.

When $\Delta x > 0$, the markers are almost indistinguishable. With a closer look, one even realizes that the hammer escapes after having hit the string for a regulation near $\Delta x = 0.2$ mm. When this happens, the finger of the pianist controls the hammer until it reaches the string, but has to force the movement of the key in order to let the hammer beak escape from the pawl notch. This phenomenon goes together with an audible "click" caused by the forced escapement of the hammer. The musician masters the behavior of the hammer throughout its entire movement, but the produced sound will certainly be poor and muffled because the prolonged contact of the hammer on the string mutes the first vibrations of

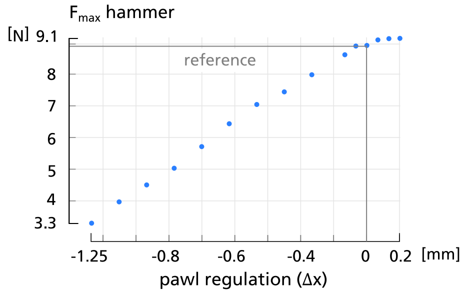

Fig. 13 The maximal force applied by the hammer on the string diminishes linearly when the pawl is moved to the left. Shifting the pawl to the right does not significantly increase the force which saturates

the latter. From the touch point of view, forcing the escapement is not acceptable since it requires a more important force and leads to a non-smooth action.

5.3 String impact force

Another important and logical characteristic of the free flight of the hammer is the fact that the hammer stops being propelled by the pawl notch, causing it to decelerate. This does not only affect the response time of the action, but also the force with which the string is struck (Fig. 13). The relation between the peak force on the string and the displacement of the pawl is linear to a large extent. This is specially the case for $\Delta x < 0$; on this side of the reference, the action loses approximately 1 N for every 0.2 mm the pawl stop is displaced. However, when $\Delta x > 0$, the force keeps approximately constant. When this happens, the pianist controls the hammer up to the point where it hits the string, meaning the hammer never decelerates, but is also unable to accelerate even more. Having reached a threshold limit in terms of impact speed, the force is also limited.

5.4 Discussion

Let us summarize these different observations and confront them with the experience of pianists and technicians. It seems the terms "rigid" and "smooth" used to define the feedback of the key is influenced by the instant of escapement and string impact, and probably even more by the duration of the free flight of the hammer. The sense of control is linked to the same values, as a large escapement height not only induces an increase of free flight duration (that is, of uncontrolled hammer travel), but also a longer time between the key depression and the produced sound. Considering the auditory feedback, it appears that pushing the pawl to the left potentially has a strong decreasing influence on the amplitude of the sound. Conversely, diminishing the escapement height even more than in the reference cases induces a very limited effect.

Having observed this via the model, we can appreciate the advantages of a well regulated action with the escapement height set between 2 mm and 3 mm. Set at this distance, the free flight is limited to a very small portion of the hammer travel; it enables the pianist to control the motion of the hammer up to the very end and to benefit from an ideal maximal force.

6 Conclusions and prospects

In this contribution, we have presented a multibody model of a Viennese action made in 1788 by Johann Andreas Stein. Besides the common elements found in such a model, like the constitutive laws for materials and the experimental comparison between a real action and the model, this paper has given the principles to address the modeling issues due to the very specific interaction between the hammer beak and the pawl which is of central importance regarding the action functioning.

The model in itself has allowed us to evaluate the order of precision required by technicians when they regulate the action; shifting the stop of the pawl by 1 mm moves the escapement height by 20 mm. Knowing that the escapement height has to be regulated with a precision of approximately 1 mm, it follows that technicians have to adjust the stop of the pawl with a precision of 0.05 mm. With a well-regulated action, the pianist feels he has a good control over the whole motion of the action. A loss of control could be due to the response time of the hammer but also to the escapement height that we have quantified for different regulations of the pawl. Finally, we have pointed out that the potential of the action to hit the string with force diminishes as the escapement height increases. Conversely, decreasing the escapement height more than its prescribed value does not lead to a significant increase in hammer–string force and can even cause the hammer to get temporarily jammed against the strings.

Future research concerning the Viennese actions relates to both the modeling part and the historical aspects of the project. As regards the engineering part, we are working on a real-time simulator of the action so that the regulation process could be performed dynamically, without interrupting the simulation. Another enhancement concerns the key input we use for the real action. For this part, we are developing an actuator which can reproduce a more realistic and repeatable input, equivalent to the finger force exerted on the key.

As regards the historical question, musicologists have observed that Viennese actions varied only slightly in design during the time they were used. Only one of its components, the pawl, has shown a noticeable evolution in shape. Specifically, the inclination of the pawl notch was of 90° in the earlier instruments similar to the one studied in this paper. Later instruments almost systematically had a notch angle which was less than 90°. Musicologists are not sure about the reason of this evolution and a dynamic model in which the pawl inclination can be changed might enhance our understanding of this morphological transformation. This part of the project is being carried out with Paul Poletti (Museu de la Música, Barcelona), a piano maker specialized in ancient pianofortes.

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Appendix C

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Historical and dynamical study of piano actions: A multibody modelling approach

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ABSTRACT

Piano actions are striking mechanisms whose functioning is based on dynamic principles; producing a sound on a struck keyboard instrument by pressing a key slowly is impossible because the hammer needs momentum to hit the strings. This is also the reason why mechanisms intended for struck keyboard instruments are difficult to study; their normal functioning speed is beyond human observation capabilities. For this reason, many modern studies on the piano take advantage of engineering tools in order to measure the exact behaviour of their actions in terms of time response, involved forces and displacement values. A complementary approach to study piano actions consists in modelling them, giving us a virtual mechanism to work with. In this case, the above-mentioned motion and behaviour are computed instead of being measured. The modelling technique used and described in this paper, called multibody dynamics, consists in computing the motion and the forces acting upon each component of the action. Subsequently, the response of the mechanism to a certain keystroke can be computed and a slow-motion animation can be produced. The aim of this paper is to give an overview of an ongoing research project in which two distinctive piano actions are modelled. Each of them is studied with a different objective in mind. Starting with the most modern, well-known but also most complex, the model of a double escapement action found in grand pianos is used to explain its functioning. This pedagogical goal is achieved with three progressive models; the first one is a simplified version of the action to which components of the complete action have been (virtually) removed. The stepwise progression leads to a single escapement action for the second model, and finally to the full double escapement action for the third. Timing of the action events and response to different types of touch are studied and compared with literature. The results show that our model is able to reproduce the same behaviour as real actions. Going back in time, the second instrument that is studied is a *Prellzungenmechanik* built by Johan Andreas Stein at the end of the 1780s. In this context, a model has been achieved to evaluate the influence of the so-called "escapement height" (a regulation parameter of the action) on the playing characteristics of the action. As with the grand piano action, timing analysis and touch comparison are performed with the model.

1. Research aims

The aim of this research project consists in studying the dynamic behaviour of modern and ancient piano actions by means of the so-called "multibody" modelling approach. Most musicological studies concerning piano actions are limited to a static observation or subjective evaluation of their performance. A multibody model enables to predict the time evolution of the physical parameters of the action (relative displacements, force between components ...). The computation of these variables can help to quantify these performances. In the general framework of this interdisciplinary project, three different actions are envisaged: the double escapement action found in modern grand pianos, an 18th century *Prellzungenmechanik* (PZM) by Johann Andreas Stein and Henri Arnaut de Zwolle's striking mechanism. The present paper focusses on the two first actions.

2. Introduction

The history of the piano is a succession of inventions. Apart from the *gravecembalo col piano e forte* of Bartolomeo Cristofori

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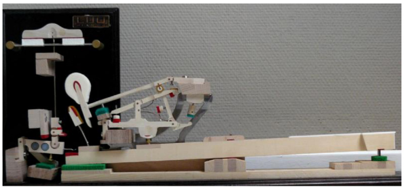
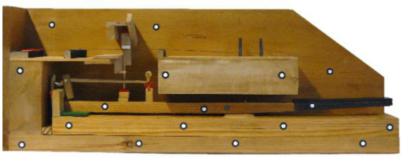


(a)



(b)

Fig. 1. The two actions studied in this paper: (a) a grand piano action with the double escapement system and (b) a *Prellzungenmechanik* by Johann Andreas Stein.

which was a very complex but accomplished instrument, the global evolution of the instrument pictures a continuous increase in sophistication. This observation is particularly true for the action, the part responsible for transmitting the musical intention of the pianist through his fingers all the way up to the strings. Even if there exists a great diversity of action designs, their common point is that their functioning relies on highly dynamic principles. Unfortunately, this characteristic also limits our ability to grasp the details of their functioning. Indeed, under normal playing conditions, it is impossible to visualise the sequence of motion of the action because of its very high working speed. When the key is depressed slowly, the hammer will not gain enough momentum to hit the strings. For this reason, many excellent studies concerning the piano take advantage of engineering tools like high-speed imaging and force sensors to observe their behaviour [1–4].

The present paper highlights a modelling method called multibody dynamics which enables to compute the motion of any polyarticulated system and to virtually interact with the action. Besides imitating the one shot experiments in which data are measured, with a model, it is possible to compare actions in which some parts have been virtually modified through simulations in identical situations. These simulations enable to compute the data that were highlighted in [1–4] rather than measuring them. Moreover, a 3D visualisation system provides the user with a user-friendly graphical tool to observe the action from the desired viewpoint.

The objective of this paper is to give an overview on an ongoing research project concerning two types of piano actions (Fig. 1), via the use of the multibody approach. The first one is the modern grand piano action, for which much technical literature is available. Even if it is the most complex one from a morphological point of view, it is certainly the best-known action. Second, we are interested in an 18th century PZM by Johann Andreas Stein, typically used by the Viennese and South-German classical piano school. The instruments which use this kind of action are fairly well preserved and frequently rebuilt by piano makers.

3. Modelling piano actions

In this section, we introduce the main principles of multibody dynamics and its application to piano actions. Thereafter, we illustrate how the models are validated. Throughout this section, we use the double escapement action as a guideline. Needless to say, exactly the same techniques are applied to the other action.

3.1. Introduction to multibody dynamics

Multibody dynamics is a branch of mechanical engineering which consists in predicting the motion of polyarticulated bodies, that is, systems composed of multiple bodies connected by joints (e.g. Hinges, telescopic arms, ball joints, etc.). Classical applications for this method range from road and rail vehicles to robotics, biomechanics, transmissions, etc. The piano action is also a polyarticulated system as it consists of multiple bodies linked to each other through rotational joints.

Multibody dynamics is based on equations known since the 18th century, namely Newton's equation of motion which yields $\boldsymbol{F} = m\ddot{\boldsymbol{x}}$, and its equivalent in rotation, Euler's law $\boldsymbol{T} = \boldsymbol{J} \times \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J} \times \boldsymbol{\omega}$ written for each body of the system. In the previous equations, $\boldsymbol{F}$ and $\boldsymbol{T}$ respectively stand for the external applied force and torque resultant with respect to its mass centre, m and $\boldsymbol{J}$ are the mass and the inertia tensor of the body with respect to its mass centre and $\ddot{\boldsymbol{x}}$ and $\dot{\boldsymbol{\omega}}$ represent the absolute linear and angular accelerations of the body. Whatever the formalism used to generate these equations of motion for the multibody structure, the system kinematics is always described in terms of so-called generalized coordinates, $\boldsymbol{q}$, from which position, orientation, velocities and accelerations will depend. In particular, $\ddot{\boldsymbol{x}} = \ddot{\boldsymbol{x}}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)$ and $\dot{\boldsymbol{\omega}} = \dot{\boldsymbol{\omega}}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)$.

Using these generalized coordinates as system variables, the multibody equations of motion can be written in the following matrix form:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{F}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{f}, \boldsymbol{\tau}\right) = \boldsymbol{0} \quad (1)$$

where $\boldsymbol{M}$ is the so-called mass matrix and $\boldsymbol{F}$ contains the centrifugal, Coriolis and gyroscopic effects as well as the forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ applied to the bodies.

The system of equations (1) can be written by hand for small academic examples, but becomes too complex for large and realistic systems for which the equations are generally non-linear with respect to $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$. We therefore use an in-house software called Robotran [5]. Starting from the system to analyse (Fig. 2a), a schematic representation can be achieved; in the schematic representation of a multibody system in Fig. 2b, ellipses stand for bodies and lines for joints. Then, on the basis of a formalism and given all the system parameters (dimensions, mass, centre of mass, inertia, etc.), Robotran automatically writes the equations of motion (1) in a symbolic manner (Fig. 2c).

At this stage, by analogy with a model of the human body, the user has in his possession a human body in free fall and without muscles, but with the correct body characteristics and joint kinematics. The next step consists in writing the law forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ appearing in (1) according to their underlying physical laws.

Once forces and torques are fully described, the differential system (1) can be easily simulated with a suitable numerical time integrator to provide the desired results (Fig. 2d).

3.2. Multibody modelling of piano actions

The main hypotheses underlying the action models are the following: the motion is planar, bodies are rigid,[1] joints are geometrically perfect (no backlash) and the string damper is not considered.

In the multibody model of a grand piano action (Fig. 3), the various rotational motions of the bodies are the generalized coordinates

[1] Regarding the body rigidity assumption, the hammer shank flexibility has also been neglected. Its flexibility will be considered in future work.

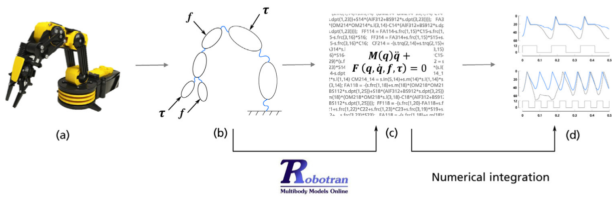


Fig. 2. Typical workflow in order to create a multibody model. A real poly-articulated system (a) is schematically represented (b). The equations of motion (c) are then automatically generated by Robotran. The results (d) are obtained after a numerical integration of these equations.

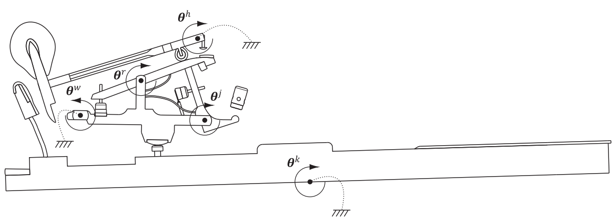


Fig. 3. The doubles escapement action possesses 5 generalized coordinates $\boldsymbol{q}$ in the form of 5 angles: θ^k the angle of the key, θ^w the angle of the wippen, θ^r the angle of the repetition lever, θ^j the angle of the jack and θ^h the angle of the hammer.

of the model: $\boldsymbol{q} = \left(\boldsymbol{\theta^k}, \boldsymbol{\theta^w}, \boldsymbol{\theta^r}, \boldsymbol{\theta^j}, \boldsymbol{\theta^h}\right)$. The body parameters (mass, centre of mass, inertia, etc.) have been experimentally identified by unmounting the components of the action. They have then been weighted and their centre of mass have been evaluated via static measurements. Their inertia has been found submitting them to small pendulum movements; in these conditions, the equations of motion can be linearized. Thanks to the expression of the natural frequency of this linearized system, one can retrieve the value of the body inertia with respect to the fixed pivot:

$$I^0 = \frac{mgd}{(2\pi\nu)^2} \qquad (2)$$

where m is the mass of the component, g the gravity, d the distance between the pivot and the centre of mass and ν the natural frequency of the pendulum. When parts could not be dismounted, the inertia has been computed with the help of a CAD software, on the basis of their scanned shape and their material.

An important part of the work refers to the force laws. For the three envisaged piano actions, forces taken into account are the friction in all the pivots (e.g., friction in the hammer shank pivot) and the forces between the interacting bodies (e.g., the hammer and the string, the key and the wippen, etc.). To model these interactions, the first step consists in assessing whether a physical contact exists between two bodies. This is achieved by approximating their contours with simple geometric shapes such as lines, circles or a combination of these. Next, we compute the location of an equivalent contact point on the body contours and deduce the interpenetration depth and velocity of the colliding bodies. Knowing this, one can apply the appropriate constitutive laws, according to models issued from the literature [6,7] (i.e. felt, leather, wood or metal). We can then compute the interacting forces between bodies, both in normal and tangent direction of the contours, and introduce them ($\boldsymbol{f}$ and $\boldsymbol{\tau}$) in system (1).

