Application and Validation of a Linear Electromagnetic Actuator within a Haptic Piano Keyboard

Abstract — Using a linear actuator in a digital keyboard allows to reproduce the touch of an acoustic piano action. Our work consists in the design of a one-key prototype actuated by a linear electromagnetic voice coil. A presizing step along with a Finite Element Method analysis produced a custom-made actuator satisfying the design requirements, in particular the touch dynamics performances.

I. Introduction

To finely master his playing, a pianist refers to an essential sensory information called the touch. Present-day digital keyboards offer the possibility to nuance the sound thanks to simplified mechanisms. However, the result is far from reproducing the dynamics of the actions equipping traditional acoustic pianos.

Several attempts have been made to create a force feedback that renders the feeling of touch. The characteristics (size, power, dynamics, and price) of the desired actuator corresponds closely to a hard disk drive voice coil, as used by Gillespie [1] for his prototype. Very different, the magneto-rheological fluids of Lozada [2] create a resistant force that damps the pianist movement.

The actuator designed in our work is a custom-made voice coil, composed of permanent magnets and a coil attached to the piano key on which the actuator force is acting. Horvath [3] proposed something very similar, focusing mainly on a detailed study of the magnetic field.

II. Haptic piano keyboard

The prototype (Fig. 1) is built from one single piano action model, where the designed actuator replaces the piano action. Based on the key kinematics captured by position sensors, the embedded controller computes in real-time the corresponding force to be applied to the key by the actuator.

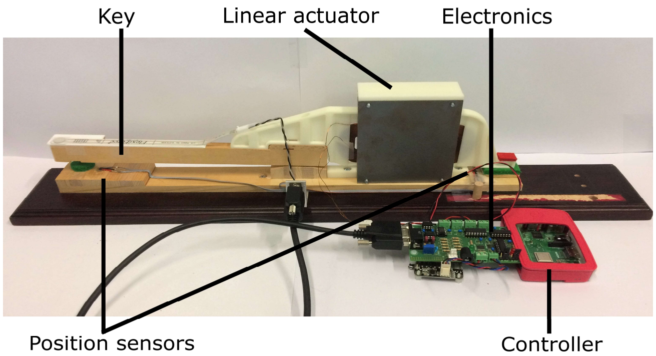

Fig. 1: Haptic piano key prototype

III. Linear actuation design

A linear voice coil actuation produces a vertical force – proportional to the current in the coil –, which can reproduce the very high dynamics of a piano action.

Starting the design process, an optimization based on an analytical magnetic model aimed at minimizing the electrical power due to Joule's losses for a specific force profile to apply. The height and width of the coil have been optimized under two constraints: the size should not exceed the key width (magnets included) nor the action height; the mass stays below 0.075 kg such that the key inertia is preserved.

In order to verify the presizing, a Finite Element Method (FEM) took other effects into account (magnetic saturation, edge effect) and validated the solution of the optimization. Globally, the actuator force $F_{actuator}$ is able to follow the required output $F_{required}$ both in amplitude and in dynamics (Fig. 2). Two force profiles were considered. The difference between the red and the blue curves is due to the coil dynamics:

$$F_{required} = F_{actuator} + m_{coil}\,(\ddot{q} + g)$$

where $\ddot{q}$ is the coil acceleration, g the gravity constant and m_{coil} is the coil mass.

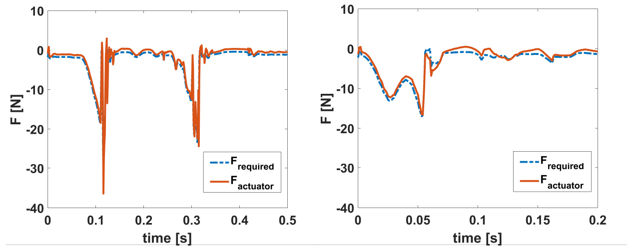

Fig. 2: Results for two considered force profiles after FEM simulations

IV. Actuator Validation

Measurements provide values (TABLE I) that appear to be close between the three design steps: presizing, FEM and experiments. However, some noticeable differences are present: the coil is lighter; the electrical resistance was underestimated; the inductance value seem to vary substantially; the small difference in the force constant is probably due to imprecision in measurements.

TABLE I
MAIN PARAMETERS OF THE ACTUATOR

Parameters [units]	Presizing	FEM	Experiments
Coil mass [kg]	0.070	0.066	0.065
Resistance [Ω]	10.78	10.68	12.6
Inductance [mH]	/	10.32	7.3
Force constant [N/A]	32.7	33.7	35.72

Thanks to the proposed approach, the voice coil designed answers to the problem requirements, especially in term of dynamics of the action and the speed. However, the final design is oversized and can be reduced. Even for a very demanding force profile, the power dissipated stays below 0.22 W, which will not cause overheating risks on the coil.

V. Outcomes

For the next steps, the actuator will be validated more precisely. The application within a haptic piano keyboard will also be discussed in more details.

VI. References

[1] B. Gillespie, "Touch Back Keyboard", in Proceedings of the International Computer Music Conference, 1992.
[2] J. Lozada et al., "A novel haptic interface for musical keyboards", in IEEE/ASME international conference on advanced intelligent mechatronics, pp.1-6, 2007.
[3] P. Horváth. "Towards to Haptic Keyboard: Modeling the Piano Action", in Mechatronics. Recent Technological and Scientific Advances. Springer, pp.49–55, 2013.