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A composite experimental dynamic substructuring method based on partitioned algorithms and localized Lagrange multipliers

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ABSTRACT

Successful online hybrid (numerical/physical) dynamic substructuring simulations have shown their potential in enabling realistic dynamic analysis of almost any type of non-linear structural system (e.g., an as-built/isolated viaduct, a petrochemical piping system subjected to non-stationary seismic loading, etc.). Moreover, owing to faster and more accurate testing equipment, a number of different offline experimental substructuring methods, operating both in time (e.g. the impulse-based substructuring) and frequency domains (i.e. the Lagrange multiplier frequency-based substructuring), have been employed in mechanical engineering to examine dynamic substructure coupling. Numerous studies have dealt with the above-mentioned methods and with consequent uncertainty propagation issues, either associated with experimental errors or modelling assumptions. Nonetheless, a limited number of publications have systematically cross-examined the performance of the various Experimental Dynamic Substructuring (EDS) methods and the possibility of their exploitation in a complementary way to expedite a hybrid experiment/numerical simulation. From this perspective, this paper performs a comparative uncertainty propagation analysis of three EDS algorithms for coupling physical and numerical subdomains with a dual assembly approach based on localized Lagrange multipliers. The main results and comparisons are based on a series of Monte Carlo simulations carried out on a five-DoF linear/non-linear chain-like systems that include typical aleatoric uncertainties emerging from measurement errors and excitation loads. In addition, we propose a new Composite-EDS (C-EDS) method to fuse both online and offline algorithms into a unique simulator. Capitalizing from the results of a more complex case study composed of a coupled isolated tank-piping system, we provide a feasible way to employ the C-EDS method when nonlinearities and multi-point constraints are present in the emulated system.

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1. Introduction

1.1. Background and motivation

In the field of simulation-based science and engineering, there are several challenges posed by the *virtual structural testing* of complex systems, e.g. the curse of dimensionality, the treatment of uncertainties, adequate parametric modelling, process/shape optimization, etc. [1]. The fundamental issue is that all these problems cannot be easily solved using standard numerical methods. As an example, Chinesta and his co-workers [2] have actively developed and implemented the proper generalized decomposition (PGD) method to address the simulation of high-dimension physical systems. The PGD can be viewed as an approach to enhance the reduced-order modelling; it is based on the numerical approximation of the unknown fields (or variable spaces) by subsequent separation of variables, successively enriched, involving a set of a priori unknown functions of clustered coordinates (or degrees of freedom). However, difficulties still persist in relation to the solution of both non-linear models and stochastic problems requiring multiscale and multiphysics methods. In this context, the dynamic substructuring coupling (DSC) method is very powerful because it can simulate system non-linearities and enable the identification and updating of damaged components/sub-systems. Thus, when the properties of one or more sub-systems are altered, the modified sub-systems alone need to be re-analyzed whilst other sub-structures are unchanged and no further analysis is needed [3].

Owing to DSC, the heterogeneous (numerical/physical) dynamic substructuring (HDS) represents a form of online simulation, which has been shown to be very efficient in solving non-linear structural dynamic problems [4,5]. In particular, the HDS isolates the physical sub-system(s) (PS), which is experimentally tested since it contains a key region (or component) exhibiting non-linear behavior, from the remainder of the system, which is numerically simulated, i.e. the numerical subsystem(s) (NS). In this context, the term online indicates that a time stepping algorithm solves the system of equations of motion of the global emulated system whilst the PS response, which is treated in a Finite Element (FE) fashion, is being measured. In detail, at each iteration of the simulation loop, a set of servo-controlled actuators imposes displacement/velocity predictors to the PS boundary and feeds back corresponding restoring forces to the time stepping algorithm, which solves the coupled equations of motion. The ratio between the wall-clock time taken by the HDS simulator to solve a single time step and the time step size itself is named testing time scale. Real-time indicates a testing time scale equal to one whilst both fast-time and pseudodynamic testing consider testing time scales larger than one, which can be afforded when the PS restoring force is rate independent. Since the inertial component of the PS restoring force measured by load cells reduces of a factor proportional to the square of the testing time scale, hardware-in-the-loop testing, which treats the PS as a black-box, always runs in real time. However, when an extended time scale is adopted, physical inertia must be numerically accounted for. This is the so called substructuring approach, which imposes to numerically solve the PS system of equation of motion as analogously done for the NS. In addition, it is important to stress that mass at interface degrees-of-freedom (DoFs) can be virtually moved from NS to PS. Although this could sound as an unnecessary complication, such approach allows for controlling the stability of the coupled simulation [6]. As an example of application to a civil engineering structure, both an as-built viaduct and the corresponding isolated and retrofitted structure, equipped with substructured sliding bearings, were part of a comprehensive investigation to evaluate the structural response under several earthquake ground motions [7]. In particular, the HDS method was employed to study two 1:2.5 scale specimens of single-bay RC frames with 2 levels (total height, 7.0 m) and 3 levels (total height, 11.5 m) at the European Laboratory for Seismic Assessment (ELSA) of the Joint Research Center of the European Community. Model reduction and updating were successfully used for the numerical modelling of pier/sliding bearings. In addition, parallel partitioned time integration algorithms played a crucial role, because the inherent subcycling capabilities enabled the synchronization of two separated integration processes (with a fine and a coarse integration time step), which were implemented to simultaneously solve the PSs and NSs, respectively [8]. More recently, the HDS method was applied to the seismic evaluation of critical industrial piping systems, by testing real components of full-scale three-dimensional piping systems in the laboratory without the need to physically model the whole piping/tank system [9]. For this purpose, two relatively inexpensive electrohydraulic actuators were employed to avoid the complexity of shaking table tests. Appropriately calibrated a posteriori reduction of bases enabled the extension of the DSC to the PS, characterized by distributed masses (piping equipment, water mass, etc.) In addition, the real time LSRT2 time-stepping algorithm [6] established a more general framework that simultaneously combines time integration algorithms, model reduction, system identification and control. In summary, HDS appears to be a very versatile method that can be applied to any class of multiphysics and multiscale engineering problems with strong/weak nonlinearities [8,10,11]. When HDS is applied to a complex mechanical system, such as the aforementioned piping system subjected to seismic loading [9], some issues arise. For instance, the piping system response is characterized by weak and localized non-linearities in elbows, flange joints, tee joints; modal damping is low (of the order of 1.5 per cent); proper boundary conditions are difficult to reproduce, etc. [9]. Therefore, adequate identification of modal damping and boundary conditions, especially at the interfaces where substructures are split, become crucial for the fidelity of heterogeneous simulations.

Due to faster and more accurate testing equipment, the DSC method has been broadly employed in mechanical engineering through the implementation of several experimental substructuring methods [3]. We recall here the impulse-based substructuring method (IBS, [12,13]); it evaluates the response of a full (emulated) system by computing the responses of its substructures through a discretization of the Duhamel integral and the enforcement of the interface compatibility at every