3.3. Experimental data

Experimental validations of the models have been performed for different parts of the actions. The models are compared with reality using a high-speed camera (3000 b/w fps). The motion of the system is retrieved using checkerboard patterns pasted on the bodies, for which the position of each square corner is tracked (Figs. 4a, b) all along the trajectory.

The friction of the hammer shank pivot is an important parameter that technicians regulate: if there is too much friction, the action will feel heavy and the motion of the hammer will be too slow. Conversely, too few frictions is also negative because the action will lack resistance. In this first experiment, the hammer is dismounted from the action and suspended by its flange. Then we make it oscillate by releasing it form a certain height (Fig. 4a). The friction parameter of the constitutive law is then tuned in order to match the tracked result (Fig. 4c).

The next step consists in observing the overall behaviour of the entire action. For the sake of repeatability, this is achieved with a mass of 1 kg which is flush with the piano key and then let off so as to depress the latter (Fig. 4b). The motion of the key is tracked and serves as the input motion of the model. We then compare the simulated and measured motion of the hammer (Fig. 4d). Different phases of motion can be observed; the first sequence, corresponding to the upward motion of the hammer towards the strings, is in good agreement with the experiment. The hammer hits the string when it is horizontal ($\theta \sim 0$), after which it rebounds and gets caught by the back check. At this point, the slight oscillation of the key causes a release of the hammer and the behaviour of the

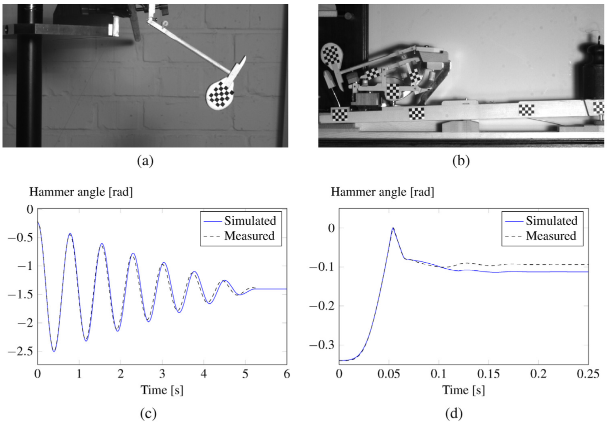


Fig. 4. The piano action models are validated using targets placed on their components and tracked by a high-speed camera. The experiments and the simulation results are compared.

action is less well caught by the model. The hammer is thus blocked somewhat further from the string, but exhibits the same residual oscillations as the real action (Fig. 4d).

4. Results and discussion

This section is organized around the two different thematic subjects we are interested in. The first one refers to the double escapement action which equips modern grand pianos and the second concerns a PZM originally conceived by Johann Andreas Stein.

4.1. The modern grand piano action

As mentioned earlier, the advantage of a model is that one can virtually remove parts of a mechanism and observe how it would behave with and without them. The multibody model and the associated computer tools can thus be judiciously exploited to explain with a pedagogical purpose how a piano action works. Due to its complexity, it would be illusory to explain the functioning of a piano action with the help of a complete grand piano action. Consequently, we suggest a process in three progressive steps, each of them having noticeably enhanced the performances of struck keyboard instruments, as follows:

- before the appearance of the piano, one finds stringed instruments (like the dulcimer and the clavichord) in which the string is struck, but without any escapement. For instance, when pressing a key of a clavichord, the tangent (equivalent to the hammer of the piano) strikes the string and remains in contact with it as long as the key is held;
- the invention of the single escapement action by Cristofori in 1700 has been a major breakthrough for stringed keyboard instruments;
- finally the double escapement action, the predecessor to those used in modern grand pianos, is patented by Érard in 1821.

In line with this, from a historical point of view, a more logical and rigorous approach would have been to model actions of authentic instruments that were contemporary with those inventions. However, the three above-mentioned steps can be explained directly from the multibody model of the grand piano action in which some articulations are intentionally locked and/or from which some components are removed. This way, the inventions can be explained stepwise on one single action, instead of three completely different mechanisms. The learner can thus focus his attention solely on the mechanical evolution and interest of these inventions without being disturbed by the changing aspect of three different actions.

4.1.1. No-escapement action

By virtually degenerating the grand piano action model, a no-escapement action can be easily produced (Fig. 5, Video 1). It consists of three articulated bodies: the key (angle θ_k), a rigidified transmission (angle θ_{tr}) and the hammer (angle θ_h). To suppress the escapement, all we have to do is to remove the escapement dolly (or escapement button) and to rigidly fix the jack of the wippen, constituting to the so-called “transmission” (Fig. 5).

With this first morphology, as the key is pressed, its rotational motion is propagated to the hammer via the transmission. Although the hammer is independent of the transmission, both of them will stay in permanent contact. Unless the pianist plays in a staccato manner, the hammer will be pressed on the string (configuration of Fig. 5) and the note will be immediately muffled because the hammer prevents the string from vibrating freely.

4.1.2. Single escapement action

With respect to the previous mechanism, the single escapement action contains three additional components: the back check, the jack and the escapement dolly (Fig. 6a, Video 2). The jack is articulated on the wippen via a revolute joint (angle θ_j) and held in place by a return spring whose role is to re-position the jack in its rest configuration against a stop mounted on the wippen. Thanks to these new components, the key motion is transmitted to the

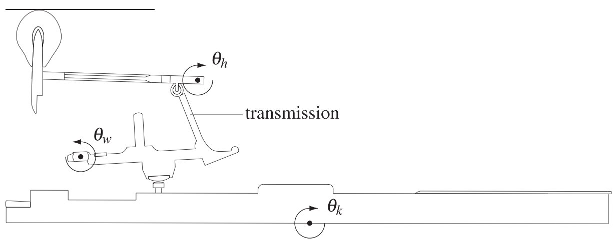


Fig. 5. When the no-escapement action hits the string, all components of the action are in contact; the hammer continuously presses the string, muffling the sound.

hammer via the two articulated bodies of the transmission: the wippen and the jack. The escapement dolly works as a mechanical stop whose function is to trip the jack up: as the jack toe collides with the escapement dolly, the jack tilts with respect to the wippen (clockwise rotation θ_j) and loses its contact with the roller of the hammer when the latter is very close to the string (Fig. 6b): this is the escapement principle. From that moment, the hammer being completely decoupled from the transmission can freely strike the string with a sharp impulse (Fig. 6c). After the impact, as long as the key is fully depressed, the hammer is pushed back by the string and caught via dry friction by the back check mounted on the key (Fig. 6d). The main function of the back check is to avoid parasitical rebounds of the hammer on the string (denoted as "jingling").

4.1.3. Double escapement action

For this last morphology, two new components are needed and thus appear in our model: the repetition lever and the drop screw (Fig. 7a, Video 3). The combination of these components is the fruit of the invention of the Frenchman Sébastien Érard at the beginning of the 19th century. In a similar way to the jack, the repetition lever is articulated on the wippen via a revolute joint (angle θ_r) and a return spring whose function is to support the hammer weight when it lies on the repetition lever. Let us note that the name "double escapement" is inappropriate as the hammer of this action escapes only once. The difference with the single escapement action lays in the fact that it allows a faster repetition of the note after the first impact, as explained hereafter.

The double escapement action works exactly the same way as the single one until the hammer has hit the string and has been caught by the back check (Fig. 7b). Therefore, let us start with this configuration: the key tip is kept in its lowest position after a finger blow (full stroke). Then, if the key is slightly released, friction between the back check and the hammer becomes too weak and the contact is lost: thanks to the return spring, the repetition lever is able to push the hammer upwards to a limit position defined by the drop screw (Fig. 7c). From this position, the key requires to be

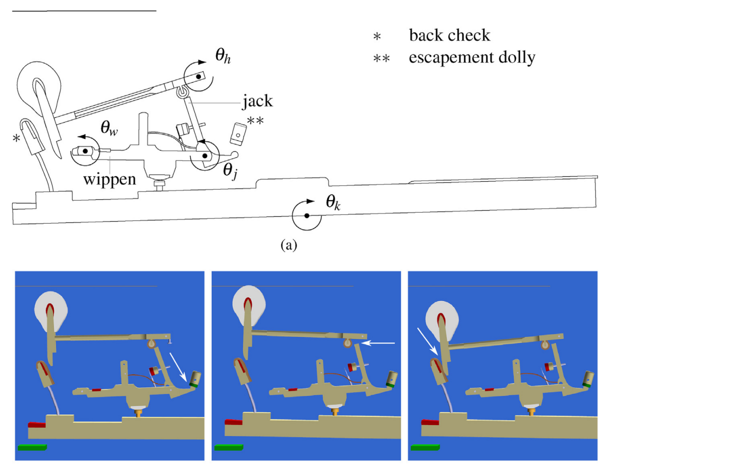


Fig. 6. Single escapement action: (a) initial configuration at rest; (b) just before the escapement; (c) after the escapement when striking the string; (d) final configuration, when the key is held fully depressed.

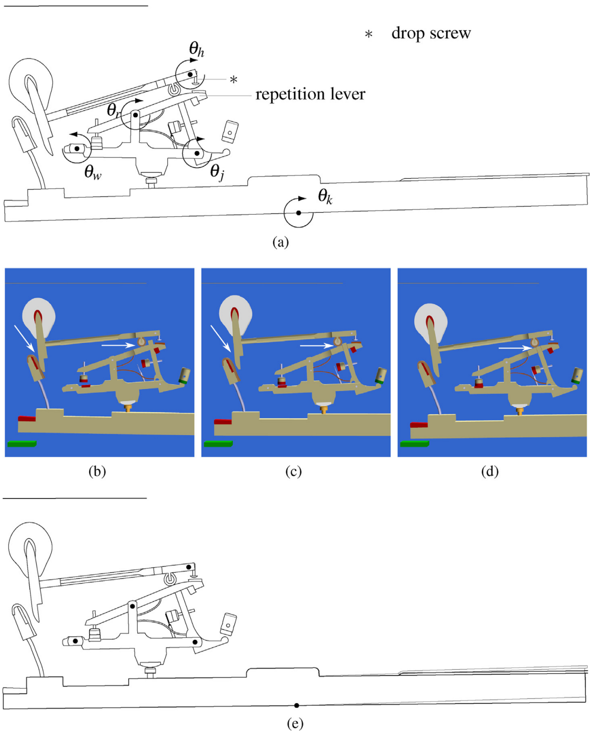


Fig. 7. Double escapement action: (a) initial configuration at rest; (b) configuration when caught by the back check; (c) after a slight release of the key, the back check frees the hammer; (d) thanks to the repetition lever, the jack has slid under the roller whereas the key is not completely released: the action is ready to repeat the note; (e) the grey key represents the repetition position of the single escapement action.

released only slightly more so that the jack can re-position itself right under the roller: the key stroke required for throwing the hammer on the string a second time is thus much shorter than in the single escapement action (Fig. 7e). A shorter stroke consequently means a faster repetition capability of the same note.

4.1.4. Response to different types of touch

We have studied the response of our model when it is subjected to different types of keystrokes; a "pressed" and a "struck" touch. The first reflects a keystroke during which the finger starts on the key (Fig. 8 left), the second starts at a certain distance from the key surface (Fig. 8 right). Data for the speed of the key provided by Goebl et al. [3] have been time integrated and differentiated in order to respectively obtain its displacement and its acceleration. Both impulses of Fig. 8 represent an equivalent of a *forte* dynamic. The key used in [3] is a C4 from a Yamaha Disklavier grand piano, whereas our multibody model represents a LUO piano action. As it is built for demonstration purposes, it isn't stated for which note it has been built, but the dimensions of the hammer suggest it corresponds to a bass note (around C1). The virtual action has been regulated, so that its hammer in rest position lies at the same distance with respect to the string as in the experimental data of [3].

Predictably, the response of the two actions (real [3] and simulated) are somewhat different. This can be explained to a large extent by the fact that the two actions differ. Although their design is almost identical, small variations in size and materials of the components at their interacting surfaces logically lead to different functioning properties. The consequences of these differences are reflected in the form of an offset in the response of the hammer. The goal being to compare motion time history but also to track interacting events of the action, the results are deliberately presented such that the time zero reference for the experimental [3] and simulated curves corresponds to the impact of the hammer on the string. As in [3] the hammer-string contact is taken as the maximal acceleration of the hammer travel, which does not necessarily coincide with the first hammer-string contact.

The curves for hammer velocity show that the model is able to catch the difference in touch of the two inputs (Fig. 8). Indeed, the simulation results for a pressed response display the typical gradual increase of speed of the hammer. At 10 ms, after hitting the string,

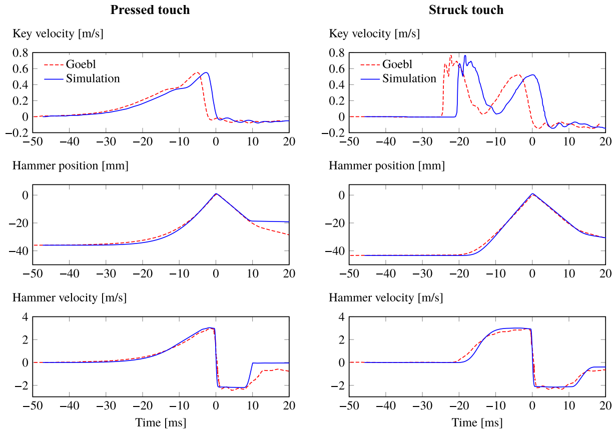


Fig. 8. The displacement caused by a pressed touch (left) and a struck touch (right) applied to a real action [3] have been used as an input for the modelled action. Speed profiles for the hammer are similar for the experimental and the simulated curves for both types of touch.

the hammer of the model is abruptly caught by the catch, whereas the hammer of [3] seems to be slowed down without being blocked. The model also gives good motion predictions for a struck touch. The curve is marked by a later and steeper increase in speed of the hammer, but the concavity is the same as for the action studied in [3]. Moreover, in both cases (struck and pressed), the speed amplitudes are similar, and except for the time offset which could be due to different felt compression characteristics, the timing of the hammer responses are very similar. Let us finally note that the modelling results do not show the oscillations found in the measured curves of Goebl et al. This is probably in part due to the rigid-body assumptions of our model.

4.1.5. Timing of the action

Thanks to the geometrical computation of contact between components of the action (see in Section 3.2), one can perform a timing analysis of the interaction between components. The *forte* pressed touch used in the previous section serves as the input for the model. Our results are compared on the basis of a 20 ms time window, centred on the impact of the string.

Under normal regulation settings (Fig. 9, middle), the first notable event is the contact between the jack and the escapement dolly, 5 ms before the string impact. This causes the jack to flip back and releases the hammer. The repetition lever is the first to loose contact with the hammer roller, closely followed by the escapement jack. The hammer is released 0.5 ms before string contact and flies freely towards it. After the hammer has rebounded on the strings (~1.5 ms contact duration), it is first intermittently slowed down by the repetition lever (2 ms after impact), then the jack (7 ms after impact). As the key is kept depressed for some time, the hammer is finally blocked by the catch (~8 ms after string impact).

