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Nonlinear substructuring control for parameter changes in multi-degree-of-freedom systems

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A B S T R A C T

Nonlinear substructuring control (NLSC) was developed to render linear substructuring control (LSC), particularly used in dynamically substructured system (DSS), more robust against nonlinearities. This NLSC was examined both numerically and experimentally via substructure tests of nonlinear single-degree-of-freedom (SDOF) systems demonstrating a base-isolated structure. This study examines the application of NLSC to nonlinear multi-degree-of-freedom (MDOF) systems. To begin, NLSC for nonlinear MDOF systems is discussed, and its stability with respect to a pure time delay, which is a critical element in many substructure tests, is analysed by applying the Nyquist criterion. Next, its controller design and stability analysis are numerically and experimentally examined via substructure tests. In the examination, a nonlinear 4DOF system subjected to a ground motion is selected as an emulated system for substructure tests. Based on this emulated system, three types of substructure tests are numerically simulated; the first simulation examines the ground floor as the physical substructure, the second one examines the ground and first floors, and the third one examines only the first floor. Finally, by using a test rig consisting of an actuator and a rubber bearing, a series of substructure experiments targeting the ground floor as the physical substructure was implemented. In both examinations, the design of the NLSC controller has established its efficiency in substructure tests of nonlinear MDOF systems. A stability analysis with respect to pure time delays has been also found useful for predicting instability conditions of substructure tests with nonlinear MDOF systems.

1. Introduction

Dynamical experiments generally serve to examine the behaviour and characteristics of a specimen under a certain input. However, such experiments cannot always be implemented because of restrictions imposed by experimental apparatus and finances. Thus, to overcome these restrictions, substructure testing methods, in which a physical experiment runs simultaneously with a real-time numerical simulation, are emerging as powerful tools in various fields of engineering.

A dynamical experiment is normally executed using the principle shown in Fig. 1(a). In contrast, the substructured experiment, developed as an alternative of the aforementioned experiment, follows the feedback principle, particularly for interactions between physical and numerical substructures. The ideal substructure test shown in Fig. 1(b) completely

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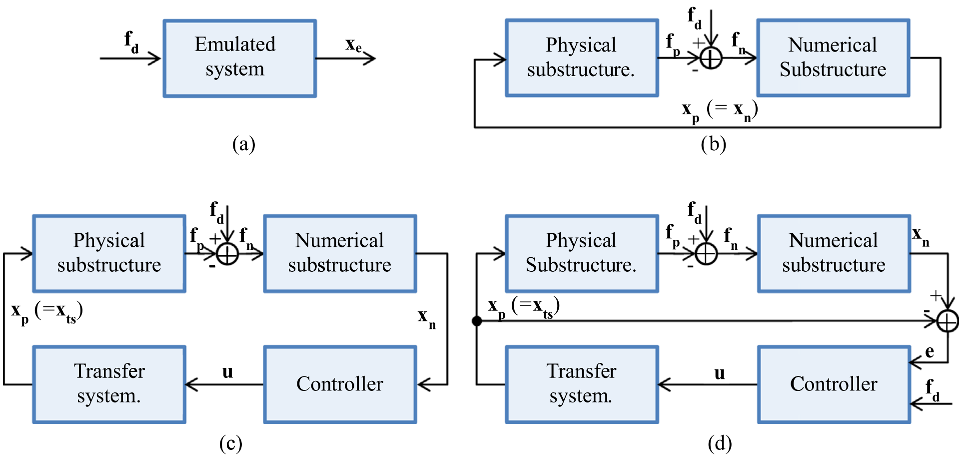

Fig. 1. Substructuring experimental methodology: (a) original test, (b) ideal substructuring, (c) hybrid simulation and (d) dynamical substructuring system.

replaces the original experiment by directly feeding the output of the numerical substructure back into the physical substructure. However, this is possible only when communication between physical and numerical substructures occurs in infinitely short time. In reality, communication between the two substructures requires transfer systems, such as actuators and measurement systems, which introduce dynamics and pure time delay into the transfer system. Although such pure time delay is generally on the order of milliseconds, it causes instability in many substructure experiments. To compensate for this influence of the transfer system, two approaches have been developed: hybrid simulation [HS; Fig. 1(c)] [e.g. 1–3] and dynamical substructure systems [DSS; Fig. 1(d)] [4–6].

Hybrid simulation is a commonly used substructuring method because of its straightforward principle. In this method, the transfer system solely becomes the controlled system and its controller is easily designed on the basis of the dynamics of the transfer system; its inverse dynamics is commonly employed as the HS controller [7–11]. However, in stability analyses [8–12], such controllers are found not to provide a sufficient stability margin with respect to pure time delay. The critical pure time delay, which is an index of the stability margin [13], depends strongly on the damping and natural frequency of the physical substructure (ω_p and ζ_p) [8–12]. When the physical substructure is a single-degree-of-freedom (SDOF) system, the critical pure time delay is given approximately by $\tau_c = 2\zeta_p/\omega_p$ [10]. In other words, the HS method is only suitable for testing highly damped systems, such as dampers, but not for testing lowly damped systems with a high natural frequency. Thus, compensating for pure time delay [1–3,14–16] has become an important topic in the field of HS.

Unlike the HS method, DSS shown in Fig. 4(d) determines the signal u input into the actuator based on the outputs x_n and x_p of numerical and physical substructures, respectively, and on the external excitation force f_d [4–6]. The basic control law of linear substructuring control (LSC) [4] is based on the dynamics of physical and numerical substructures in addition to the actuator dynamics. The advantage of DSS with LSC is the separation of emulated system dynamics from closed-loop error dynamics. Thus, even very lightly damped emulated systems can be represented by a DSS configuration with large stability margins designed into the system. Upon comparing DSS and HS schemes [10], DSS is found to be at least 10 times more robust against pure time delay than the HS scheme. However, this robustness is obtained by incorporating information from substructures prior to the substructure experiments. This conflicts with the motivation of such experiments, which normally involve investigating the properties and dynamics of physical substructures.

To address this problem, the first DSS study [4] used an adaptive control scheme, which was referred to as minimal control synthesis (MCS) [17], instead of LSC. MCS automatically tunes its controller gain in the time domain for the control of systems for which the available information is limited. On the contrary, nonlinear substructuring control (NLSC) [18] was developed as a direct extension of LSC. The NLSC controller is based on linear models of substructures expressed in Laplace domain, indicating that its design requires only nominal information of the substructures. This characteristic becomes greatly beneficial particularly for the control of systems with nonlinearities or unknown parameters, because this method is capable of reasonable control without knowing the detail of the controlled systems. NLSC has obtained this advantage by employing the concept of nonlinear signal-based control [19], which uses an inverse transfer function of a linear model of the nonlinear system for its control. In the first study of NLSC [18], controllers were designed independently of the substructures and achieved stable and accurate control of a nonlinear SDOF system demonstrating a base-isolated structure. Through the study, the efficiency of NLSC for nonlinear SDOF systems was verified numerically and experimentally.

In this study, we extend this previous work of NLSC for use with nonlinear MDOF systems and analyse their robustness against pure time delay, as described in detail in Section 2. The performance of NLSC and its stability analysis are numerically and experimentally examined in Sections 3 and 4, respectively, via substructure tests on nonlinear 4DOF systems.