Parallel Real-Time Hybrid Simulation of Structures Using Multi-Scale Models

Abstract: Real Time Hybrid Simulation (RTHS) is used to study the behavior of structures by partitioning the structure into two substructures, one that is constructed physically and the other that models the remainder of the structure numerically. These substructures are coupled physically using transfer devices such as hydraulic actuators and the simulation is performed in real time (usually using a time-step corresponding to 1024-Hz). The constraints imposed by the real-time nature of these simulations have historically precluded all but small and relatively simple numerical models that can be run deterministically in a fraction of a second. In this study we advance state of the art RTHS through the use of realistic multi-level finite element models that model the behavior of the structure accurately while still meeting the constraints of real-time computation.

The multi-time-step (MTS) time integration method enables one to use a refined model with a small time-step in the immediate vicinity of the physical substructure to match its fast time-scale, while a relatively coarser model with a large time-step is used for other parts of the structure. A systematic approach for traversing the space of possible MTS decompositions and characterizing the nature of how solution errors and computational costs vary for different decompositions is presented. Based on this approach, optimal decompositions that maximize the benefit of the MTS methods are identified. It is also shown that MTS methods can be used effectively to lower computational cost while maintaining accuracy of the solution by distributing errors evenly across the problem domain.

The MTS time integration method is adapted to RTHS, called MTS+RTHS. Specifically, a predictor is used for the MTS coupling to reduce errors incurred by applying asynchronous updates to the physical substructure. An in-depth study is conducted investigating a series of choices of the predictor, and the effect of predictor choice on the error in both the physical and numerical substructures. It is demonstrated that MTS+RTHS is not only viable, but essential when using high-fidelity models. It is shown that the synchronization error for a problem with high time step ratios is the same order of magnitude as experimental error for a benchmark problem.

Parallel multi-scale RTHS is used to allow high fidelity numerical models in RTHS. Large numerical models that are multi scale in both *space* and *time* use a finer spatial discretization are used in RTHS. The coupling of linear beam elements with nonlinear continuum elements is used to create models that capture nonlinear behavior at structural joints, but are still capable of being solved in real time. The **Cybermech** platform is used to conduct these parallel experiments, and demonstrate the benefits of high fidelity models.

Perfectly Matched Layers (PML) is used as an absorbing boundary for the Helmholtz problem. A parallel, ellipsoidal formulation for PML is presented for acoustic elements, minimizing the need for large numbers of elements in the exterior of the domain. Such a tool could be used a RTHS experiment involving soil structure interaction, reducing the size and number of elements in the soil domain. A comparison between the PML formulation and ellipsoidal infinite elements is conducted, focusing on iteration counts of the parallel linear solver. Perfectly Matched layers are shown to outperform infinite elements on large parallel problems, where the poor matrix conditioning of higher order infinite elements results in increased computational cost.