It is interesting to highlight the differences in timing of this modelled *forte* key stroke with the results of [1] for the same dynamics. Let us note that the definition of hammer impact in [1] is given as the first contact with the string, not the peak in acceleration as we have chosen. The timing results of Askenfelt et al. discussed in this

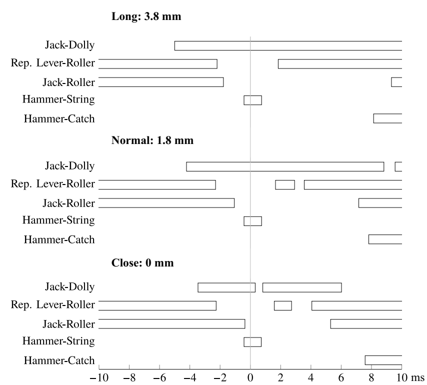


Fig. 9. Contact duration for the grand piano action set-up for a long, normal and close escapement height.

paper are thus shifted in time by ~1 ms and will be referred to as "corrected time". Most notable is the offset in time for the escapement; in [1], the contact between jack and roller is lost after the first contact of the hammer with the string, but before the string impact event (approximately −0.8 ms in corrected time). In our model, hammer-string contact occurs before the first string impact. String contact is slightly longer in [1]; 2 ms versus 1.5 ms in the multibody model. After the hammer rebounds from the string, the timing is different: the repetition lever catches the roller ~1 ms later in the multibody model, but the jack-roller contact occurs even later (1 ms vs 8.5 ms in the model). One of the possible causes of this difference might be due to different initial key height. Indeed,

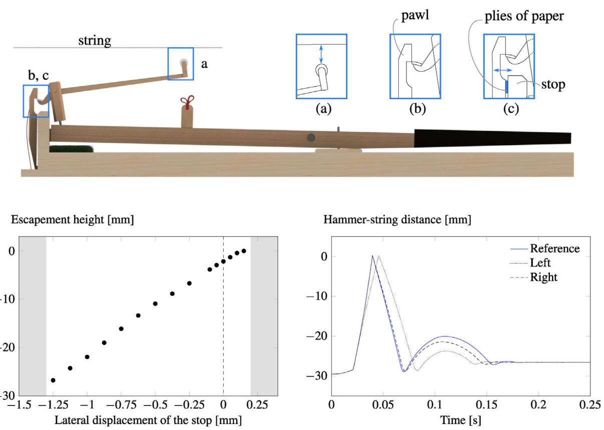


Fig. 10. Above: solidworks representation of the action modelled in Robotran. The real action is a replica held at the Brussels Musical Instrument Museum of the one found in a pianoforte preserved at the Germanisches Nationalmuseum (MIR1097). Left: inserting a sheet of paper of 1 mm induces a shift of the escapement height of 20 mm. The grey areas indicate the functioning limits of the action. Right: compared to the reference case, when the pawl is shifted to the left, the hammer escapes sooner and thus slows down. The influence on the hammer trajectory of a shift to the right is more complex.

the key motion (Fig. 8) has been obtained by time integrating the experimental key velocity, which can only provide a vertical travel but not the initial configuration. Consequently, if the key is depressed too deeply (further than the key-bottom felt), the jack is tripped too far away from the roller as shown in Fig. 9. This hypothesis could also explain why the simulated hammer is caught by the catch whereas it is not in the experimental case (Fig. 8, between 10 and 20 ms).

4.1.6. *Influence of the escapement height on the timing of the action*

Pianists are very keen on the touch a piano confers when its key is being depressed. Technicians can meet this sensitivity by carefully tuning parameters related to the geometry and stiffness of certain components. An example of the refinement of the regulations is found in the notion of escapement height. The escapement height is defined as the distance between the hammer and the string once the hammer has escaped from the rest of the action and flies freely towards the strings. Pianists are extremely sensitive to this parameter, as a greater or smaller escapement height leads to a smoother or stiffer sensation of control.

We compared the response of our model to variations in let-off distance with the results of Askenfelt et al. [1]. It was chosen to keep the same regulations as in [1]; a normal, short and long setting for which escapement respectively occur at 1.8 mm, 0 mm and 3.8 mm. Being limited to the data available in literature, we use the pressed touch with *forte* dynamics of [3] (Fig. 8, left), contrary to Askenfelt et al. who perform their comparison at *piano* level dynamics. However, according to [1], the only major influence of dynamics lies on the timing of the key-bottom contact which occurs earlier regarding the string impact in the case of louder dynamics. In the same vein, lower dynamics appear to have characteristic longer delays between the events.

Let us now compare the influence of setting the let-off distance at different heights (Fig. 9). The escapement height is increased by lowering the escapement dolly, it is thus logical to observe that the jack is tilted later with the decrease in escapement distance. When escapement is set close to the string, the jack intermittently loses contact with the escapement dolly. The contact between the repetition lever and the escapement dolly is fairly consistent over the entire time range, apart from some rebounds of the hammer when set in normal and close configuration. The fact that contact is lost and restored at the same moments of time is due to the drop screw which limits the motion of the repetition lever. Contact with the repetition lever will consequently always be lost at the same point. The jack-roller contact gives the same tendencies as in [1]: free flight before string impact diminishes with escapement height. The same can be said for free flight after the impact, but as indicated above, the jack is probably too far from the escapement dolly, delaying its contact with the hammer roller. Hammer-string contact and hammer-catch contact are not visibly influenced by a change in let-off height.

4.2. *The* Prellzungenmechanik

The PZM we have modelled is a copy based on the 1788 Johann Andreas Stein *pianoforte* held at the Germanisches Nationalmuseum (MIR1097). The name '*Prellzungenmechanik*' comes from the fact that the working principle of the action is based on the rebound (*prellen* in German) of the hammer beak on the so-called "pawl" (*Prellzunge* in German, Fig. 10). PZM actions have been largely used throughout Vienna and northern Germany from 1770 to the end of the 19th century, up to a point where the mass of the hammers became so large that they became too sluggish compared to other types of actions which were powerful and agile at the same time.

In this section, we first compare how the regulations made by technicians affect the behaviour of the PZM. Next, we analyse the response of the action to three different inputs corresponding to various playing styles; a pressed touch, a struck touch and a falling mass.

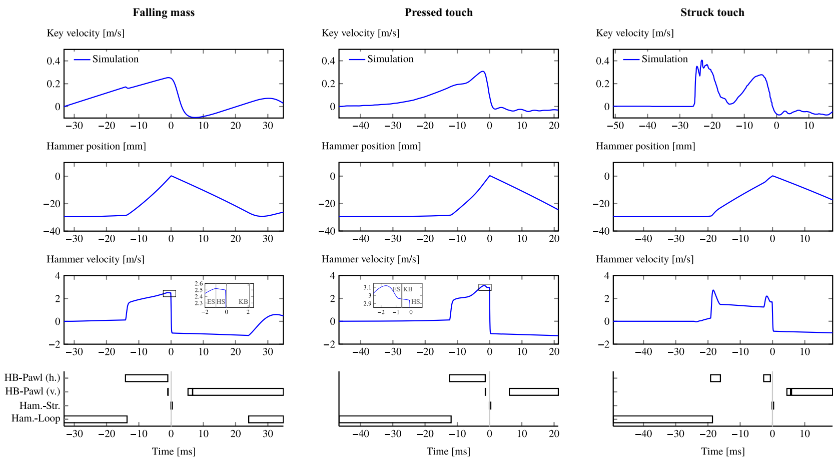


Fig. 11. Response of the PZM model to a falling mass of 400 g, a pressed touch and a struck touch. Three events are highlighted in the hammer velocity graph: escapement of the hammer (ES), hammer-string contact (HS) and key-bottom contact. The time-event graphs indicate when pairs of bodies are contacting: the pawl with the horizontal and vertical part of the hammer-beak (HB), hammer-string contact and interaction between the hammer and the felt loop that supports it.

4.2.1. Regulation of the escapement height

The model of Stein's PZM enables us to confront simulation results with the experience of piano technicians used to regulate this kind of actions. More precisely, we are looking at the influence of the regulation of the action on its behaviour. This kind of analysis has never been formally quantified for PZM actions. In Viennese actions, the escapement height is defined as the distance between the hammer (Fig. 10 above, (a)) and the string once the beak has escaped from the pawl (Fig. 10 above, (b)) and flies freely towards the string. As in Section 4.1.5, we illustrate this with the regulation of the escapement height. In the early Stein actions, technicians had to adapt the escapement height by adding or suppressing plies of paper of different thicknesses between the pawl and the stop which limits its movement (Fig. 10 above, (c)).[2]

When performing this regulation in the model, one can notice a very high sensitivity by inspecting the linear relation with a 1/20 slope between the escapement height and the number of plies of paper (Fig. 10 left). In other words, moving the stop 1 mm will cause a 2 cm displacement of the escapement height. Furthermore, the admissible regulation range is very limited as the action stops functioning when too many plies of paper are added or removed (grey area in Fig. 10 left). Knowing that the regulation of the escapement height must be carried out with a precision of about 1 mm, one can easily imagine the delicate tuning work of the technicians for setting up such instruments. Time-event diagrams analysis were also carried out, but the results did not provide significant variations for the different regulations leading to a playable instrument.

The global motion of the hammer also gives a good idea of the consequences of the set-up of the pawl. Two different cases have been studied and compared with a reference where the action is well tuned (Fig. 10 right, continuous). In the first case, the pawl has been shifted 1.13 mm to the left (Fig. 10, right dotted). Because the hammer escapes early, it is also rapidly subjected to gravity without any further driving force to propel it towards the strings. This means that the hammer decelerates over a longer period of time and hits the strings with less force. As a consequence, the bouncing of the hammer on the string is of lesser intensity, and the hammer also falls down more slowly. In the second case, the hammer has been shifted 0.15 mm to the right (Fig. 10 above, dashed). Even if this value is very close to the functioning limit of the action, the consequence of this shift on the hammer motion is not as impressive as in the first case; up to 0.75 s, the two curves are almost identical. The smaller amplitude of the hammer bounce after 0.75 s can be explained by the increase in friction between the hammer beak and the pawl due to the new resting position of the latter. Because of this increase in friction, the hammer loses more speed when falling back in rest position and logically bounces less on the felt loops located at the middle of the action.

4.2.2. Response to different types of touch

Following the same principles as in Section 4.1.4, we have applied three different types of keystroke to the PZM action (Fig. 11). For the pressed and struck touch, the speed curves of [3] have been scaled so that the total key-depth would reach the 47 mm of our Stein action. The third type of key-depression is imposed by a falling cylindrical mass of 400 g placed on the key surface. The escapement height has been set to 2.5 mm.

Before analysing the simulation results, let us discuss the issues of imposing either a displacement or a force at the key front. Be it in the form of motion or force, measurements can only be reused with a certain degree of certitude as input data in a model. Indeed, the force that the pianist applies on the key is directly dependant of the resistance the action opposes. Consequently, the motion of the key and the force needed to put it in motion are directly linked to the resistance it offers. In our case, with the displacement driven-models, it could very well be that the displacement of the key is at moments too slow or too fast, simply because the resistance of the double escapement action differs from the PZM, according to their

[2] Johann Andreas Stein's daughter Nannette introduced screws to adjust the escapement soon after taking over her fathers' shop [8].

respective stage of motion. Since we lack precise data concerning PZM keystrokes, we use the "falling mass" simulation as a reference curve. Even if [1] has shown for the grand piano action that a falling mass (or equivalent mechanical system) does not reproduce human touch, this kind of input can illustrate how the action reacts when subjected to a gravity-type input. Indeed, contrarily to a human force input, a falling mass can be considered as a neutral input since its effect is independent from all the mechanical events in the action. More precisely, it can give us an idea of the resistance felt by the pianist.

Let us analyse the simulation results for the falling mass in depth (Fig. 11 left). During the first 20 ms (from −33 to −14 ms), the mass sets the key in motion, but the hammer barely moves; its velocity is almost zero and it is in contact with the felt loop that supports it. This can be explained by the design of the PZM (Fig. 10 above); one has to wait until the hammer beak hits the pawl before the hammer starts to rise significantly. At −14 ms, the hammer steeply accelerates thanks to this interaction. At that stage of the movement, the velocity of the key is slightly diminished because of the supplementary mass of the hammer that has to be propelled. With a 400 g mass, the effect is marginal, but when lowering this mass (corresponding to softer dynamics), the speed decrease is far more pronounced. Even with less heavy masses, the light hammer takes advantage of the momentum of the key and is sharply accelerated. Once put in motion, its speed increases linearly until contact with the pawl is lost (−1 ms, ES on Fig. 11 left). The hammer is then in free flight for about 1 ms before it hitting the string; the slope of the hammer velocity becomes negative as it is subjected to gravity. Shortly after the impact of the string, the key reaches the key-bottom (2 ms, KB on Fig. 11 left). As in [3], key-bottom contact is taken as the maximal acceleration of the key when it is in contact with the stop that limits its movement. The effect of the 400 g weight is not sufficient to continuously keep the key in its lower position; after hitting the key-bottom, the key rebounds before reaching equilibrium (the equilibrium state is not visible in Fig. 11). Also, as the key is constantly depressed, the hammer beak is kept against the vertical side of the pawl. The hammer falls down and rebounds on the felt loops.

Comparing these results with those obtained for the double escapement action, we can already outline three characteristics of the PZM; the hammer accelerates (1) suddenly but (2) with a certain delay compared to the motion of the key and (3) the abrupt increase in speed of the hammer causes a slowdown of the key (this effect of resistance can be felt when playing a real PZM action). The differences in behaviour are mainly due to the fact that the hammer of the PZM is directly hinged on the key and that the component responsible for the propulsion (the pawl) is not initially in contact with the hammer.

Looking at the results for the pressed touch (Fig. 11, middle), one can observe the same tendencies in hammer response; a fast acceleration followed by a steadier acceleration phase that has a shape similar to the key velocity. The escapement of the hammer and the key-bottom event occur approximately at the same time (−0.54 and −0.34 ms, respectively ES and KB on Fig. 11). With this input pattern, the hammer loses speed even before having escaped. This is due to the speed profile of the key which displays a deceleration before the hammer-string impact. As long as the hammer has not escaped, the influence of key motion is very important since it is directly coupled with the hammer through the beak-pawl contact. Once the hammer has escaped, the lever effect is lost and the motion of the key has a limited influence on the hammer; from that point on, the speed curve displays a constant slope, mainly influenced by gravity.

Using the scaled struck touch profile of the grand piano action (Fig. 11 right) shows an interesting case in which the hammer "outruns" the action; since the first impulse causes a violent shock when the hammer and the pawl collide, the light hammer is immediately propelled at a higher speed than the key. The normal interaction, during which the beak and the pawl are continuously in contact, is interrupted at −17 ms. At that point, the hammer escapes a first time by outrunning the pawl, but is steadily slowed down by gravity. This deceleration allows the key and pawl to catch up with the hammer beak; a second impact occurs at −3 ms, followed by the geometrical escapement.[3] The loss of contact is clearly visible both in the time–event diagram and the hammer velocity graph (Fig. 11 right). This profile shows a case where the action is outrun, but then caught up again, resulting in a two-phase, unstable acceleration of the hammer. It can also happen that the hammer outruns the action up to the point where it hits the string without being caught again by the pawl.

5. Conclusions and prospects

This paper illustrates the interest in using multibody dynamics for studying the action of stringed keyboard instruments. A general introduction to multibody dynamics has been given and the workflow needed to obtain a model is illustrated with the guideline example of the double escapement action. Next, we have presented the validation procedure that has been carried out with the help of high-speed imaging.

The ongoing project concerns three different actions, each of which is being studied with a specific objective. The double escapement action is probably the best known of the three, but is also the most complex to understand. For this reason, the main objective for this action is to exploit the model as a versatile tool for educational purposes. Thanks to the multibody approach, which allows us to easily transform a given action into another one by virtually gluing, adding or removing components, the explanation of the escapement functioning has been achieved in a very progressive way. Besides the educational purpose, the model has also been exploited for achieving precise measurements in the form of timing of events, motion and/or forces. The model was precise enough to measure the different reactions of the hammer when the key is subjected to different types of touch. The comparison of these results also highlighted some improvements that need to be made in order to catch even more precise events. Above all, the need to work with exactly the same action in simulation and validation; using data from literature proved to be sufficient to highlight the general behaviour of the grand piano action, but also showed the uncertainties and unknowns they imply can lead to discrepancies in the results. Future work will thus take advantage of measurements on our own piano actions. A second improvement that would probably enhance our results is the inclusion of a flexible hammer shank. This is currently carried out using a multibody flexible formulation.

In the case of an ancient PZM, the model has proven useful when evaluating the sensitivity of the regulations imposed on the action. It also allowed us to study the response of the action to different types of input patterns of the key. Besides the enhancements envisaged for the grand piano action which also apply to the PZM, the project envisions an issue in connection with the historical evolution of the PZM; in its early versions, the pawl is placed according to a different configuration than in the later versions of the instruments. This change of morphology leads to actions with a different dynamic behaviour. It is hoped that a multibody model will be able to shed light on the reasons of this evolution.

