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Research paper

Multibody system dynamics interface modelling for stable multirate co-simulation of multiphysics systems

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ABSTRACT

Many industrial applications benefit from predictive computer simulation to reduce costs and time, and shorten product development cycle. Computational multibody system dynamics formalisms and software tools have proved to be particularly useful in the simulation of machinery and mechanical systems. Nowadays, however, the complexity of the applications under study often makes it necessary to consider the interaction of mechanical systems with other components of different nature, physical behaviour, and time scale, such as hydraulics or electronics. Co-simulation is an increasingly important approach to formulate and solve the dynamics of these multiphysics setups. In these, modelling techniques and solvers that are tailored to the requirements of each subsystem execute in parallel and are coupled via the exchange of a limited number of inputs and outputs at certain communication times. Co-simulation has clear potential in the modelling of complex engineering systems. On the other hand, there are also challenges. The use of co-simulation may compromise the stability of the numerical solution, especially when non-iterative coupling schemes are used.

In this work, we introduce a modelling technique to improve the dynamic interfacing of mechanical systems in co-simulation setups, based on a reduced representation of multibody systems. This reduced order model is used to obtain a physically meaningful prediction of the evolution of the multibody subsystem dynamics that enables the improvement of the solution of other subsystems. The technique is illustrated in the co-simulation of some examples that include both mechanical and hydraulic components. Results show that dynamic interfaces based on reduced models can be used to improve the stability of non-iterative co-simulation schemes in multiphysics engineering systems, enabling the use of larger communication step-sizes.

1. Introduction

Computer simulation of mechanical systems has reported significant benefits to industry during the last decades, shortening product development cycles and reducing the costs associated with testing, validation, and re-design of new products. In particular, advances in multibody system (MBS) dynamics research have enabled the use of realistic models of complex,

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large-scale mechanical systems in demanding simulation environments, e.g., those that require real-time execution. Nowadays, various methods exist for the effective simulation and analysis of multibody systems [1,2], and a large array of software tools have been developed to carry out this task. However, there is increasing practical demand to couple multibody simulation to models of subsystems of other physical domains, such as hydraulics and electronics. The individual subsystems in such multiphysics settings can have quite different properties, and may require the use of different solvers and time scales.

The modelling and simulation of multiphysics systems can be approached in several ways. A possibility is to define an all-encompassing set of equations that describes the response of every element in the system [3]. This technique is sometimes referred to as *monolithic simulation*. Another increasingly important option is the coupling of different domain-specific solvers in a *co-simulation* setup. This makes it possible to use modelling and solution techniques tailored to the requirements and time-scale of each subsystem. The numerical integration of the subsystems is coordinated via the exchange of input and output quantities at certain communication points in time. Such an approach makes it possible to use domain-specific tools to model each component; moreover, these can often be executed in parallel, reducing the wall-clock time elapsed in computations. Multirate integration can also be used in this case, adjusting the step-size in each subsystem to its particular time-scale [4]. The simulation of a vast range of multiphysics systems can be addressed this way. To achieve this, a large number of partition methods, communication strategies, and time-stepping approaches can be found in the literature [5,6].

In spite of its advantages, co-simulation poses a series of challenges that need to be addressed to obtain reliable and robust code execution. The co-simulation of dynamic models requires common interface definitions to facilitate the exchange of information between subsystems. This issue has been tackled with the introduction of standards like the Functional Mock-up Interface (FMI) [7]. Another major problem stems from the fact that solvers in a co-simulation environment receive information from other subsystems in discrete time. Inter-solver information exchange occurs only at discrete communication points, at which subsystems are synchronized; the time interval between two communication points is usually referred to as *macro time-step*. This inherently introduces coupling errors and discontinuities in the system dynamics, sometimes making it difficult to guarantee that the integration proceeds in an accurate or stable way [8]. This problem can be alleviated adopting iterative coupling schemes [9]. However, these may become too time-consuming for some applications, such as those that require real-time execution; besides, they cannot be used with certain simulation tools that do not allow for subsystem resetting.

When non-iterative co-simulation is used, additional steps have to be taken to ensure that the obtained results are accurate and the coupled integration process remains stable [10]. Adaptive stabilization strategies, that extract information from subsystem dynamics to improve the communication procedures, are gaining importance nowadays [11]. Possible ways to do this include adjusting the integration step-sizes as a function of the system instantaneous frequency [12,13] or energy level [14], introducing adaptive damping to dissipate the excess energy generated at the interface [15], and interpolating or extrapolating the system inputs to minimize the effect of discrete-time input exchange. The simplest way to handle the inputs that a subsystem receives at the beginning of a macro time-step is to consider that they remain constant until the next communication point. This extrapolation is known as zero-order hold (ZOH). Higher order polynomials [16,17] or smoothing techniques [18,19] can also be used to extrapolate or predict unknown values of the input data. Nevertheless, the above mentioned coupling techniques can be made more accurate if some additional information about the internal dynamics of each subsystem is available at each macro time-step. For example, stabilized coupling approaches were derived in [20–22] based on the availability of the partial derivatives of the subsystem states with respect to the coupling variables at the interface.

In this work, we propose to use a *reduced order model* to characterize the dynamics of a multibody subsystem at the interface that connects it to the rest of components in a multiphysics co-simulation setup. Model order reduction is used in a variety of applications to decrease the size of the system under study while preserving its most representative dynamic behaviour. This is often done for efficiency reasons, e.g., to shorten simulation times when dealing with large finite element models. Reduced order models are also used to this end in the context of multibody system dynamics, usually when dealing with models that account for the structural properties of the system [23,24]. A review and comparison of existing model order reduction methods for structures and large flexible systems can be found in [25,26]. In this paper, we also use a reduced order model but this is conceptually different from the aforementioned models. Our reduced model replaces the original full model during a macro time-step in a co-simulation setup, during which it communicates to another subsystem. In many cases, this other subsystem has different properties, i.e., smaller time scales and faster dynamics. This is often the case of hydraulics elements and microelectronics controllers. Accordingly, their integration requires shorter step-sizes, and more than one integration step takes place within a macro time-step. The reduced model is updated at the beginning of each macro time-step and is subsequently used to obtain information about the evolution of the mechanical subsystem until the next communication point occurs. During this interval, the integration of the reduced model proceeds at a faster rate than that of the original full multibody model, closer to the time scale of the other subsystem in the co-simulation. We will refer to this reduced model as *reduced interface model* (RIM) in this paper.

The RIM reduces the computational complexity of the full model in two ways. First, in most cases it has fewer degrees of freedom than the original model due to the projection of the system dynamics to the interface subspace; moreover, if the original modelling was carried out using dependent coordinates, then the kinematic constraint equations are no longer present in the RIM, which can be expressed as a system of ordinary differential equations. Second, the mass matrix and