Evaluation of indicators for the accuracy and stability of explicit co-simulation schemes

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Industrial applications of co-simulation, such as those interfacing physical components to virtual simulations, require the use of explicit, noniterative coupling schemes. This is the case of, for example, cyber-physical systems, virtual-physical hybrid test benches, Hardware-in-the-Loop (HiL) setups, and System-in-the-Loop (SITL) environments in general. Compared to their iterative counterparts, explicit co-simulation algorithms are more likely to suffer from instability issues and degraded accuracy, as the errors introduced by the discrete-time exchange of coupling variables between simulators cannot be corrected within each macro step-size. For industrial use, it is therefore important to understand and monitor co-simulation stability and accuracy.

The stability of explicit co-simulation schemes can always be improved by decreasing the communication step-size to minimize the inconsistencies in the coupling variables exchanged by the subsystems. This, however, may be incompatible with real-time execution constraints. Alternative approaches to keep co-simulation stable without penalizing computational efficiency are, therefore, of interest to the research community. Polynomial extrapolation or approximation of subsystem inputs is a popular method that aims to alleviate the issues originating from discontinuities in coupling variables. While easy to implement, polynomial extrapolation is not directly related to the physical behaviour and properties of the subsystems in the co-simulation environment, but more to digital signal processing techniques. The selection of polynomial degree and the maximum achievable communication step-size often need to be determined from previous expert knowledge or by trial and error [1, 2]. Conversely, it would be convenient to have access to quantities with a physical meaning as they convey information about the dynamic behaviour of the system under test. Energy indicators, for instance, have been proven to be useful to quantify the deviation of a co-simulated system from ideal behaviour [3]. These enable the introduction of correction methods to compensate energy errors and maintain the stability and accuracy of the simulation. In most cases, however, either a reference solution, which is not available in the majority of industrial applications, or detailed information about the internals of every subsystem, are required to monitor the energy of the overall system and act accordingly.

Ideally, co-simulation indicators should provide physics-based information regarding the stability and accuracy of the numerical integration process in the absence of a reference solution, with minimal requirements imposed on the data that the co-simulation subsystems must provide. The residual power δP and residual energy δE were defined in [4] as a means to keep track of the energy losses or gains at the co-simulation interface. These indicators are evaluated using only the information contained in the coupling variables exchanged between subsystems, when the product of the involved variables has units of power. They have been proven to be meaningful measurements in explicit Jacobi, single rate co-simulation schemes with zero-order hold (ZOH) extrapolation. In this research, we study their applicability when using other co-simulation schedules, such as Gauss-Seidel communication approaches, and multi-rate environments. Moreover, the integration of the residual energy from δP may be conducted using different integration formulas; their impact on the evaluation of the indicator, especially when extrapolation techniques other than zero-order hold are applied to subsystem inputs, is also discussed.

To gain insight into the information conveyed by the above-mentioned indicators, several benchmark examples were tested with different co-simulation configurations. The two-degree-of-freedom linear oscillator in Fig. 1 [3] was simulated using two different configurations, namely with and without dissipative elements. Figure 2 compares

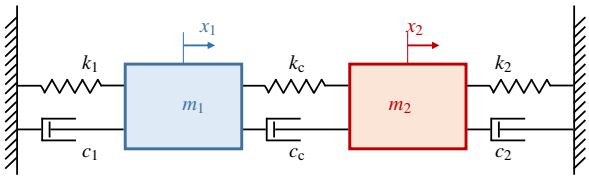
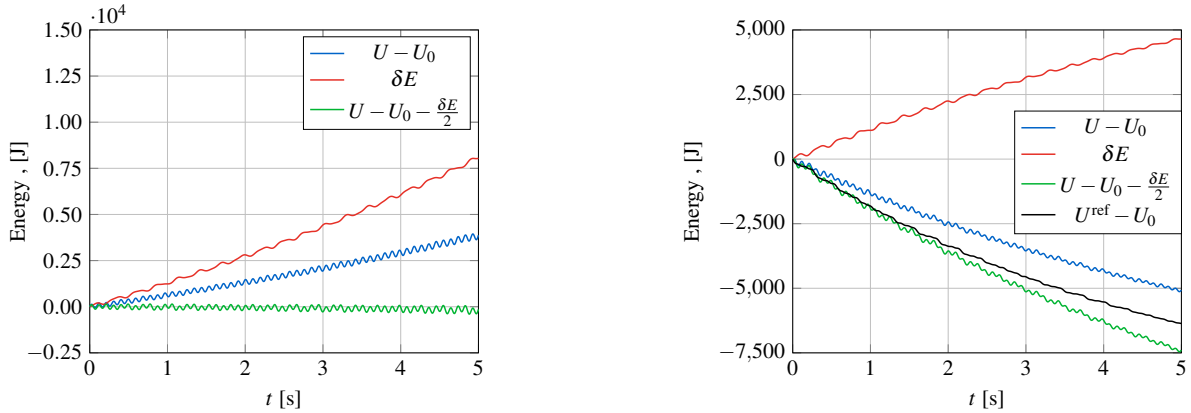


Figure 1: A two-degree-of-freedom linear oscillator.

the value of the residual energy, δE and the energy balance of the system. Regardless of the energy dissipated by the dampers, the total energy balance of the system at time t should be $U(t) - U_0 - W_{\text{nc}}(t) = 0$ where U is the mechanical energy of the system and W_{nc} is the work of the non-conservative forces. U_0 is the initial energy level. Results suggested that δE can be used to indicate the deviation from this ideal balance introduced by the co-simulation interface. In conservative systems this is equivalent to the excess of mechanical energy accumulated in the subsystems as a result of delays and numerical errors at the co-simulation interface. If dissipative elements are present, however, the interface introduces an error in the work of the non-conservative forces as well.



(a) $c_1 = c_2 = c_c = 0$ Ns/m.

(b) $c_1 = c_2 = c_c = 0.1$ Ns/m.

Figure 2: Energy measurements for the co-simulation of the linear oscillator.

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