The last action in the scope of this project has not been treated in this paper. It concerns an action which has not survived in any physical form whatsoever. Indeed Arnaut de Zwolle's fourth

[3] The hammer beak is said to escape geometrically when it has passed the angled corner of the pawl and therefore loses contact with the horizontal side of the latter.

striking mechanism has reached us through a drawing in his manuscript [9]. Many unknowns concerning its dimensions and proportions still remain and it is uncertain whether Arnaut de Zwolle's sketches refer to a working action that really existed. Therefore, a parametrized model of the action might end up with the best candidate for a working action. After the numerical investigation, if it appears the action is viable, it is planned to build a real exemplary in collaboration with the Musical Instruments Museum Brussels and the Hogeschool Gent.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.culher.2016.04.010.

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Appendix D

Cristofori

LES PREMIERS *PIANOFORTE* DE BARTOLOMEO CRISTOFORI

Au-delà les querelles historiques relatives à l'attribution de l'invention du *pianoforte*, Bartolomeo Cristofori est désormais reconnu comme le génie qui parvint à donner toute son expressivité au clavecin. Le bénéfice qu'il put tirer de son invention ne fut malheureusement pas à la hauteur de l'avancée technologique et artistique que représenta sa création. Malgré ce manque de reconnaissance, le *gravicembalo col piano e forte* fit l'objet d'un article qui décrit en détail ses avantages et son fonctionnement. Cet éloge à l'inventeur, écrit par l'humaniste Scipione Maffei, fut édité deux fois sous sa forme originale et ensuite traduit en allemand dans le premier quart du XVIII^e^ siècle[1]. Les différents tirages de l'article et les trois instruments complets[2] que nous avons conservés illustrent toute l'inventivité et le souci de perfection du facteur italien ; entre le premier modèle de mécanique illustré dans l'article et celui que l'on observe une vingtaine d'années plus tard dans les instruments conservés, la conception, allant de la forme des étouffoirs au principe de fonctionnement global, varie considérablement. Si les instruments survivants permettent d'apprécier cette évolution au travers de preuves tangibles, l'étude de l'article de Maffei, bien que plus abstrait, offre un aperçu d'une évolution encore plus grande.

L'objet de la présente recherche concerne les premières mécaniques de Cristofori dont nous avons conservé une trace grâce à l'article de Maffei. Les éléments biographiques de la vie de Cristofori donnent une première mesure du caractère inhabituel de sa carrière qu'il doit sans doute à son talent. Nous proposons ensuite d'étudier les premières traces écrites qui reprennent des éléments d'information à propos de ses *pianoforte*. Il s'agit des inventaires d'instruments de la cour des Medici et de l'article de Scipione Maffei. Les inventaires nous donnent des indices quant à la date de fabrication des premiers instruments, tandis que l'article permet de cerner avec plus de détails les intentions de l'inventeur et la physionomie de la mécanique de l'instrument.

1. CRISTOFORI ET LA FAMILLE DE MEDICI

Le registre baptismal de l'église Saint-Luc à Padoue indique que Cristofori est né dans cette ville le 4 mai 1655 et a été baptisé deux jours plus tard[3]. Certains chercheurs ont cru que le *Bartolomei Christofari*, cité lors d'un recensement dans la maisonnée du célèbre luthier crémonais Nicolò Amati, correspondait au facteur de pianos[4]. Comme la plupart des apprentis

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[1] Scipione MAFFEI, « Nuovo invenzione d'un gravecembalo col piano e forte. Agguinte alcune considerazioni sopri gli strumenti musicali », *Giornale de' Letterati d'Italia*, Venise, (5) 1711, p. 144-159; Scipione MAFFEI, « Descrizione d'un gravicembalo col piano, e forte. Aggiunte alcune considerazioni sopra gli strumenti musicali », *Rime e prose*, Venise, 1719, p. 309-315; Scipione MAFFEI (trad. König), « Beschreibung eines neuerfundenen Claviceins, auf welchem das piano und forte zu haben, nebst einigen Betrachtungen über die Musicalische Instrumente », *Critica musica*, éd. par Johann Mattheson, Hambourg, 2 (1725), p. 335-342.

[2] Les *pianoforte* se trouvent au Metropolitan Museum à New York (1720) au Museo Nazionale degli Strumenti Musicali à Rome (1722) et au Musikinstrumenten-Museum de Leipzig (1726).

[3] Un fac-similé de l'acte de baptême se trouve dans Bruno Brunelli BONETTI et Adelmo DAMERINI, *Bartolomeo Cristofori inventore del pianoforte*, Padoue : Tip. Antoniana, 1955, p. 31.

[4] Notons la confusion qui peut régner autour du nom de Cristofori, dont la graphie n'était pas aussi figée au XVIII^e^ que de nos jours. Ainsi, on retrouve le prénom orthographié Cristofori, Christofori, Cristofari, Cristofali et Cristofani. Son prénom subit, dans une moindre mesure, le même sort et est écrit Bartolomo, Bartolomeo, Bartolommeo ou Bortolo, donnant lieu à son surnom *il Burtulo*. Nous supposons que l'orthographe « Bartolomeo

séjournaient chez leur maître, il est probable que cette personne ait suivi un apprentissage dans le domaine de la lutherie. Cependant, le document est daté de 1680 et mentionne que le jeune homme est âgé de 13 ans, alors que Cristofori avait à ce moment déjà 25 ans[5]. Il ne peut donc s'agir du même personnage.

Entre le baptême de Cristofori et son engagement auprès de la famille des Medici, on ne conserve aucune information. Au tournant du XVII[e] siècle, la cour florentine du prince Ferdinando III de Medici compte au moins une centaine d'artistes. Outre son intérêt pour la musique et la peinture, le prince commande régulièrement des tableaux pour lesquels il suggère personnellement des thèmes et des compositions inhabituelles. Parmi ses traits de caractère, il amusant de constater une caractéristique récurrente parmi personnages-clés de l'évolution des instruments à clavier : une passion pour les horloges[6]. C'est dans cet environnement propice aux idées nouvelles et ingénieuses que Cristofori remplace le facteur et restaurateur d'instruments Antonio Bolgioni, décédé en 1688[7].

La légende selon laquelle le prince Ferdinando est personnellement entré en contact avec Cristofori lors de son retour du carnaval de Venise de 1688, a été avancée pour la première fois par le musicologue Leto Puliti en 1874[8]. Cette version des faits est encore couramment véhiculée, mais il n'y a pas de preuve que la rencontre ait véritablement eu lieu. Quoi qu'il en soit, dans un premier temps, après avoir demandé à Cristofori de venir travailler à son service, le prince essuie un refus. Scipione Maffei, écrivain et intellectuel de Vérone dont il sera question ci-dessous, rapporte « qu'il a été dit au prince qu'il [Cristofori] ne voulait pas [le rejoindre] ; il [le prince] répondit qu'il ferait en sorte qu'il le veuille »[9]. En fin de compte, le prince obtient gain de cause et Cristofori emménage chez les Medici au plus tard au mois de mai de 1688[10].

Nombre de détails de la carrière de Cristofori reflètent sa renommée auprès de ses contemporains. Le simple fait qu'il ait été appelé à la cour des Medici, alors que Florence

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Cristofori » a été retenue par les musicologues en raison de ses nombreuses apparitions dans les comptes de la cour des Medici.

[5] La note est reproduite dans Stewart POLLENS, *The Early Pianoforte*, Cambridge : Cambridge University Press, 1995, p. 45.

[6] L'inventaire de ses biens rédigé à sa mort fait état d'une quarantaine d'horloges. L'engouement commun de facteurs d'instruments à clavier pour les horloges, et plus largement les instruments astrologiques qui leur sont associés, est étudié en détail dans Standley HOWELL, « Medical Astrologers and the Invention of Stringed Keyboard Instruments », *Journal of Musicological Research*, 10 (1991), p. 1-17.

[7] POLLENS, *op. cit.*, p. 47.

[8] Leto PULITI, « Della vita de Ser.[mo] Ferdinando dei Medici Granprincipe di Toscana e della origine del pianoforte – cenni storici – Memoria letta nell'Adunanza del dì 7 Dicembre 1873 », *Atti dell'Accademia del R. Istituto Musicale di Firenze*, t. 7, 1874, p. 130.

[9] *Che fu detto al Principe, che non volevo ; rispos' egli il farò volere io*. Vérone, BIBLIOTECA CAPITOLARE, cod. dcccclx, fasc. vi, n. 1.

[10] Sa présence est attestée dans une liste d'objets ménagers qui lui sont distribués lors de son installation : « 1688/A dí 6 maggio/A Bartolomeo Cristofori Padovano nuovo strumentaio del Serenissimo Principe Ferdinando ». ARCHIVIO DI STATO DI FIRENZE, *Guardaroba Medicea*, fichier 903, p. 129 ; un fac-similé se trouve dans Giuliana MONTANARI, « Bartolomeo Cristofori : A List and Historical Survey of His Instruments », *Early Music*, 19.3 (août 1991), p. 385. Pollens cite un texte de la cour daté du 30 avril 1688 où Cristofori est déjà mentionné. Le texte en question se trouve dans L'ARCHIVIO DI STATO DI FIRENZE, *Depositeria Generale*, 434, fol. 53 r°. POLLENS, *op. cit.*, p. 47.

regorgeait d'excellents facteurs, en atteste[11]. Les archives de la cour signalent que plusieurs techniciens indépendants aidaient son prédécesseur Bolgioni dans ses tâches. Pourtant, aucun d'entre eux ne sera promu au rôle de technicien principal. En étant le seul musicien à obtenir une nomination fixe à la cour, Cristofori bénéficie incontestablement d'un statut particulier ; sa fonction lui assure un traitement stable que le prince lui paye jusqu'en 1698. En outre, il est rémunéré par pièce produite ou restaurée, et Ferdinando prend en charge le loyer de son habitation[12]. Grâce à ces divers revenus, Cristofori est largement mieux payé que ses collègues. C'est probablement une des raisons pour lesquelles il n'a jamais dû adhérer en tant que *legnaiolo* (menuisier) à *l'Università di Por San Piero e Fabbricanti*, alors que les autres facteurs en ont tous fait partie[13].

Au début de sa carrière, Cristofori exerce son métier avec tous les artisans regroupés dans les grands ateliers appelés *uffizi*, installés dans la *Galleria dei Lavori*. Dans son entrevue avec Maffei, il reconnait que cet environnement est très bruyant, mais qu'il y a beaucoup appris des autres artisans[14]. Pour échapper au tumulte des *uffizi*, Cristofori installe son atelier dans sa maison dès 1690. Son testament fournit l'adresse précise de son domicile, qui se situe à proximité des ateliers. Il est fort probable qu'il y ait vécu dès son arrivée à Florence, soit de 1688 à 1731[15].

Le livre de comptes des Medici qui se rapporte aux années 1690-1698 est riche en renseignements concernant ses fonctions exactes. On y trouve la mention de tâches de restaurations, d'entretien et d'accord[16]. Une autre occupation de Cristofori consiste à déménager les instruments, principalement depuis et vers *Pratolino* (la villa Medici, située à 12 km au nord de Florence), mais aussi entre le *Palazzo Pitti* (le centre artistique de la famille de Medici à Florence), sa propre maison et la villa du prince à Poggio a Caiano (en Toscane). Enfin, Cristofori est aussi chargé de la construction de nouveaux instruments ; durant les huit années envisagées ci-dessus, un orgue, deux épinettes et six clavecins voient le jour sous ses mains. Le fait que ces travaux soient rémunérés en plus de son traitement fixe pourrait indiquer que son devoir n'est pas simplement d'entretenir la vaste collection de la cour[17]. Il est possible que le salaire fixe versé par la prince Ferdinando ait été destiné aux travaux de recherche de Cristofori, car il n'existe aucune trace de payement pour des *pianoforte*, alors que la cour en possédait au moins un en 1720[18]. Par ailleurs, durant la période 1698-1720, il

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[11] *Ibid.*
[12] Plusieurs fiches de paye peuvent être retrouvées dans l'ARCHIVIO DI STATO DI FIRENZE, dans la *Depositaria Generale*, et dans la *Guardaroba Medicea*, dossier 1073, n. 325.
[13] POLLENS, *op. cit.*, p. 47-48.
[14] « Qu'il a beaucoup appris des autres après être venu ici. Qu'au début, c'était très fatigant pour lui d'être dans la grande salle avec ce bruit assourdissant », *Che molto ha imparato quì dopo venuto da gli altri. che da principio durava fatica ad andare nello stanzone in questo strepito.* Vérone, BIBLIOTECA CAPITOLARE, cod. dcccclx, fasc. vi, n. 1.
[15] ARCHIVIO DI STATO DI FIRENZE, Testament de Bartolomeo Cristofori, établi par Ser Cristofano Nacchianti, le 24 janvier 1728. L'adresse indiquée est Via Canto agli Alberti, désormais connue en tant que Via de' Neri, dans le quartier de San Remigio. MONTANARI, *op. cit.*, p. 385.
[16] Les notes dans le carnet recensent seize restaurations au total, parmi lesquelles neuf pour des clavecins, cinq pour des épinettes et deux pour des orgues.
[17] La cour possède 37 instruments à clavier en 1700 et atteint le nombre de 45 dès 1716.
[18] David SUTHERLAND, « Bartolomeo Cristofori's Paired Cembalos of 1726 », *Journal of the American Musical Instrument Society*, 26 (2000), p. 29.

ne subsiste pas de mentions de pension fixe pour Cristofori dans les comptes. Ce manque de régularité peut être lié aux problèmes financiers du prince[19] ou à une volonté de Cristofori de s'affranchir de son mécène. Néanmoins, comme la période d'interruption des payements coïncide grosso modo avec l'invention de son *pianoforte,* l'hypothèse selon laquelle le salaire de Cristofori était destiné à soutenir ses activités de recherche demeure la plus probable[20]. En tout état de cause, Cristofori conserve des liens avec la famille ; on retrouve quelques payements dans les livres de comptes de 1713 pour des tâches d'entretien et il n'est pas à exclure qu'il ait continué à lui fournir des instruments[21].

À la mort de Ferdinando en 1713, Cristofori est cité dans la liste de ses employés, au même titre que plusieurs autres artistes, en tant que « virtuose de la chambre » (*virtuoso da camera*)[22]. Ce privilège ne sera accordé à aucun autre facteur d'instruments. Par la suite, le père de Ferdinando, le grand-duc Cosimo III, le nomme gardien (*custode*) des instruments de musique, confirmant la position de choix dont il bénéficie auprès de la famille. Il s'agit probablement d'un titre purement honorifique qui permet à Cosimo de lier officiellement la renommée de Cristofori à sa famille ; aucun payement relatif à cette fonction ne figure dans les livres de comptes[23]. Cependant, le nom de Cristofori réapparait en 1720 et on apprend à cette occasion que la cour a des dettes envers lui.

Quoique les obligations de Cristofori à la cour se soient limitées aux instruments à clavier, plusieurs contrebasses et violoncelles fabriqués dans les années 1715-1720 lui sont attribués[24]. L'absence totale de notes de frais pour la construction ou la restauration de ce type d'instruments rend leur attribution à Cristofori suspecte, même s'il apparait lors de l'interview avec Maffei que le facteur possédait des connaissances en rapport avec les instruments à cordes frottées qu'il a pu étudier lors de son service auprès du prince[25]. Quoi qu'il en soit, s'il ne peut être établi avec certitude que Cristofori soit à l'origine de ces instruments à cordes frottées, les quelques instruments à claviers qui nous sont parvenus illustrent son génie créatif. Ainsi, il construit une épinette à structure ovale (1693) et n'hésite pas à bouleverser les standards de fabrication des instruments pour améliorer leur structure[26].

Le décès de Cristofori est signalé dans le journal de Niccolò Susier, joueur de théorbe à la cour, à la date du 27 janvier 1731 (style florentin)[27]. Cristofori a rédigé un testament à deux

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19 Michael Kent O'BRIEN, « Bartolomeo Cristofori at Court in Late Medici Florence », thèse de doctorat, Catholic University of America, 1994, p. 86-89.

20 Les comptes de 1720 reportent une dette de 300.4.7.7 *scudi* en faveur de Cristofori. SUTHERLAND, *op. cit.*, p. 31.

21 POLLENS, *op. cit.*, p. 52.

22 Les autres *Virtuosi da Camera* sont entre autres Francesco de Castris, Rafaello Baldi (Rafaelino), Martino Bitti, Niccola Susier, Francesco Manucci, etc. La liste se trouve dans l'ARCHIVIO DI STATO DI FIRENZE, *Guardaroba Medicea*, dossier 1213[bis]. MONTANARI, *op. cit*., p. 386.

