Int. Conf. on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2007
M. Papadrakakis, E. Oñate and B. Schrefler (Eds)

MULTIPHYSICS MODELING OF MECHATRONIC MULTIBODY SYSTEMS: APPLICATION TO VEHICLE DYNAMICS

N. DOCQUIER[*1], M. DELANNOY[*], L. SASS[†] AND P. FISETTE[*]

[*]Center for Research in Mechatronics (CEREM)
Université catholique de Louvain
Plcace du levant, 2, B-1348 Louvain-la-Neuve, Belgium
e-mail: info@cerem.be, web page: http://www.cerem.be

[†]Colegio Politecnico
Universidad San Fransisco
Campus Cumbayá- Diego de Robles y Vía Interoceánica, Quito, Ecuador
e-mail: laurents@usfq.edu.ec

Key words: Multibody, Multiphysics, Dynamics, Vehicles

1 INTRODUCTION

Modeling mechatronic multibody systems requires the same type of methodology as for designing and prototyping mechatronic devices: a unified and integrated engineering approach. Various formulations are currently proposed to deal with *multiphysics* modeling, such as linear and bond graph theories, equational approaches and co-simulation techniques (see section 2). In previous CEREM research works (ex. [1] for the case of electromechanical multibody systems), it was objectively pointed out their relative advantages and disadvantages, depending on the application to be dealt with. With this respect, the present contribution aims at showing that, for industrial mechatronic systems, a so-called "equational" approach based on multibody dynamics formulation can be generalized to deal with *strongly* or *weakly* coupled multiphysics applications. Vehicle dynamics analyses will be presented, for which a real coupling problem was identified and thus modeled with the proposed multibody approach.

2 MODELING OF MULTIPHYSIC SYSTEMS

Unified modeling of mechatronic applications with strongly coupled mechanical, electrical, hydraulic, or thermic effects can be achieved using different approaches, among which: the linear graph theory, the bond graph theory and a so-called "equational" formulation. A short overview of these methods is proposed in this section.

[1]FNRS Research Fellow

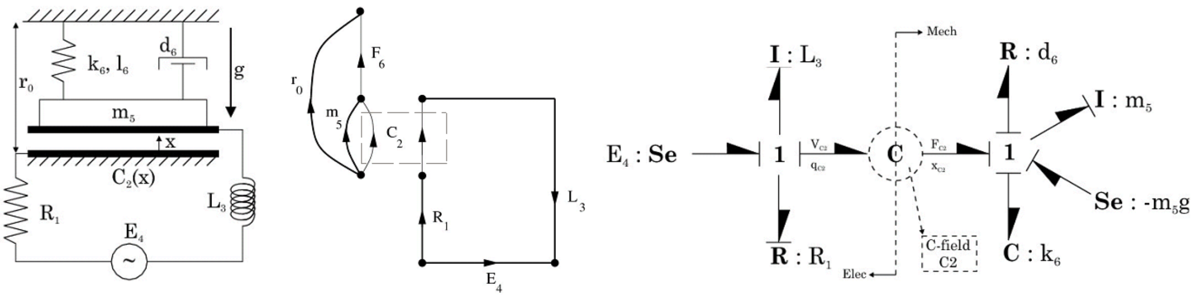

Figure 1: A loudspeaker electromechanical model (left), its linear graph (center) and bond graph (right) representations

2.1 Linear and Bond graph approaches

The Linear graph theory is a branch of mathematics devoted to the study of systems topology. It was invented by L. Euler in the 1700s to study problems of connectivity and was extended in the 1900s to the modeling of physical systems: individual components are identified and their constitutive equations are determined (theoretically and/or experimentally). In these equations, one distinguishes the so-called *through* variables (measured by an instrument in series with the component) from the *across* variables obtained by an instrument in parallel.

Fig. 1 illutrates an example of linear graph (center) representing the electromechanical model of a loudspeaker (left), made of a variable capacitor connected in series with a resistor, an inductor and a voltage source (electrical part) and linked, on the other side, with a spring-damper system (mechanical part). Without going into details, linear graph components are of two types : "storage" if they are able to store energy or "dissipation" if they dissipate energy. Using the Linear graph rules, the dynamic equations — of simple systems — can be derived from the graph for the global system in a straightforward manner.

Bond graphs are more recent. They have been introduced by H.M. Paynter in 1959 and published in 1961 [3]. Bond graphs are based on the notion of energy whose exchange between components and with the environment is done via "interactive ports" which involve two scalar variables: a *flow*-type and an *effort*-type. Their product represents the instantaneous transmitted power.

