Monitoring Energy Errors in Explicit Co-Simulation Setups

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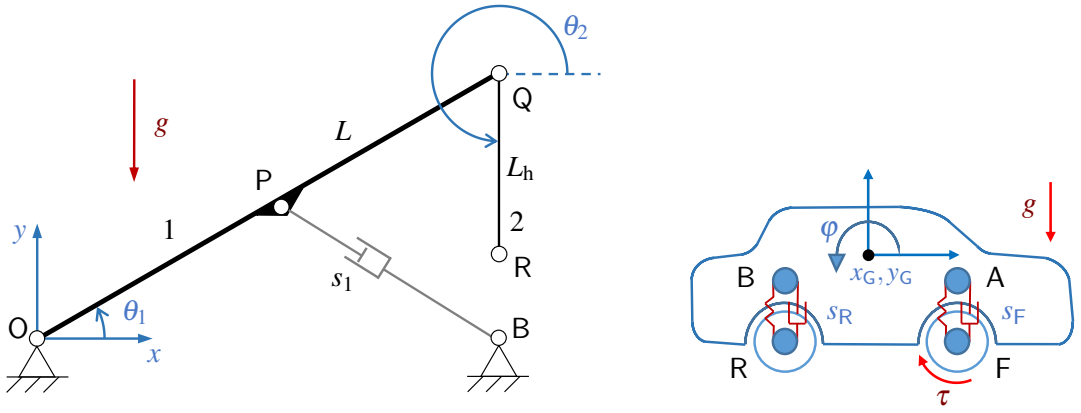
Abstract

In a considerable number of engineering applications, e.g., heavy machinery and automotive systems, mechanical components are interfaced to elements that do not fall within the scope of multibody systems (MBS) dynamics. The use of co-simulation schemes enables solving the dynamics of the mechanical elements in the assembly using MBS solution algorithms while considering their interactions with non-mechanical subsystems. These, in turn, can be simulated using solvers specifically developed to match their dynamic behaviour. Moreover, co-simulation has additional advantages, such as preventing the disclosure of the implementation details of each subsystem to its environment and making it easier to distribute the computational workload between several processing units. On the other hand, co-simulation requires the exchange of information between subsystems in a discrete-time fashion. This gives rise to discontinuities at the interface and can result in inaccurate results and the instability of the simulation process. This issue is particularly problematic in real-time applications, such as Hardware-in-the-Loop (HiL) and System-in-the-Loop (SiTL) setups, which are often constrained to use explicit co-simulation schemes and cannot take advantage of the better stability properties of iterative coupling approaches [1].



(a) Hydraulically actuated crane model (b) Planar model of electric vehicle

Figure 1: Examples of nonlinear, multiphysics co-simulation benchmark problems

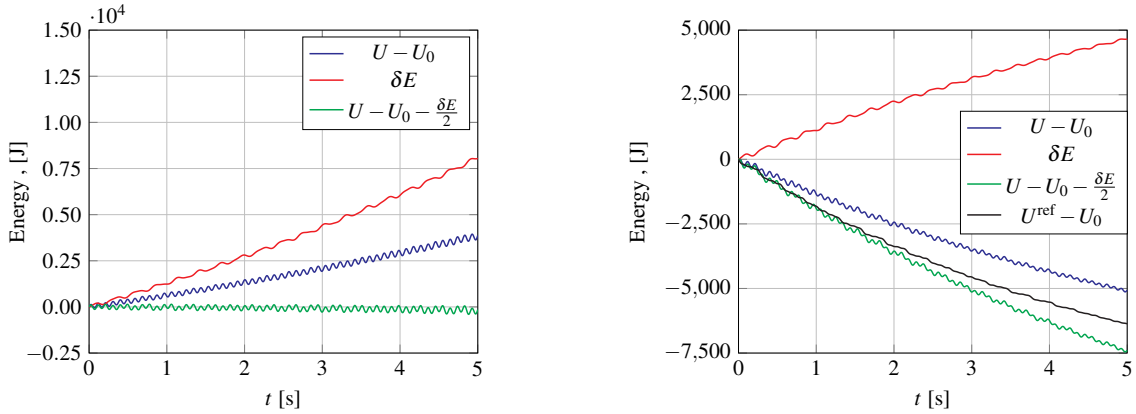
The stability properties of co-simulation schemes are often studied by means of linear systems theory. Most mechanical systems of interest, however, are highly nonlinear. To gain insight into the properties of frequently used co-simulation schemes, a set of benchmark problems composed of mechanical and non-mechanical elements has been put forward. These are relatively simple mechanical systems, easy to model, actuated with hydraulics [2] or electric elements. Some examples are shown in Fig. 1. These can be used to verify whether the properties of co-simulation schemes still hold when they are applied to nonlinear, multiphysics assemblies.

The proposed benchmark models have also been used to validate performance indicators for co-simulation setups. An example is the residual power, introduced in [3] for co-simulation setups with two subsystems

$$\delta P = -\left(P_1 + P_2\right) = -\tilde{\mathbf{u}}^{\mathrm{T}} \cdot \mathbf{y} \tag{1}$$

where P_1 and P_2 represent the power that flows through the interface of the subsystems at a given time, which can be computed as a product of its inputs $\mathbf{u}$ and outputs $\mathbf{y}$. The sum of powers that flow through

the co-simulation interface should be equal to zero; deviations from this value can be used to detect inaccuracies in the coupled numerical integration.
Preliminary results showed that the residual energy δE obtained by integration of the residual power δP over time can be used to determine the deviation of the co-simulation results from the energy balance $U(t) - U_0 - W_{\text{nc}}(t) = 0$, where U is the energy stored in the subsystems, W_{nc} is the work done by non-conservative forces, and U_0 is the initial energy level.



(a) Conservative system.

(b) Dissipative system.

Figure 2: Energy measurements in the co-simulation of a two-mass linear oscillator.

Figure 2 shows energy balances for a two-mass linear oscillator. The indicator δE provides accurate information about the excess energy introduced by the co-simulation interface and stored as mechanical energy in the subsystems if the system under study is conservative. If dissipative elements are introduced in the oscillator, then the indicator reflects how much the overall energy balance deviates from zero. Fig. 2b shows that the error in the mechanical energy of the oscillator with respect to that of the exact solution of the system, U^{ref}, is smaller than the deviation indicated by δE. This deviation now has two components that affect the internal energy of the subsystems and the work of the non-conservative forces, respectively.

Acknowledgments

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