23 SUTHERLAND, *op. cit.*, p. 30.

24 Montanari en établit une liste exhaustive. MONTANARI, *op. cit*, p. 388-395.

25 POLLENS, *op. cit*., p. 50, n. 30. Il n'est pas à exclure que les instruments à cordes frottées soient l'œuvre d'un facteur homonyme. Il pourrait aussi bien s'agir du *Bartolomei Christofari* de Crémone que d'un autre personnage inconnu.

26 Voir à ce propos Gabriele ROSSI-ROGNONI, *Bartolomeo Cristofori : The 1690 Oval Spinet, Study and Research*, Livourne : Sillabe, 2002.

27 Le calendrier florentin commençait le jour de l'Annonciation, soit le 25 mars. Selon le calendrier moderne, il s'agit donc de l'année 1732, voir Mario FABBRI, « Nuova luce sull'attività fiorentina di Giacomo Antonio

reprises[28]. Dans le premier, daté du 17 février 1729, il lègue ses outils et le matériel pour construire les instruments à son étudiant et assistant Giovanni Ferrini qui continuera à construire des *pianoforte* tels que développés par son maître. La seconde version, datée du 23 mars 1729, amenuise considérablement les biens à destination de Ferrini : il lui accorde 5 *scudi* et offre son matériel de travail ainsi que la somme de 200 *scudi* aux sœurs Del Mela. Il est possible qu'Anna et Margherita Del Mela soient apparentés à Domenico Del Mela (1683-après 1751), qui pourrait être le second apprenti de Cristofori et à qui on impute la fabrication du premier piano droit en 1739[29].

2. Les premiers *pianoforte* et l'inventaire des instruments de la cour des Medici

La première mention d'un instrument qui correspond à la description du *pianoforte* figure dans l'*inventario di diversi sorti d'instrumenti musicali in proprio del Serenissimo Sig. Principe Ferdinando di Toscana*, compilé en 1700 par un auteur anonyme[30]:

Un Arpicembalo di Bartolomeo Cristofori di nuova inventione, che fa' il piano, e il forte, a' due registri principali unisoni, con fondo di cipresso senza rosa, con fascie e scorniciatura mezza tonda simile, con filetto d'ebano, con alcuni salterelli con panno rosso, che toccano nelle corde, et alcuni martelli, che fanno il piano, et il forte, e tutto l'ordingo vien serrato, e coperto da un piano di cipresso filettato di ebano, con tastatura di bossolo, et ebano senza spezzati, che comincia in cisolfaut ottava stesa, e finisce in cisolfaut, con n. quaranta nove tasti, tra' bianchi, e neri, con due sodi laterali neri, che uno da levare, e porre, con due palline nere sopra, longo B.ª tre, e sette ottavi, largo nel davanti B.ª uno, e soldi sei, con suo leggio di cipresso, e sua contro cassa d'albero bianca, e sua coperta di cuoio rosso foderata di tafettà verde e orlata di nastrino d'oro.

Un *Arpicimbalo* de Bartolomeo Cristofori, d'invention nouvelle, qui produit [les nuances] *piano* et *forte*, dont les deux registres principaux sont à l'unisson, avec une table d'harmonie en cyprès, sans rosette, avec des éclisses et une moulure semicirculaire également en cyprès, avec un filet d'ébène, avec des sautereaux équipés d'étoffe rouge. Les sautereaux touchent les cordes, de même que les marteaux qui produisent le *piano* et le *forte* ; et toute la machine est enserrée et couverte d'une plaque de cyprès fileté d'ébène, avec des touches de buis et d'ébène, sans feintes brisées, qui commence en *do*$_1$ et se termine en *do*$_5$, avec quarante-neuf touches noires et blanches, avec deux blocs de clavier noirs, l'un pour soulever et l'autre pour poser [le clavier], avec deux boutons noirs par-dessus. [L'instrument est] long de trois *braccia* et sept huitièmes, large à l'avant d'un *braccio* et six *soldi*. [Il possède] un pupitre de cyprès, un coffre de bois blanc et une couverture de cuir rouge, garnie de taffetas vert et bordée d'un ruban d'or.

On ne connait pas le nom que Cristofori a lui-même attribué à son invention. L'appellation *Arpicimbalo* n'est utilisée que dans cet inventaire ainsi que par Federigo Meccoli, le directeur musical de la cour de Ferdinando III. Elle sous-entend que l'instrument avait un son de harpe

Perti, Bartolomeo Cristofori e Giorgio F. Haendel ; valore storico e critico di una "memoria" di Francesco M. Mannucci », *Chigiana*, 21 (1964), p. 172, n. 83. Le journal se trouve à Florence, Biblioteca Moreniana, *Acquisti diversi* 54, fols. 73rº, 73vº, transcrit et traduit en anglais dans Pollens, *The Early Pianoforte*, *op. cit.*, p. 55.

[28] Les testaments se trouvent à l'Archivio di Stato di Firenze, *Notarile Moderno*, 23370, testaments 1728-1733, 5091/8, fol. 39 vº et sont reproduits et traduits dans O'Brien, *op. cit.*, p. 191-214.

[29] Montanari, *op. cit.*¸p. 387.

[30] L'inventaire original se trouve dans l'Archivio di Stato di Firenze, *Guardaroba Medicea*, 1117, fol. 30. Le texte en italien est issu de Pollens, *op. cit.*, p. 43. La page de garde de l'inventaire est manquante, mais l'auteur pourrait être Giovanni Fuga, un musicien de la cour. Dans une lettre datée de 1716 et désormais incluse dans l'inventaire, Fuga écrit « mon inventaire, dans lequel votre sérénissime altesse pourra puiser des informations », *mio inventario dal quale V.S. ne potrà cavare qualche buon lume*. Archivio di Stato di Firenze, *Guardaroba Medicea*, 1117, fol. 1a. Pollens, *op. cit*., p. 43-44.

(*arpi*) et l'apparence d'un clavecin (*cimbalo*)[31]. Meccoli explique d'ailleurs que l'instrument est capable d'imiter le son de la harpe[32]. Concernant les unités de mesure utilisées, un *braccio* est constitué de douze *soldi* et la conversion d'un *braccio* varie entre 54.8 cm et 61.4 cm[33]. Le *pianoforte* de l'inventaire mesurerait en conséquence entre 212.35 cm et 237.96 cm de long, pour une largeur comprise entre 82.2 cm et 92.1 cm.

Cet inventaire est la première trace écrite trouvée à ce jour qui fasse référence à un *pianoforte* de Cristofori. Malheureusement, l'instrument cité n'est pas conservé et nous ne pouvons que le comparer aux trois exemplaires survivants qui datent des années 1720. Toutefois, plusieurs termes confirment qu'il s'agit bien d'un *pianoforte* et non d'un clavecin muni de différents registres. L'inventaire fait référence à des « marteaux qui produisent le *piano* et le *forte* », tandis que le terme *saltarelli*, généralement utilisé pour décrire les sautereaux de clavecins, désigne les étouffoirs qui ont la même forme que les actionneurs d'un clavecin. Enfin, l'ambitus décrit correspond à celui d'un des pianos conservés[34].

Il est donc établi que Cristofori avait construit au moins un *pianoforte* en 1700. Un élément supplémentaire permet d'ailleurs le confirmer : Meccoli écrit dans les annotations de son exemplaire personnel des *Institutioni harmoniche* de Zarlino[35] :

> Voici les façons dont on peut jouer de l'*Arpi Cimbalo* en *piano* et *forte*, inventé par Bartolomeo Christofari, Padouan, en l'an 1700, facteur de clavecins pour le sérénissime grand prince Ferdinando de Toscane[36].

Certains auteurs estiment que Cristofori songeait déjà à la construction de son *arpicimbalo* dès 1698. Cette date peut être mise en rapport avec une lettre de 1710 due à un certain Francesco Manucci[37], découverte et éditée en 1964, dans laquelle il cite

> un nouveau clavecin avec *piano* et *forte*, fabriqué dans les ateliers, sur demande du sérénissime Ferdinando, entamé deux ans avant le jubilé [en 1698][38].

L'authenticité de ce recueil est néanmoins remise en question en raison d'incohérences historiques et linguistiques[39]. Malgré des efforts considérables réalisés pour remettre la main sur les lettres, elles demeurent introuvables. La seule trace qui en subsiste est la transcription

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[31] Edwin Marshall GOOD, *Giraffes, black dragons, and other pianos : a technological history from Cristofori to the modern concert grand*, 2e éd., Stanford : Stanford University Press, 2001, p. 34.

[32] Stewart POLLENS, « Arpicembalo », *Grove Music Online. Oxford Music Online* (2011), http://www.oxfordmusiconline.com/subscriber/article/grove/music/43237 (consulté le 12/07/2013).

[33] Grant O'BRIEN, *The use of simple geometry and the local unit of measurement in the design of Italian stringed keyboard instruments*, http://www.claviantica.com/Geometry_files/Italian_geometry_table_11.htm (page consultée le 11/03/2013).

[34] Il s'agit de l'instrument de 1726, qui couvre quatre octaves, de do_1 à do_5.

[35] Edwin Marshall GOOD, « What did Cristofori call his invention ? », *Early Music*, 33/1 (2005), p. 96.

[36] *Questo sono gl'andamenti che si possono adattare in su l'Arpi Cimbalo del piano e forte, inuentato da Mro Bartolomeo Christofari Padouano. L'Anno 1700. Cimbalaro del Ser.mo Gran P.pe Ferdinando di Toscana*. Cité d'après GOOD, *Giraffes, black dragons, and other pianos*, *op. cit*., p. 35.

[37] Manucci était *Virtuoso da Camera* à la cour comme Cristofori.

[38] *nuovi Cimbali con piano e forte, fabricati nel Laburatorio per volere del Ser.mo Ferdinando, conunciando du' anni prima del Giubileo.* La transcription complète des notes se trouve dans FABBRI, *op. cit.*, p. 145-149.

[39] Pour une analyse plus détaillée, voir les études de Antonella FURNARI et Carlo VITALI, *Händels Italienreise : neue Dokumente, Hypothesen und Interpretationen*, Kassel : Göttinger Händel-Beiträge, 1991.

de 1964. Aucune preuve tangible ne permet donc d'établir que Cristofori aurait développé son instrument avant 1700.

Néanmoins, au vu de la carrière de Cristofori auprès des Medici, il est possible que la conception de l'instrument, à tout le moins d'un point de vue théorique, soit antérieure à l'entrée en service de Cristofori et que c'est cette invention qui aurait poussé le prince à l'engager[40]. Comme on l'a vu ci-dessus, la première version du nouvel instrument achevée, le prince aurait pu décider qu'il ne valait plus la peine de soutenir financièrement les recherches du facteur padouan. Il semble en tout cas peu probable que Cristofori ait pu inventer une mécanique à ce point complexe l'année-même de sa construction. Seul le bon sens permet de penser qu'il a probablement entamé sa conception quelques années avant le changement de siècle.

3. L'ARTICLE DU *GIORNALE DE' LETTERATI D'ITALIA*

Scipione Maffei aurait vu trois des instruments de Cristofori en 1709 alors qu'il rendait visite au prince Ferdinando dans le but de solliciter son soutien pour la création d'un journal littéraire. Deux ans plus tard, grâce à ses notes personnelles et à quelques consultations auprès de personnages bien placés, Maffei publie un article élogieux à propos des mécaniques de Cristofori dans son *Giornale de' Letterati d'Italia*[41]. Il joint à son article un schéma de la mécanique qu'il prétend avoir dessiné de mémoire (Figure 1).

3.1 ÉDITION ET TRADUCTION DE L'ARTICLE

L'article de Maffei se présente en trois parties : la première est une argumentation rhétorique qui défend tant le nouvel instrument que son inventeur, la seconde est plus technique et comprend l'explication du fonctionnement du mécanisme de cet instrument, accompagné d'un schéma. La dernière ne concerne plus le *pianoforte* de Cristofori, mais évoque « quelques remarques à propos des instruments de musique », c'est-à-dire des questions d'ordre acoustique et relatives aux tempéraments ; pour cette raison, nous n'en proposons pas de traduction. Toutefois, nous verrons plus loin que la rédaction de cette partie du texte éclaire celle de la totalité de l'article[42].

Nuova invenzione d'un gravecembalo col piano, e forte; aggiunte alcune considerazioni sopra gli strumenti musicali.	Nouvelle invention d'un clavecin avec les nuances *piano* et *forte* ; et quelques remarques à propos des instruments de musique.
Se il pregio delle invenzioni dee misurarsi dalla novità, e dalla difficoltà, quella, di cui siamo al presente per dar ragguaglio, non è certamente inferiore a qualunque altra da gran tempo in qua si sia veduta. Egli è noto a chiunque gode della musica, che uno de' principali fonti, da' quali traggano i periti di quest'arte il segreto di singolarmente dilettar chi ascolta, è il	Si la valeur des inventions doit être évaluée d'après leur nouveauté et leur complexité, celle dont nous allons rendre compte n'est certainement pas inférieure à une quelconque autre que l'on aurait vue depuis longtemps. Tous ceux qui apprécient la musique savent que l'un des principaux moyens par lequel les experts dans cet art trouvent le secret d'enchanter tout

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[40] David SUTHERLAND, *op. cit.*, p. 29.
[41] Scipione MAFFEI, « Nuovo invenzione d'un gravecembalo col piano et forte ; aggiunte alcune considerazioni sopri gli strumenti musicali », *op. cit.*, p. 144-159.
[42] La subdivision du texte en paragraphes n'est pas originale mais a pour but de conserver une correspondance entre le texte italien et français présentés en vis-à-vis. Nous remercions Anne-Emmanuelle Ceulemans pour son aide dans la traduction de ce texte.

piano, e'l fortezo, sia nelle proposte e risposte, o sia quando con artifiziosa degradazione lasciandosi a poco a poco mancar la voce, si ripiglia poi ad un tratto strepitosamente: il quale artifizio è usato frequentemente, ed a maraviglia ne' gran concerti di Roma con diletto incredibile di chi gusta la perfezione dell'arte.

particulièrement celui qui écoute, c'est la nuance de *piano* et de *forte* dans le thème et sa réponse, ou quand on laisse sa voix s'amenuiser peu à peu, dans un *diminuendo* artistique, pour ensuite reprendre d'un seul coup en *forte*. Cet artifice est souvent utilisé et avec le plus merveilleux effet, dans les grands concerts de Rome, pour l'incroyable ravissement de celui qui goûte la perfection de l'art.

Ora di questa diversità, ed alterazione di voce, nella quale eccellenti sono fra gli altri gli strumenti da arco, affatto privo è il gravecembalo; e sarebbe da chi che sia, stata riputata una vanissima immaginazione il proporre di fabbricarlo in modo, che avesse questa dote. Con tutto ciò una sì ardita invenzione è stata non meno felicemente pensata, che eseguita in Firenze dal Sig. BARTOLOMMEO CRISTOFALI, Padovano, Cembalista stipe[n]diato dal Serenissimo Principe di Toscana. Egli ne ha finora fatti tre della grandezza ordinaria degli altri gravecembali, e son tutti riusciti perfettamente. Il cavare da questi maggiore, o minor suono dipende dalla diversa forza, con cui dal sonatore vengono premuti i tasti, regolando la quale, si viene a sentire non solo il piano, e il forte, ma la degradazione, e diversità della voce, qual sarebbe in un violoncello.

Cependant, cette diversité et altération de la voix, dans lesquelles les instruments à archet excellent, le clavecin en est entièrement dépourvu, et on aurait pu croire qu'il était vain de tenter de le fabriquer en sorte qu'il soit pourvu de cette qualité. Pourtant, une invention aussi audacieuse a été conçue et réalisée à Florence par M. BARTOLOMMEO CRISTOFALI, de Padoue, claveciniste au service du sérénissime prince de Toscane. Il en a déjà construit trois, de la taille habituelle des autres clavecins, et ils sont tous réussis à la perfection. La production de plus ou moins de sonorité dépend du degré de puissance avec lequel le joueur appuie sur les touches. Lorsqu'il adapte cette dernière, on entend non seulement le *piano* et *forte*, mais aussi le *diminuendo* et la diversité de puissance du son, comme dans un violoncelle.