A bond graph is obtained by the interconnection of *junctions* and *elements* by means of *bonds* [2], according to the system topology. Contrary to linear graphs (see figure 1), a bond graph does not bear much resemblance to the physical system but actually indicates the structure through which energy is exchanged. This can be of interest to visualize online the instantaneous transmitted power between components and between domains.

State equations can be obtained from the graph and their input/ouptut formulation can be chosen because Bond graph are intrinsically acausal.

Graph theories and multibody dynamics: Several authors have extended the concept of linear graph and bond graph to multibody systems ("MBS"). According to the comparison study presented in [1], the linear graph is more appropriate in that case, and it is noticeable that the topological analysis automatically solves the kinematic problem (ex. closed loops, etc.). In [5], it is also demonstrated the relevance of the linear graph method in electromechanics. The main interest of linear and bond graph methods consists in using analogies between sub-domains via the use of *power* variables. However, in case of systems involving complex mechanics (3D MBS with specific constraints), the formulation of the equations is far from being optimal in terms of efficiency, unless a post-process is used to simplify them via the resort to recursive techniques, symbolic manipulations, etc.

2.2 Equational approach

Let us consider the field of electromechanical (multibody) systems. Using the Lagrange formulation (which, in fact, can be deduced from the Virtual Work Principle), it is shown in [1] that the Lagrange equations of the *electromechanical* system reads:

$$\frac{d}{dt}\left(\frac{\partial L_{em}}{\partial \dot{s}}\right) - \frac{\partial L_{em}}{\partial s} - \Gamma = 0 \tag{1}$$

where: $L_{em} = L_m + L_e$ represents the "electromechanical" Lagrangian,
$s = (s_m,\ s_e)$ represents the mechanical and electrical generalized coordinates,
Γ are the mechanical and electrical applied "generalized forces".

From the computer implementation point of view, modern multibody formalisms using recursive approaches and relying on advanced techniques (symbolic generation, coordinate partitioning, parallel computation, etc.) allow us to produce the above dynamic equations for complex systems (ex. full vehicles) in a very compact form (in terms of arithmetical operations). In case of *multiphysic* multibody systems (i.e. involving other domains like electrical actuation, hydraulic circuits, etc.), similar techniques can be used to generate a fully coupled system of differential/algebraic equations describing the system dynamics, exactly as when using the above-mentioned graph theories, but without being limited to "academic problems".

3 APPLICATIONS

The three multiphysic industrial applications in the field of vehicle dynamics depicted in Fig. 2 have been carried out by the CEREM. Those studies identify real coupling problems modeled with a multibody-based equational approach.

- The first one consists of an Audi A6 equipped with a semi-active hydraulic suspension. This analysis aims at improving by optimization the passenger comfort (measured by the vertical rms acceleration) and the car handling (measured by the road-tire force).

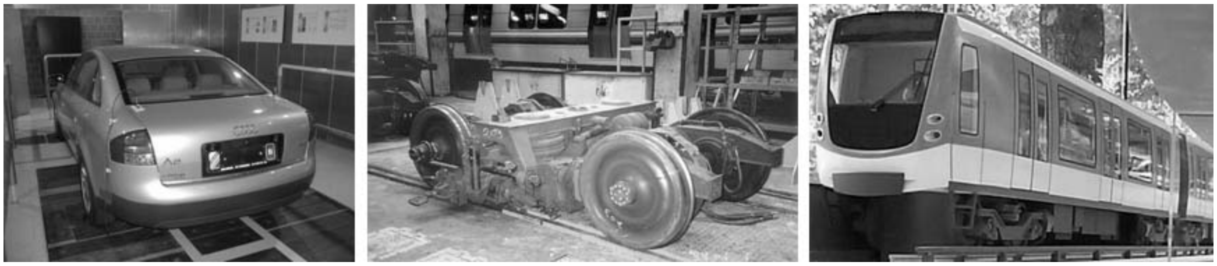

Figure 2: a car with semi-active suspensions (left), electrical actuation of an articulated bogie (center), a railway vehicle with pneumatic secondary suspensions (right)

- The second one illustrates an articulated bogie actuated by two three-phase induction motors. The goal was to check whether the torque oscillations of the electrical motors could lead to mechanical fatigue in the chassis.
- The third one deal with railway vehicle equipped with pneumatic suspensions. For instance, undesired pneumatic valve openings could lead to spurious oscillations of the carbody.

A strongly coupled model for the two first applications has been established while a co-simulation approach has been used for the last one. Those applications will be presented in further details during the oral presentation.

4 Acknowlegments

Nicolas Docquier is supported by the Fonds de la Recherche Scientifique - FNRS.

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