Benchmark problems for co-simulation methods

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Simulation of complex engineering systems is an essential part in the development of machinery nowadays. It allows predicting the behaviour of engineering systems while avoiding the need to manufacture physical prototypes, which are only needed in final stages of the design process. This dramatically reduces the time and cost spent in product development. On top of that, System-in-the-Loop (SITL) solutions allow merging together simulation and testing by connecting a physical component (instead of its virtual equivalent) to the virtual system to be simulated. In this way, early physical prototypes can be tested while the overall system is still unfinished; partner companies can also test their devices without having a prototype of the whole system.

Latest researches are increasingly studying the co-simulation method, which allows carrying out simulation in a modular way, enabling the parallelisation code execution for different components or domains (mechanics, hydraulics, electronics, etc.) within the same application. Co-simulation can help reducing computational cost when implemented in multicore computing environments. Moreover, Tier 1-2 suppliers can protect their intellectual property: each subsystem can be contained in a black box whose internals remain undisclosed, but exchanges data with its environment. In addition, co-simulation facilitates SITL simulation, as each virtual module can be easily replaced by its physical counterpart.

A major drawback of co-simulation is the need to perform the communication between modules at discrete points in time. In between these, there is no exchange of information among subsystems, so inputs need to be extrapolated. This compromises precision in the simulation, but it is complicated to know up to what extent in the absence of a reference solution. It is known that smaller step sizes generally lead to higher precision, but without some measure of the error, the time step is often selected by trial and error [1].

Current research is focusing on this, especially on the definition of meaningful error indicators [2]. These indicators show the error introduced in a specific magnitude due to the use of co-simulation. However, the relation between these error indicators and the actual error of the simulation with respect to its ideal solution is not clear yet. Therefore, a correlation between the error indicator and the accuracy and/or stability of the system is yet to be established. Hence the need for benchmark models, to study and compare results from a co-simulated system to a reference solution. With both results at hand, the error induced by the co-simulation can be calculated and compared to the error indicators with the aim of studying whether any correlation exists and determining if it is possible to predict the behaviour of the co-simulation from the values of one or several error indicators.

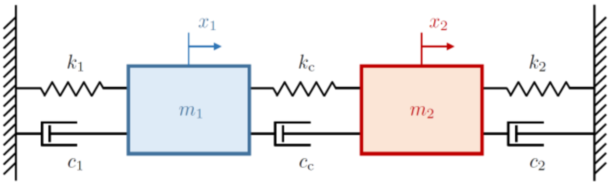

Figure 1: Linear oscillator model.

In this paper, three benchmark examples are presented: a linear oscillator, a hydraulic crane, and an electric car. The linear oscillator has its own analytic solution, which is taken as reference. Both the hydraulic crane and the electric car lack this kind of solution, so a reference solution obtained at convergence is employed.

The three examples presented here are planar systems. For the purposes of this study, all of them were divided into two subsystems and integrated using non-iterative explicit co-simulation schemes. The linear oscillator, a linear system, can be seen in Fig. 1. It is a two-degree-of-freedom system, formed by two masses connected to each other and to the ground by three spring-damper assemblies. Force-displacement and displacement-displacement couplings are common ways to divide the oscillator into subsystems. The hydraulic crane is a nonlinear system, comprised of a two-degree-of-freedom double pendulum, and a hydraulic subsystem with a piston that actuates on the angular coordinate of the first bar of the double pendulum [3], as shown in Fig. 2, left. The last example is the simplified nonlinear model of an electric vehicle, a basic model that features a five-degree-of-freedom car and a three-phase induction motor, which does not include the inverter for simplicity, as presented in Fig. 2, right. Rolling between the massless wheels and the road is assumed. In this case, the mechanical model of the vehicle and the electric motor model are one subsystem each.

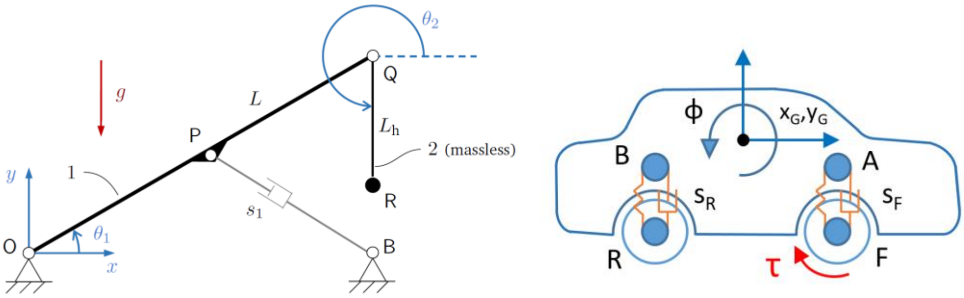

Figure 2: Non-linear benchmark problems. Hydraulic crane model (left). Electric car model (right).

These benchmarks have served to test an in-house developed, FMI-compatible co-simulation library. The subsystems in each problem were encapsulated as Functional Mock-up Units (FMU) and interfaced in co-simulation setups defined using the above-mentioned software tool. Two issues were addressed via the simulation of these examples. First, the ability of proposed error indicators to warn of the accumulation of integration errors and unstable behaviour during runtime was assessed. Second, different co-simulation configurations were compared in terms of their efficiency and accuracy. The selection of coupling variables and the choice between Jacobi and Gauss-Seidel schemes, among other factors, have an impact on the efficiency of code execution. Moreover, parallel co-simulation can be achieved on the basis of shared memory, e.g., via OpenMP, or through interprocess communication, for instance with TCP/IP sockets. These different options were evaluated in this research to shed light on the complexity of the analysis of co-simulation error.

Acknowledgments

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