Alcuni professori non hanno fatto a quest'invenzione tutto l'applauso ch'ella merita; prima, perchè non hanno inteso, quanto ingegno si richiedesse a superarne le difficoltà, e qual maravigliosa delicatezza di mano per compirne con tanta aggiustatezza il lavoro: in secondo luogo, perchè è paruto loro, che la voce di tale strumento, come differente dall'ordinaria, sia troppo molle, e ottusa; ma questo è un sentimento, che si produce nel primo porvi su le mani per l'assuefazione, che abbiamo all'argentino degli altri gravecembali; per altro in breve tempo vi si adatta l'orecchio, e vi si affeziona talmente, che non sa stancarsene, e non gradisce più i gravecembali comuni; e bisogna avvertire, che riesce ancor più soave l'udirlo in qualche distanza. E' stata altresì opposta eccezione di non avere questo strumento gran voce, e di non avere tutto il forte degli altri gravecembali. Al che si risponde prima, che ha però assai più voce, ch'essi non credono, quando altri voglia, e sappia cavarla, premendo il tasto con impeto; e secondariamente, che bisogna saper prendere le cose per lo suo verso, e non considerare in riguardo ad un fine ciò ch'è fatto per un'altro.

Certains professionnels n'ont pas accordé à cette invention toutes les louanges qu'elle mérite. En premier lieu, ils n'ont pas vu toute l'ingéniosité nécessaire pour en surmonter les difficultés, ni la merveilleuse délicatesse de la main nécessaire pour accomplir cet effet avec tant de précision. Et deuxièmement, il leur a semblé que le son d'un tel instrument, différent de l'ordinaire, était trop doux et indistinct. Mais c'est un sentiment qui se produit la première fois qu'on y pose les mains, en raison de l'habitude que nous avons du timbre argentin des autres clavecins. Néanmoins, en peu de temps, l'oreille s'y adapte et en devient à ce point charmée, qu'elle ne peut s'en lasser et que le clavecin commun ne lui plait plus. Il faut par ailleurs attirer l'attention sur le fait que son audition devient encore plus douce à une certaine distance. Il a ensuite été reproché à cet instrument de ne pas avoir un son puissant, ni tout le *forte* des autres clavecins. À cela, on peut répondre, premièrement, qu'il a beaucoup plus de puissance qu'on ne l'imagine, pour autant que celui qui le désire et est capable de l'utiliser enfonce les touches avec vigueur ; et, deuxièmement, qu'il faut savoir prendre l'objet pour son propre timbre, et ne pas considérer par rapport à un certain but une chose qui est destinée à un autre.

Questo è propriamente strumento da camera, e non è però adattabile a una musica di Chiesa, o ad una grand' orchestra. Quanti strumenti vi sono, che non si usano in tali occasioni, e che non pertanto si stimano de' più dilettevoli? Egli è certo, che per accompagnare un cantante, e per secondare uno strumento, ed anche

Ceci est véritablement un instrument de chambre, et il n'est ni prévu pour la musique d'église, ni pour un grand orchestre. Combien d'instruments y a-t-il, utilisés en de pareilles occasions, qui ne soient pas considérés parmi les plus agréables ? Il est certain que pour accompagner un chanteur et pour jouer avec un per un moderato concerto riesce perfettamente: benchè non sia però questa l'intenzion sua principale, ma sì quella d'esser sonato a solo, come il leuto, l'arpa, le viole da sei corde, ed altri strumenti de' più soavi. Ma veramente la maggior opposizione, che abbia patito questo nuovo strumento, si è il non sapersi universalmente a primo incontro sonare, perchè non basta il sonar perfettamente gli ordinarj strumenti da tasto, ma essendo strumento nuovo, ricerca persona, che intendendone la forza vi abbia fatto sopra alquanto di studio particolare, così per regolare la misura del diverso impulso, che dee darsi a' tasti, e la graziosa degradazione a tempo e luogo, come per iscegliere cose a proposito, e delicate, e massimamente spezzando, e facendo camminar le parti, e sentire i soggetti in più luoghi.

autre instrument ou même pour un petit concert, il convient parfaitement, bien que ce ne soit pas sa finalité principale. En effet, il est plutôt prévu pour être joué seul, comme le luth, la harpe, les violes à six cordes et d'autres instruments des plus agréables. Cependant, la principale cause de l'opposition que ce nouvel instrument a rencontrée, c'est en réalité le fait que l'on ne sache pas en jouer parfaitement dès l'abord. En effet, il ne suffit pas de jouer parfaitement des instruments à clavier ordinaires. Comme il s'agit d'un nouvel instrument, il faut une personne qui, comprenant ses capacités, l'ait étudié de façon particulière, de façon à régler la mesure de la force variable requise sur les touches et son gracieux diminuendo, au bon moment. Il faut aussi choisir des pièces qui lui conviennent pour leur délicatesse, et spécialement en séparant et en faisant promener les voix, afin que les sujets soient entendus à plusieurs endroits.

Ma venendo alla struttura particolare di questo strumento, se l'artefice, che l'ha inventato, avesse così saputo descriverlo, come ha saputo perfettamente fabbricarlo, non sarebbe malagevole il farne comprendere a' lettori l'artifizio: ma poichè egli non è in ciò riuscito, anzi ha giudicato impossibile il rappresentarlo in modo, che se ne possa concepire l'idea, è forza, ch'altri si ponga all'impresa, benchè senza aver più lo strumento davanti agli occhi, e solamente sopra alcune memorie fattesi già nell'esaminarlo, e sopra un disegno rozzamente da prima disteso.

Mais venons-en à la structure particulière de cet instrument. Si l'artisan qui l'a inventé avait aussi bien su comment décrire l'instrument que de le fabriquer, il n'aurait pas été difficile d'expliquer le mécanisme aux lecteurs ; mais comme il n'y est pas parvenu et qu'il a estimé qu'il était impossible de le représenter de telle sorte qu'on puisse s'en faire une idée, il faut que quelqu'un d'autre s'y attelle, bien que je ne dispose plus de l'instrument devant les yeux, mais seulement de quelques notes réalisées en l'examinant et d'un modèle dessiné grossièrement à ce moment-là.

Diremo adunque primieramente, che in luogo degli usati salterelli, che suonano con la penna, si pone qui un registro di martelletti, che vanno a percuotere la corda per di sotto, avendo la cima, con cui percuotono, coperta di dante. Ogni martello dipende nel suo principio da una rotella, che lo rende mobile, e le rotelle stanno nascoste in un pettine, nel quale sono infilate. Vicino alla rotella, e sotto il principio dell'asta del martello vi è un sostegno, o prominenza, che ricevendo colpo per di sotto, alza il martello, e lo spinge a percuoter la corda con quella misura d'impulsione, e con quel grado di forza, che vien dato dalla mano; e quindi viene il maggiore, o minor suono a piacere del sonatore; essendo agevole anche il farlo percuotere con molta violenza, a cagione, che il martello riceve l'urto vicino alla sua imperniatura, che vuol dire, vicino al centro del giro, ch'egli descrive; nel qual caso ogni mediocre impulso fa salire con impeto un raggio di ruota.

Nous dirons donc, en premier lieu, qu'au lieu des sautereaux habituels qui produisent le son à l'aide d'une plume, il y a une rangée de marteaux qui frappent la corde par le bas et dont les sommets sont couverts de daim. Chaque marteau a son extrémité insérée dans une petite roue, qui le rend mobile, et ces roues sont cachées dans un peigne [récepteur] sur lesquels ils sont enfilés. Près de la roue et en dessous du début de la tige du marteau, il y a un support ou une saillie, qui, recevant une impulsion du bas, soulève le marteau, faisant en sorte qu'il frappe la corde, d'après la mesure de l'impulsion et le degré de force qui est donné par la main [de l'interprète] ; et donc, le son est plus ample ou plus faible selon le bon vouloir du musicien. Aussi est-il possible de le faire frapper avec beaucoup de violence, parce que le marteau reçoit l'impulsion près de son axe, c'est-à-dire près du centre de la rotation qu'il décrit. En conséquence, même une impulsion médiocre fait monter avec fougue un rayon de la roue.

Ciò che dà il colpo al martello sotto l'estremità della prominenza suddetta, è una linguetta di legno, posta sopra una leva, che viene all'incontro del tasto, e ch'è alzata da esso, quando vien premuto dal sonatore. Questa linguetta non posa però sopra la leva, ma n'è alquanto sollevata, e si sta infilzata in due ganasce

Ce qui donne l'impulsion au marteau sous la saillie susmentionnée est la languette de bois, placée sur un levier qui se trouve devant la touche et qui est soulevé par cette dernière, lorsqu'elle est enfoncée par le musicien. Cette languette, toutefois, ne repose pas sur le levier, mais est légèrement surélevée et coincée sottili, che le son poste a questo effetto una per parte. Ma perchè bisognava, che il martello percossa la corda subito la lasciasse, staccandosene, benchè non ancóra abbandonato il tasto dal sonatore; ed era però necessario, che il detto martello restasse subito in libertà di ricadere al suo luogo; perciò la linguetta, che gli dà il colpo, è mobile, ed è in tal maniera congegnata, che va in su, e percuote ferma, ma dato il colpo subito scatta, cioè passa; e quando lasciato il tutto, ella torna giù, cede, e rientra, riponendosi ancora sotto il martello.

entre deux petites pièces en forme de mâchoire qui sont placées à cet effet de chaque côté. Mais comme il était nécessaire que le marteau, ayant frappé la corde, la quitte instantanément – bien que le joueur n'ait pas encore quitté la touche – et que le marteau devait être immédiatement prêt à retourner en place, la languette qui donne l'impulsion est mobile et connectée de sorte qu'elle bouge vers le haut et frappe avec vigueur ; mais, ayant donné l'impulsion, elle se libère immédiatement, c'est-à-dire qu'elle retombe ; et quand tout est lâché, elle redescend, cède et revient, en se replaçant sous le marteau.

Questo effetto ha conseguito l'artefice con una molla di filo d'ottone, che ha fermata nella leva, e che distendendosi viene a battere con la punta sotto la linguetta, e facendo alquanto di forza la spinge, e la tiene appoggiata a un altro filo d'ottone, che ritto, e fermo le sta dal lato opposto. Per questo appoggio stabile, che ha la linguetta, e per la molla, che ha sotto, e per l'imperniatura, che ha dalle parti, ella si rende ora ferma, ed ora pieghevole, secondo il bisogno. Perchè i martelli ricadendo dopo la percossa non risallissero, e ribattessero nella corda, si fanno cadere, e posare sopra una incrociatura di cordoncini di seta, che quetamente li raccoglie.

L'inventeur a obtenu cet effet grâce à un ressort en fil de cuivre qu'il a fixé au levier et qui, en se détendant, frappe avec la pointe sous la languette, la pousse avec une certaine force et la tient pressée contre un autre fil de cuivre, qui se tient droit et ferme au côté opposé. Grâce à ce support ferme de la languette et grâce au fil qui se trouve en dessous, de même que par l'équilibre de l'ensemble, elle devient à un moment ferme et à un autre pliable, selon ce qui est requis. Afin que les marteaux, tombant en arrière après la frappe, ne remontent pas [une seconde fois] et de cette sorte ne refrappent la corde, ils sont conçus pour tomber et reposer sur de petites ficelles en soie [qui sont] croisées et qui les reçoivent sans faire de bruit.

Ma perchè in questa sorte di strumenti è necessario spegnere, cioè fermare il suono, che continuando confonderebbe le note che seguono, al qual effetto hanno le spinette il panno nelle cime de' salterelli; essendo anche necessario in questo nuovo strumento l'ammorzarlo affatto, e subito; perciò ciascheduna delle nominate leve ha una codetta, e sopra queste codette è posto un filare, o sia un registro di salterelli, che dal loro ufizio potrebbero dirsi spegnitoj. Quando la tastatura è in quiete, toccano questi la corda con panno, che han su la cima, ed impediscono il tremolare, ch'essa farebbe al vibrarsi dell'altre sonando: ma compresso il tasto, ed alzata da esso la punta della leva, viene per conseguenza ad abbassarsi la coda, ed insieme lo spegnitojo, con lasciar libera la corda al suono, che poi s'ammorza lasciato il tasto, rialzandosi lo spegnitojo stesso atoccar la corda.

Comme dans cette sorte d'instrument, il est nécessaire d'étouffer, c'est-à-dire d'arrêter le son, qui, en se prolongeant, brouillerait les notes suivantes, les épinettes [c.-à-d. les *pianoforte*] ont à cette fin du tissu à l'extrémité des sautereaux ; et il est également nécessaire dans ce nouvel instrument de l'amortir entièrement et immédiatement ; en conséquence, chacun des leviers cités précédemment a une petite extrémité, et sur ces extrémités est placée une rangée ou un registre de sautereaux, qui de par leur fonction, peuvent être appelés étouffoirs. Lorsque les touches sont au repos, ceux-ci touchent les cordes avec du tissu, qui se situe à leur sommet, et ils évitent la vibration qui serait causée par la frappe d'autres cordes ; mais lorsque la touche est enfoncée et la pointe du levier surélevée, l'extrémité est en conséquence abaissée, et avec elle l'étouffoir, de façon à laisser la corde vibrer librement, qui ensuite s'étouffe quand la touche est lâchée et que l'étouffoir lui-même remonte toucher la corde.

Ma per conoscere più chiaramente ogni movimento di questa macchina, e l'interno suo artifizio, si prenda per mano il disegno, e si osservia parte a parte la denominazione di esso.

Mais pour comprendre plus clairement chaque mouvement de ce dispositif et son mécanisme intérieur, laissons le lecteur examiner le dessin et observer la dénomination de chacune de ses parties.

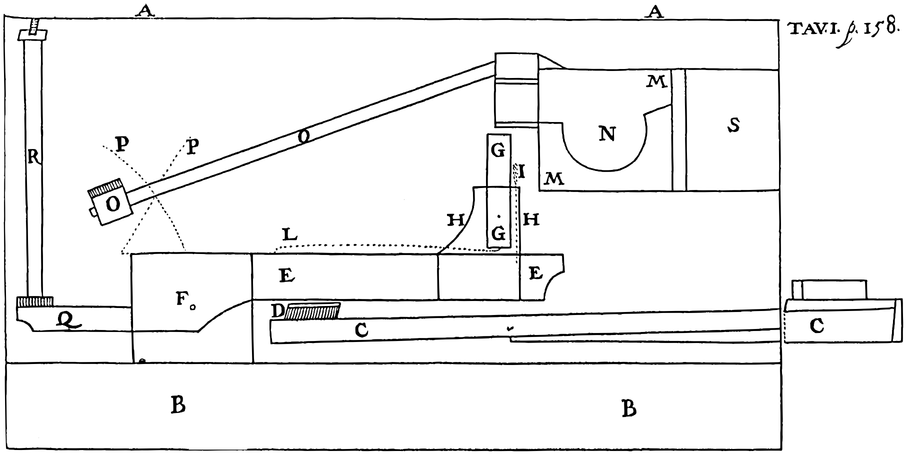

Figure 1 : Schéma de la mécanique de Cristofori. Scipione MAFFEI, « Nuovo invenzione d'un gravecembalo col piano e forte », *Giornale de' Letterati d'Italie*, 5 (1711), p. 158[43].

spiegazione del disegno

A. corda
B. telajo, o sia pianta della tastatura.
C. tasto ordinario, o sia prima leva, che col zoccoletto alza la seconda.
D. zoccoletto del tasto
E. seconda leva, alla quale sono attaccate, una per parte le ganasce, che tengono la linguetta.
F. perno della seconda leva.
G. linguetta mobile, che alzandosi la seconda leva, urta, e spinge in su il martello.
H. ganasce sottili, nelle quali è imperniata la linguetta.
I. filo fermo d'ottone schiacciato in cima, che tien ferma la linguetta.
L. molla di fil d'ottone, che va sotto la linguetta, e la tiene spinta verso il filo fermo, che ha dietro.
M. pettine, nel quale sono sequitamente infilati tutti i martelletti.
N. rotella del martello, che sta nascosta dentro al pettine.
O. martello, che spinto per di sotto dalla linguetta va a percuoter la corda col dante, che ha su la cima.
P. incrociatura di cordoncini di seta, fra' quali posano l'aste de' martelli.
Q. coda della seconda leva, che si abbassa nell'alzarsi la punta.
R. registro di salterelli, o spegnitoj, che,

explication du dessin

A. corde
B. cadre, ou support du clavier.
C. touche ordinaire, ou premier levier, qui soulève le second levier par le bloc.
D. bloc de la touche
E. second levier, aux extrémités duquel est attachée, de part et d'autre, une pièce en forme de mâchoire pour supporter la languette.
F. pivot du second levier.
G. languette mobile qui, lorsque le second levier monte, frappe et pousse le marteau.
H. pièces en forme de mâchoires entre lesquelles pivote la languette.
I. fil rigide de cuivre, replié au sommet, qui maintient la languette en place.
L. ressort de cuivre qui se loge sous la languette et la maintient fermement contre le fil qui se trouve derrière.
M. le récepteur, dans lequel les marteaux se logent à la suite l'un de l'autre.
N. partie circulaire du marteau, qui est caché dans le récepteur.
O. marteau qui, quand il est envoyé en l'air par la languette, frappe les cordes avec le daim à son sommet.
P. cordes en soie croisées, sur lesquelles les tiges des marteaux reposent.
Q. extrémité du second levier qui s'abaisse lorsque la pointe [c'est-à-dire l'extrémité de la touche] monte
R. registre de sautereaux ou étouffoirs, qui, la

[43] Les traces d'encre du schéma original ont été effacées, suite à quoi l'image a été vectorisée.

premuto il tasto si abbassano, e lasciano libera la corda, tornando subito a suo luogo per fermare il suono.
S. regolo pieno per fortezza del pettine.

touche étant enfoncée, s'abaissent et laissent la corde libre, retournant immédiatement à leur place pour arrêter le son.
S. partie du cadre qui renforce le récepteur.

