Proceedings of the ASME 2020 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2020
August 17-19, 2020, Online Conference,

DETC2020-22060

USE OF ENERGY INDICATORS IN THE EXPLICIT CO-SIMULATION OF MULTIBODY SYSTEMS

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ABSTRACT

Co-simulation, or solver coupling, enables the efficient numerical integration of complex engineering applications composed of subsystems with different physical properties and behavior. In co-simulation setups, the dynamics of each subsystem is integrated by its own dedicated solver. Communication between solvers takes place at discrete-time intervals, through the exchange of a limited set of coupling variables. The internals of each subsystem remain thus undisclosed to the rest of the co-simulation environment. The discrete-time nature of the coupling interface inherently leads to the introduction of delays and discontinuities in the coupling variables, which affect negatively the accuracy of the numerical integration and may eventually cause it to become unstable, particularly in the case of explicit, non-iterative co-simulation schemes. Several methods have been proposed in the literature to detect and prevent instability in explicit co-simulation setups. In this research, we use energy indicators to monitor the effect of co-simulation schemes and coupling options, such as extrapolation methods, on the overall simulation stability. Energy correction approaches can be developed based on the information provided by these indicators. A set of benchmark problems was defined and used to assess the ability of the selected methods to detect stability issues in explicit co-simulation setups and to address them without compromising the accuracy of the simulation.

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1 INTRODUCTION

Expectations about the efficiency and the level of detail delivered by the simulation of engineering applications continue to grow steadily, in parallel with the increase in computational power and resources that are available to researchers. Moreover, complex engineering projects often require the consideration of multiphysics phenomena. Co-simulation schemes provide a way to successfully perform the numerical integration of such problems [1]. They are modular and enable the distribution of computational workload between several processing units. Besides, they are convenient to protect intellectual property, as the implementation details of the solvers and models used inside each subsystem do not need to be disclosed to other simulators in the environment. On the other hand, co-simulated subsystems are synchronized via the discrete-time exchange of coupling variables at communication points, which can result in inaccurate results and unstable behavior [2]. Iterative co-simulation can be used to alleviate these issues [3]. However, this would require to retake the integration steps of one or more subsystems, which may not be possible in some applications. This is the case of Hardware-in-the-Loop (HiL) and System-in-the-Loop (SITL) setups, and also a common occurrence in systems that require real-time performance. If iterative methods cannot be used, explicit co-simulation schemes are needed to couple the subsystems.

Non-iterative co-simulation is prone to introducing energy errors at the coupling interface. Integration steps in the subsystems cannot be repeated or corrected, and so discontinuities are introduced in the coupling variables at each communication point. Monitoring energy exchanges at the interface is a way

to detect the accumulation of errors and to define methods to keep the numerical integration stable, e.g., adjusting the size of the communication step [4], or modifying the subsystem inputs to remove the surplus energy introduced by the co-simulation scheme [5,6].

In this work, we studied how energy indicators can be used to describe the stability behavior of co-simulated systems. The effect on energy errors of selecting a particular co-simulation scheme or set of parameters, such as the input extrapolation order, was evaluated by means of a set of benchmark problems.

2 METHODS

A set of benchmark examples was defined to evaluate the suitability of indicators to monitor the energy of co-simulated systems. These include the two-d.o.f. linear oscillator, Fig. 1, commonly used in the literature [2–4], a hydraulically actuated crane [7], and a 2-D model of an electric vehicle, shown in Fig. 2.

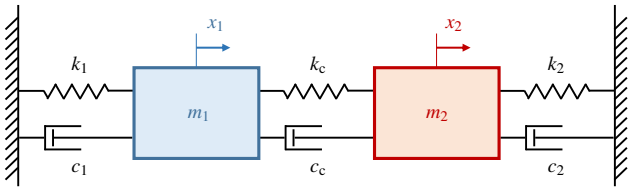

FIGURE 1. A TWO-D.O.F. LINEAR OSCILLATOR.

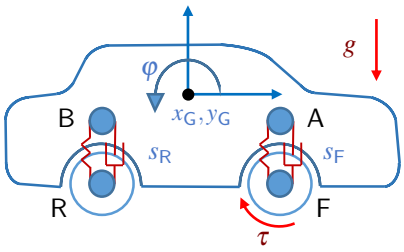

FIGURE 2. 2-D MODEL OF AN E-VEHICLE.

These benchmark models include nonlinear and multiphysics problems, that require multirate co-simulation for efficient execution. They were used to verify the range of applicability of already proposed indicators, such as the power residual δP introduced in [4]. Preliminary results showed that δP can be used to indicate the deviation ε from zero of the total energy balance of the co-simulated system at time t

$$U(t) - U_0 - W_{\text{nc}}(t) = \varepsilon \tag{1}$$

where U is the mechanical energy of the system and U_0 is its initial value, and W_{nc} is the work carried out by the non-conservative forces. It is also possible to use the information conveyed by the power residual to correct the coupling variables and remove energy artifacts in the system in single-rate co-simulations with zero-order hold input extrapolation. The indicator needs to be modified to be able to deal with higher extrapolation orders, as well as multirate co-simulation setups; this task is currently in progress.

ACKNOWLEDGMENT

The work reported here was supported by the Spanish MINECO through project TRA2017-86488-R and the Ramón y Cajal contract RYC-2016-20222, and by the Galician Government under grant ED431C 2019/29.

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