Dopo di tutto questo è da avvertire, che il pancone, dove si piantano i bischeri, o piroli di ferro, che tengono le corde, dove negli altri gravecembali è sotto le corde stesse, qui è sopra, e i bischeri passano, e le corde vi si attaccano per di sotto, essendovi bisogno di più sito nel basso, affinchè v'entri tutta la macchina della tastatura. Le corde sono più grosse delle ordinarie, e perchè il peso non nocesse al fondo, non sono raccomandate ad esso, ma alquanto più alto.

Ensuite, il faut observer que la planche dans laquelle sont plantées les chevilles ou vis en fer qui tiennent les cordes, et qui dans les autres clavecins se situe sous les cordes, se trouve ici au-dessus ; les chevilles passent au travers, et les cordes y sont attachées par-dessous, car il faut plus de place dans les basses pour loger tout le mécanisme de la touche. Les cordes sont plus grosses qu'habituellement, et, afin que leur tension n'abime pas le fond, elles ne sont pas ancrées dedans, mais attachées un peu plus haut.

In tutti i contatti, che vale a dire in tutti i luoghi, dove si potrebbe generar rumore, è impedito con cuojo, o con panno; specialmente ne' fori, dove passano perni, è posto da per tutto con singolar maestria del dante, e il perno passa per esso. Quest'invenzione è stata dall'artefice ridotta ad effetto anche in altra forma, avendo fatto un altro gravecembalo pur col piano e forte con differente, e alquanto più facile struttura, ma nondimeno è stata più applaudita la prima.

En tout point de contact, c'est-à-dire à tous les endroits où pourrait apparaitre un bruit parasite, celui-ci est évité par du daim ou du tissu ; en particulier, dans les trous par lesquels les pivots passent, on a placé partout du cuir avec une singulière maîtrise et le pivot passe au travers. Cette invention a aussi été effectuée sous une autre forme, l'inventeur ayant fabriqué un autre clavecin avec le *piano* et *forte*, d'une forme différente et plus simple ; mais le premier a néanmoins été plus applaudi.

2 Rédaction de l'article

Le compte rendu de la rencontre avec Cristofori qui a servi à Maffei pour écrire son article est conservé à la Biblioteca Capitolare de Vérone[44]. Il s'agit de notes prises au vol, intitulées *Instromenti da suonare*, qui permettent de reconstituer en partie l'histoire de la rédaction de l'article du *Giornale*. Le manuscrit contient deux feuillets composés de trois colonnes de notes. Le premier reprend un texte relativement structuré, tandis que le second (Figure 2) est marqué par une plus grande discontinuité des notes. De toute évidence, une fraction d'entre elles ont été rédigées après l'entrevue des deux hommes.

[44] Verone, Biblioteca Capitolare, cod. dcccclx, fasc. vi, n.1. Le texte en italien et une traduction en anglais se trouvent dans Pollens, *The Early Pianoforte*, *op. cit.*, p. 232-237.

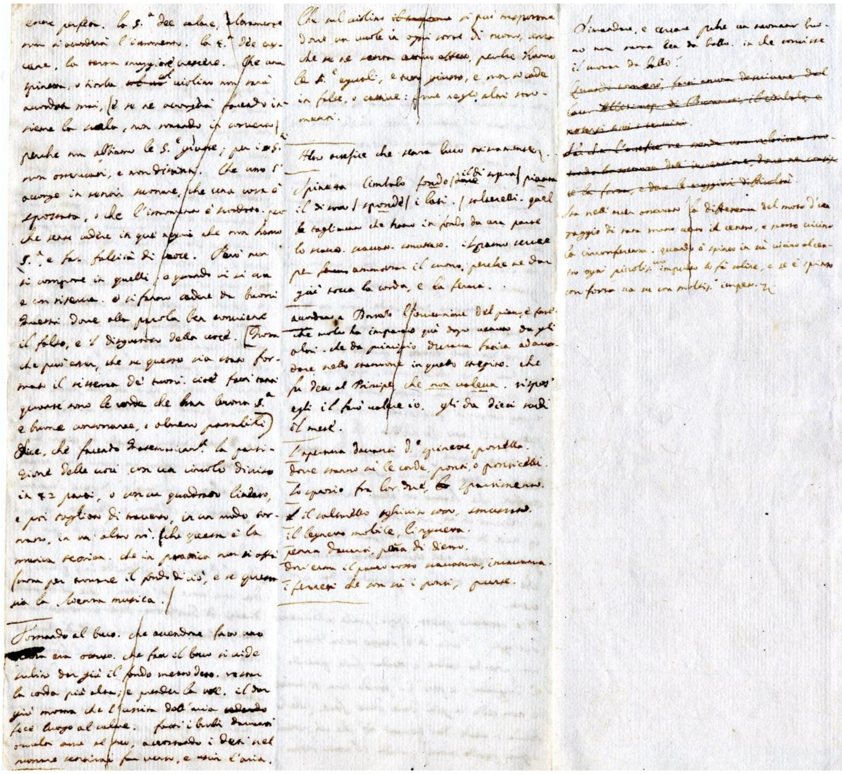

Figure 2: Second feuillet des notes intitulées *Instromenti da suonare* de Maffei, prises lors de son entrevue avec Cristofori. La colonne de droite comporte les annotations prises après leur entrevue. Vérone, BIBLIOTECA CAPITOLARE, cod. dccccclx, fasc. vi, n.1.

Conformément au titre donné au manuscrit, son contenu est consacré aux instruments de musique avec un éclairage particulier sur l'accord et les méthodes de construction des instruments à clavier de Cristofori. Vu l'importance de la partie consacrée au *pianoforte* dans l'article final, on pourrait s'attendre à une information exhaustive à ce propos dans les notes. Pourtant, parmi les quelque mille mots qui composent ses annotations, moins de cinquante sont dédiés avec certitude à la mécanique du *pianoforte*[45] (il s'agit des derniers paragraphes de la troisième colonne sur la Figure 2) :

> Cela provient d'avoir observé la différence du mouvement d'engagement de la noix vers le centre, et près de la circonférence. Lorsqu'il [le marteau] est poussé en haut vers le centre, la moindre impulsion le fait monter, et s'il est poussé avec force il monte avec beaucoup de pression. etc.[46]

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[45] Denzil WRAIGHT, « Recent Approaches in Understanding Cristofori's Fortepiano », *Early Music*, 34.4 (2006), p. 636.

[46] *Sta nell'aver osservato la diferenza del moto d'ingaggio di rota mosso verso il centro, e posto vicino la circonferenza. Quando è spinto in sù vicino al centro ogni piccoli.mo impulso lo fà salire, e se è spinto con forza va su con moltis.o impeto. ecc.*

Il est difficile d'imaginer qu'à partir de ces quelques mots, une personne qui n'est pas habituée à des systèmes mécaniques complexes puisse écrire un article comme celui du *Giornale*[47]. Le manuscrit contient deux autres notes qui permettent de se faire une idée du processus de rédaction du texte paru dans le journal littéraire. Ces notes, qui sont barrées, sont situées dans la dernière colonne du deuxième feuillet (Figure 2) et doivent avoir été écrites peu de temps après l'interview :

> Quand je reviens, je ferai décrire par le Cavalier Albisi, neveu de Buonarroti[48], le *cembalo* [*pianoforte*], et noter tous les termes.
>
> Faire [en sorte] que l'artisan rédige un document soulignant les substances de l'invention, où se trouve sa force, et où se situent ses plus grandes difficultés[49].

Le fait que les notes soient barrées ne signifie pas nécessairement que Maffei ait voulu s'attribuer les informations transmises en effaçant leurs origines, comme le soutient Laura Och[50]. Il pourrait s'agir plutôt d'une liste de choses à faire, notées après la rencontre. Maffei a pu biffer les différents paragraphes pour se souvenir que les tâches avaient été accomplies[51]. D'ailleurs, au-dessus de ces notes raturées en figure une autre qui rappelle à l'auteur de se renseigner sur les façons de jouer dans les bals. Cette note n'est pas barrée, et il n'est pas non plus question de musique de danse dans le texte final. Maffei aurait donc laissé tomber cette idée pour recentrer son article sur l'invention de Cristofori.

Nous pensons que Maffei a rencontré Cristofori afin d'alimenter un article à propos d'instruments de musique, mais en abordant le sujet de façon relativement vaste. Après avoir engagé la conversation sur le sujet de départ, Cristofori a dû donner des explications concernant la mécanique de son invention. On peut imaginer que l'inventeur ait voulu montrer ses instruments, plutôt que de les décrire en restant assis face à son interlocuteur. Il est possible que la prise de notes de Maffei ait été moins appliquée à ce moment, car le manuscrit contient des bouts de phrases indistincts concernant la morphologie d'instruments à clavier (2e colonne sur la Figure 2). Étant donné la concentration nécessaire pour comprendre le fonctionnement de la mécanique, Maffei n'aurait rien écrit pendant les explications et aurait en conséquence dû faire appel à des personnes externes pour les lui rappeler. Il aurait alors indiqué les actions à entreprendre à côté des notes de l'entrevue et tenté de transcrire les quelques éléments d'information qui lui seraient restés en mémoire. Dans son article, il laisse d'ailleurs planer le doute sur l'identité de l'auteur de la description :

> Si l'artisan qui l'a inventé avait aussi bien su comment décrire l'instrument que de le fabriquer, il n'aurait pas été difficile d'expliquer le mécanisme aux lecteurs ; mais comme il n'y est pas parvenu et

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[47] *Ibid.*
[48] Il s'agit probablement de Filippo Buonarroti, un nom souvent présent dans la correspondance de Maffei entre 1716 et 1724. Il est possible que l'amateur d'Antiquité classique, souvent cité comme *Senatore Buonarroti*, soit un ami d'enfance de Maffei. Laura OCH, « Bartolomeo Cristofori, Scipione Mafei e la prima descrizione del gravicembalo col piano e forte », *Il Flauto Dolce*, 14-15 (1986), p. 22, n. 55.
[49] *Quando tornerò, farsi ancora descrivere dal cav. Albisi, nepote di Buonarroti, il cimbalo, e notarsi tutti i termini.*
Far che l'artefice ne stenda una relazione notando la sostanza dell'inventione, dove ne consiste la forza, e dove la maggiori difficoltà.
[50] OCH, *op. cit.*, p. 19.
[51] WRAIGHT, « Recent Approaches in Understanding Cristofori's Fortepiano », *op. cit.*, p. 637.

> qu'il a estimé qu'il était impossible de le représenter de telle sorte qu'on puisse s'en faire une idée, il faut que quelqu'un d'autre s'y attelle, bien que je ne dispose plus de l'instrument devant les yeux, mais seulement de quelques notes réalisées en l'examinant et d'un modèle dessiné grossièrement à ce moment-là.

Bien que Maffei semble se désigner lui-même comme auteur de cette description, il est plus probable qu'il ait sollicité l'aide du *Cavalier Albisi* afin de compléter ses notes lacunaires. En effet, au moins deux membres de la famille Albizi ont gravité autour du duc et de son facteur d'instruments. Le conseiller principal de Ferdinando était le *Marchese Luca degl'Albizi* dont les comptes relatent qu'il était rétribué ponctuellement pour des transcriptions de partitions musicales[52]. Les testaments de Cristofori font également état d'un certain *Cavaliere Cosimo Albizi*. Quoi qu'il en soit, il est étonnant que Maffei ait envisagé de demander à une autre personne que Cristofori d'expliquer son invention. Il n'est pas impossible que l'écrivain ait fait appel aux connaissances techniques du *Cavalier Albisi* pour rédiger sa description. Wraight envisage plutôt la possibilité que, si la requête de Maffei avait bien été transmise à Albisi, ce dernier ait agi pour que la demande soit directement sous-traitée à Cristofori[53].

En recoupant les éléments qui figurent dans les notes manuscrites et l'article, on se rend compte que Maffei a procédé à une vérification précise du contenu qu'il a introduit dans son texte final. Ce phénomène ressort particulièrement dans la dernière partie de celui-ci, qui, comme on a vu plus haut, ne porte pas sur le *pianoforte* mais sur des questions d'accords et de tempéraments. En effet, chaque paragraphe biffé y est repris, parfois mot à mot. Les parties des notes qui sont laissées intactes concernent soit des conseils de Cristofori pour réparer un instrument de Maffei, soit la matière que Maffei a visiblement moins bien assimilée (ces parties sont marquées de nombreuses ratures). En tout état de cause, l'article final apparait ainsi comme une synthèse de plusieurs textes, dont le style a été harmonisé par Maffei.

Une telle compilation représente un témoignage encore plus précieux qu'un article dont Maffei serait le seul auteur. La première partie est une formulation de première main du sentiment de l'inventeur face à son instrument et à sa réception. Les éloges à son égard pourraient avoir été ajoutés par Maffei qui, au vu de la place qu'occupe l'*arpicembalo* dans son article, semble conquis par l'inventeur et sa création. Le fait qu'aucun brouillon du schéma de la mécanique ne figure dans les notes de l'interview est un argument supplémentaire qui nous mène à penser que la description n'a pas été fournie directement par Maffei, mais bien par Cristofori ou par le biais du *Cavalier Albisi*[54]. Quant à la dernière partie,

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[52] Michael Kent O'BRIEN, « Bartolomeo Cristofori at Court in Late Medici Florence », *op. cit.*, p. 53.

[53] Denzil WRAIGHT, *Differences between Maffei's article on Cristofori's piano in its 1711 and 1719 versions, their subsequent transmission and the implications*, p. 12, version 1.3 du 19/12/2015, http://www.denzilwraight.com/Maffei.pdf (page consultée le 20/12/2015). Nous remercions Denzil Wraight d'avoir attiré notre attention sur l'identité du *Cavalier Albisi* et d'avoir partagé sa version des faits (communication personnelle avec Denzil Wraight du 06/12/2015 et du 07/01/2016). Par ailleurs, Wraight souligne à quel point il est étrange qu'après avoir tant loué les qualités de Cristofori, l'article mette en doute les capacités du facteur à expliquer le fonctionnement de ses instruments. Wraight estime probable que Cristofori ait explicitement cherché à décourager la divulgation des détails de son invention en prétextant à Maffei que l'explication de son fonctionnement serait trop ardue. Cette réticence pourrait être expliquée par la forte concurrence qui régnait entre facteurs d'instruments. *Ibid.*, p. 10.

[54] Wraight considère qu'il est normal de ne pas retrouver de dessin de la mécanique dans les notes ; l'article de Maffei aurait suivi un procédé éditorial classique dans lequel le graveur ne lui aurait pas renvoyé l'original de

qui traite du sujet initialement prévu et auquel le sous-titre de l'article final fait référence, Maffei a pu l'écrire en grande partie à l'aide de ses notes prises lors de sa rencontre avec Cristofori et l'a complété d'informations puisées auprès d'autres personnes qui ont permis d'éclaircir et d'illustrer les points moins précis de ses notes.

Dans cette version des faits, tant Cristofori que Maffei sont gagnants : le premier parce qu'il peut diffuser son invention et répondre aux critiques sous le nom d'un auteur de renom, le second parce qu'il n'a qu'à reformuler un article susceptible d'intéresser un cercle d'érudits[55].

3.3 Explication de la mécanique

La seconde partie de l'article de Maffei explique le fonctionnement de la mécanique de Cristofori. Sa compréhension est grandement facilitée par le schéma que l'auteur dit avoir dessiné de mémoire, quelque temps après son entretien avec l'inventeur[56]. Au vu de ce schéma, la disproportion des éléments de la mécanique semble évidente. Cet effet est principalement dû à la représentation de la touche qui n'est pas dessinée dans sa totalité[57]. L'ensemble procure dès lors un aspect massif à une mécanique qui était plus que probablement légère et délicate. En se basant sur les dimensions des *pianoforte* qui nous sont parvenus, il est possible de réaliser un schéma qui représente la mécanique dans des proportions plus réalistes (Figure 3)[58].

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son dessin après la mise sous presse. Wraight, *op. cit.*, p. 12. Nous sommes d'avis que Maffei, ou tout autre dessinateur, a forcément dû s'y prendre à plusieurs reprises avant d'obtenir une version satisfaisante de son dessin et qu'en conséquence, il aurait dû au moins esquisser en quelques traits l'aspect de sa mécanique dans ses brouillons. Cette version des faits n'exclut toutefois pas la possibilité que ces brouillons n'aient pas été conservés avec les feuillets manuscrits.

[55] Eleanor Selfridge-Field, « The Invention of the Fortepiano as Intellectual History », *Early Music* 33.1 (2005), p. 87-88.

[56] Jusqu'à l'ère de la numérisation de notre patrimoine littéraire, il n'était pas donné à tout le monde de consulter l'article original du *Giornale*. En conséquence, les transcriptions du schéma varient d'un auteur à l'autre. Cette thématique est étudiée en profondeur dans Denzil Wraight, *op. cit.*

[57] Le fait que la mécanique soit représentée de façon raccourcie est sans doute lié aux contraintes de mise en page de la revue. Si Maffei avait décidé de représenter la touche dans sa totalité, il n'aurait pu illustrer avec autant de détails la partie de la mécanique qui est réellement intéressante.

[58] La présente illustration est largement inspirée de Michal Cole, *The Pianoforte in the Classical Era*, Oxford : Clarendon Press, 1998, p. 7. Les annotations et les éléments colorés sont dus à nos soins. Outre la reconstitution proposée par Michael Cole, il existe une version qui suit de plus près le schéma de l'article au département des instruments de musique de la *Galleria dell'Accademia* à Florence, n. 1988/103 Cherubini.

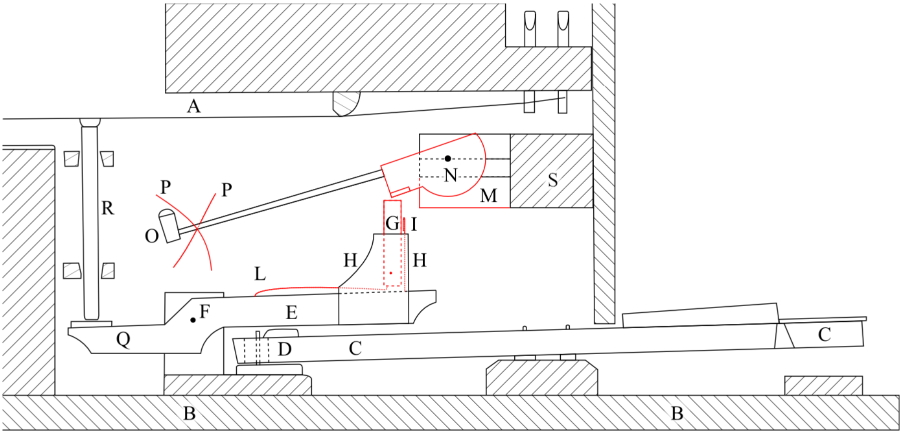

Figure 3: Reconstitution de la mécanique de l'article du *Giornale* adaptée d'après, COLE, *The Pianoforte in the Classical Era*, p. 7.

Maffei décrit avant toute chose l'élément le plus novateur de l'instrument en le comparant à ce qui existait jusque-là : les cordes sont actionnées par des marteaux (*martelli*) au lieu de sautereaux (*salterelli*). Il ne s'agit pas de la première fois qu'on appelle l'élément percussif de la mécanique par le nom qui nous est désormais familier. Maffei semble ici confirmer l'usage du terme déjà rencontré dans l'inventaire de 1700, ce qui pourrait indiquer que Cristofori l'ait approuvé, voire proposé dans le cadre d'un instrument de musique. Le dessin de Maffei suggère une construction des marteaux semblable à ceux de l'instrument de 1720. Les deux éléments rectangulaires entre le marteau et « l'élément circulaire du marteau » (c'est-à-dire la noix, N sur les Figures 3 et 4) forment la saillie qui transmet le mouvement de la languette au marteau. En conséquence, les trois éléments précités forment un assemblage qui pivote autour d'un point fixe (approximativement situé en N sur les Figures 3 et 4). L'interprétation logique de ces éléments est visible à la Figure 3. L'article du *Giornale* signale par ailleurs que les marteaux ainsi que leur noix sont logés dans un rail commun appelé « récepteur » ou « peigne » (M sur la Figure 4). De toute évidence, l'analogie au peigne fait référence aux dents entre lesquelles viennent se loger les noix des marteaux.

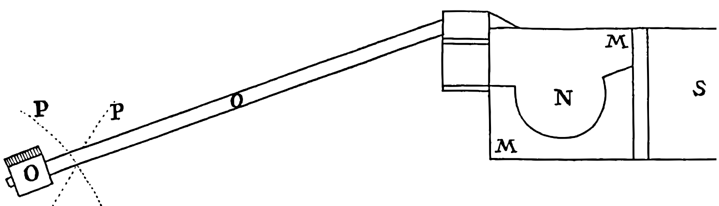

Figure 4 : Détail du marteau et de son logement selon l'article du *Giornale* : les deux formes rectangulaires entre le marteau (O) et la noix du marteau (N) logé dans les peignes (M) correspondent à l'excroissance qui transmet le mouvement de propulsion depuis la languette.

L'auteur des explications de la mécanique semble avoir été conscient du paramètre crucial qu'est la vitesse du marteau dans les claviers à cordes frappées. Il explique que Cristofori a conçu sa mécanique de sorte que le mouvement de la languette (G) soit transmis près du centre de rotation du marteau, profitant de cette sorte d'un effet de levier avantageux. Grâce au positionnement ingénieux des points de pivots et à la succession de trois leviers, la mécanique propose un effet multiplicatif intéressant de la vitesse du marteau[59]. Maffei précise par ailleurs que même avec une faible impulsion de la touche, l'instrument produit un son. On peut en conclure que le marteau doit échapper très près des cordes, à environ 2-3 mm, de sorte qu'il possède suffisamment d'inertie pour frapper les cordes en vol libre, même s'il n'a pas été actionné avec force[60].

Outre l'effet de démultiplication de la vitesse, un élément-clé des mécaniques de frappe est le phénomène d'échappement, qui fait en sorte que « le marteau, ayant frappé la corde, la quitte instantanément ». L'échappement correspond à la languette (G) qui peut pivoter autour d'un axe fixé entre deux pièces « en forme de mâchoire » (H). Le fait de surélever l'échappement par rapport au second levier lui permet de tourner librement autour de son axe, sans que les extrémités inférieures de la languette ne touchent le levier auquel elle est attachée. Le maintien de l'échappement en position d'équilibre est assuré selon les mêmes principes que dans une mécanique de piano à queue moderne : d'un côté un fil de cuivre fait office de ressort de rappel, de l'autre côté une butée faite du même matériau limite le mouvement engendré par le ressort[61]. Notons que le bon fonctionnement du dispositif requiert que le ressort de cuivre soit en contact avec la languette à gauche de son point de rotation[62]. La position relative entre la saillie du marteau et la languette est le paramètre qui va influencer le moment auquel le marteau échappe.

Suite à l'enfoncement de la touche, le mouvement de rotation des leviers a pour conséquence de diminuer la surface de contact entre les pièces précitées, jusqu'au moment où le marteau vole librement vers les cordes. Juste après l'avoir frappée, le marteau rebondit sur la corde et est recueilli silencieusement par deux fils de soie entrecroisés qui empêchent une seconde impulsion du marteau ; Cristofori a inventé l'attrape. Il est intéressant de noter que ce système rudimentaire mais ingénieux n'est plus utilisé sous cette forme dans ses pianos plus tardifs. Si la touche est maintenue enfoncée, la saillie du marteau vient se loger contre la languette (G) qui pivote dans le sens inverse des aiguilles d'une montre. Au moment où la touche est relâchée, le ressort permet à la languette de se remettre en place contre la butée.

À l'extrémité gauche de la mécanique, on trouve un système d'étouffoirs semblable aux sautereaux d'un clavecin, mais qui étouffe la corde par le bas. Il se présente sous la forme

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[59] COLE, *op. cit.*,p. 7. Michael Cole obtient un rapport multiplication de 10 entre la vitesse de la touche et du marteau. Une étude cinématique sommaire de son schéma donne néanmoins un rapport de 6,5.
[60] *Ibid.*, p. 6.
[61] C'est le plus grand problème que posent les diverses reproductions modernes du schéma : parfois, les deux ressorts sont reliés, parfois ils ne sont pas fixés au même point d'application et l'on observe des variations dans leur forme. L'ambiguïté de la position de ces deux éléments sur les schémas des reproductions de l'article de Maffei vient probablement du fait qu'on peut facilement attribuer une fonction de ressort à la butée, bien que l'auteur de l'article spécifie que ce fil de cuivre se tient « droit et ferme ».
[62] S'il était placé à droite, la languette tournerait dans le sens inverse des aiguilles d'une montre et s'écarterait de sa butée (Figure 2 et 3).

d'un bout de tissu, probablement rouge à en croire l'inventaire de 1700, collé à la face supérieure du « sautereau » (R). Au repos, le tissu est en contact avec la corde et empêche toute vibration. En enfonçant la touche, la partie gauche du second levier (Q) descend et entraine ledit sautereau vers le bas. Maffei propose de l'appeler *spegnitoj*.

Une autre particularité intéressante que l'on n'observe dans aucun instrument antérieur[63], est l'inversion de la fixation des cordes : Cristofori les tend en les fixant au bas de chevilles qui passent au travers du sommier. Cette disposition particulière serait justifiée par l'encombrement de la mécanique utilisée dans les notes graves, ce qui peut laisser supposer que Cristofori adaptait déjà la taille de la mécanique et en conséquence de ses marteaux au registre auquel il correspondait. Il n'applique toutefois pas systématiquement cette inversion de la fixation des cordes à tous ses instruments.

Conclusion

Il n'est plus à prouver que la collection d'instruments de musique attribués à Cristofori recèle des pièces qui illustrent tout son génie d'inventeur. Toutefois, ne pas prendre en compte les quelques témoins écrits de son œuvre reviendrait à passer à côté d'une grande partie de sa carrière. Lorsque Maffei rencontre Cristofori, ce dernier a déjà atteint la cinquantaine et a acquis une expérience considérable. L'étude des manuscrits qui témoignent de cette entrevue peut en conséquence nous offrir une belle perspective de son œuvre.

On peut affirmer sans hésitation que Cristofori a construit au moins un *gravicembalo* en 1700. Tant la complexité de l'invention, que le désir évident de perfectionner ses inventions impliquent que son *pianoforte* n'a pu être créé dans l'espace de quelques mois à peine. Outre la mécanique qui constitue la partie la plus complexe et innovante, son utilisation requiert une tension des cordes plus élevée et nécessite en conséquence des développements particuliers de la caisse du clavecin. La dénomination variable des premiers *pianoforte* du facteur padouan et son désir de faire valoir son timbre propre laisse penser que la motivation du facteur dans était de produire un instrument tout à fait neuf, mais qui héritait de divers avantages d'autres instruments.

Au travers de l'article de Maffei, et plus encore grâce aux notes prises lors de sa rencontre avec Cristofori, ce dernier se présente comme un inventeur mal compris des musiciens à qui on offre l'opportunité de défendre son invention. Ainsi, il évoque dans l'article du *Giornale* des professionnels qui n'ont pas su apprécier à sa juste valeur son instrument. De même, lors de son entrevue avec Maffei, il revient à deux reprises sur la forme des ouïes du clavecin, pour laquelle il se montre en désaccord total tant avec les anciens facteurs qu'avec ses contemporains.

Il est difficile de mesurer l'impact qu'eut la publication de Maffei, mais il est certain qu'elle revêtait, aux yeux de son auteur, une valeur telle qu'elle méritait d'être publiée une seconde fois. Du reste, on suppose que la version allemande traduite par le poète de la cour de Dresde

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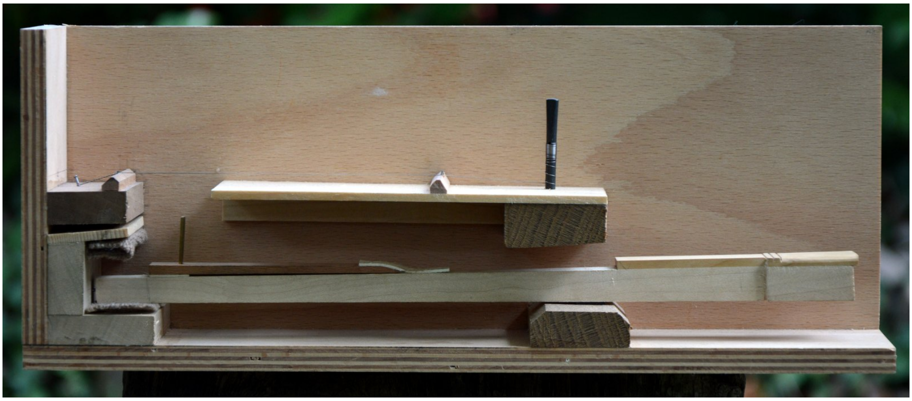
[63] *Ibid.*, p. 8.

Johann Ulrich König a grandement inspiré Gottfried Silbermann dans l'élaboration de ses instruments, vu qu'ils comportent des mécaniques similaires à celles du facteur italien.

Les *pianoforte* survivants de Cristofori ont été fabriqués plus d'une décennie après la rédaction de l'article, les premiers pour lesquels on garde une trace écrite sont antérieurs d'une petite décennie. Si les trois pianos conservés sont de solides témoins de l'évolution des instruments de Cristofori, l'article de Maffei démontre avec une force égale cette quête du progrès. L'auteur conclut la description technique de l'instrument par une phrase dans laquelle il affirme que « cette invention a aussi été effectuée sous une autre forme, l'inventeur ayant fabriqué un autre clavecin avec le piano et forte, d'une forme différente et plus simple ; mais le premier a néanmoins été plus applaudi ». Cristofori était peut-être conscient du fait que sa mécanique était trop complexe pour être répandue à grande échelle. Il semble avoir voulu la simplifier pour finalement arriver à la conclusion que chaque élément de son invention était primordial pour donner toute son expressivité aux *cembali* qu'il construisait. Il faudra près d'un siècle pour que ses successeurs reproduisent ce schéma de simplification puis de complexification qui les mènera à la même conclusion.

Appendix E

Arnaut de Zwolle



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B. Bokiau, A.-E. Ceulemans and P. Fisette. ‘Multibody dynamics as a tool for historical research. Study of an 18th century piano action of Johann Andreas Stein’. In: *Multibody System Dynamics* 37.1 (2016), pp. 15–28.

B. Bokiau, A.-E. Ceulemans and P. Fisette. ‘Historical and dynamical study of piano actions: A multibody modelling approach’. In: *Journal of Cultural Heritage* (2016). In Press, Corrected Proof (available online 25 May 2016).

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