Journal of Sound and Vibration 346 (2015) 1–16

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Stability analysis and comparative experimentation for two substructuring schemes, with a pure time delay in the actuation system

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ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form
12 February 2015
Accepted 13 February 2015
Handling editor: I. Lopez Arteaga
Available online 11 March 2015

ABSTRACT

In recent years there has been a focus on two types of scheme for dynamical substructure testing: the hybrid scheme (HS) and the dynamically substructured system (DSS) scheme. Although these approaches are fundamentally different in the manner of compensation/control, the comparative performance of the schemes has not yet been studied in simulated or real experimental tests. This paper studies the performance of these schemes via tests on a simple base-isolated structure with a natural rubber bearing.

In dynamical tests, a guarantee of stability for the experimental system is essential in order to achieve a safe and reliable result. Pure time delays can be present in such experimental systems, primarily due to discrete-time computational elements, which will promote instability. This paper studies the stability of HS and DSS test systems, with a prime focus on the effect of pure time delays. In particular the schemes were applied to the substructure testing of a rubber isolation bearing, where the overall system included a digital computation time delay of $\tau = 6$ ms resulting from a series of control, data acquisition and signal filter elements. Neither delay compensation nor adaptive/self-tuning methods were included in these tests, in order to establish a fair and objective comparison between the basic forms of the two schemes. It was found that DSS stability was preserved in the presence of the 6 ms delay, whereas HS was rendered unstable. This increase in robustness was due to a linear substructure controller (LSC) used in the DSS, which was based upon a knowledge of the dynamics of the transfer system and substructures.

In addition, DSS exhibited significant robustness to further artificial increases in the pure time delay, eventually yielding to instability at a value of $\tau = 17$ ms. Analysis of the two schemes was found to be effective at predicting accurate stability conditions in advance of actual experimentation.

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http://dx.doi.org/10.1016/j.jsv.2015.02.024
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1. Introduction

Substructure testing, whereby an experiment is conducted simultaneously on both physical and real-time simulations of components (or *substructures*) of a complete dynamical system (or *emulated system*), has become a key experimental method in a wide range of engineering fields. In principle, there may be more than one physical and one numerical substructure within such a system. However, without loss of generality, we assume the simplest case of just one substructure of each type in this paper.

Historically, it is the hybrid scheme (HS) approach that has been commonly applied to the problem of experimentation with substructured systems, possibly because the method is relatively intuitive in concept and straightforward in execution. For example, HS have been widely used in pseudo-dynamically substructured tests [1–6] and then extended to the problem of entirely dynamically substructured tests [7–17]. The HS method uses feedback of the numerical substructure output as an input to the physical substructure. This is achieved via an actuator together with a series compensator, which attempts to cancel the dynamics of the actuator and its associated servocontroller, the complete subsystem being known as the transfer system. Further details on the structure of the HS are given in Section 2 and Fig. 3.

More recently, a framework for synthesising dynamically substructured systems (DSS) has been proposed from the perspective of automatic control system design [18]. The resulting DSS controller generates an input signal to the transfer system that, in turn, drives the physical substructure so that its output closely matches that of the corresponding output of the numerical substructure. In this way, the substructure interface variables are said to be synchronised. The difference between the two schemes, in automatic control engineering terms, is that the parallel structure of the DSS controller is able to achieve a high margin of relative stability, whilst the series compensator approach of the HS can only achieve (at best) a margin of relative stability that is governed by the dynamics of the emulated system. For example, an emulated civil engineering structure might typically have a damping ratio of 0.05. Even if the HS compensator is perfectly formulated, the resulting scheme will exhibit a relative stability margin equivalent to this damping ratio, i.e. a phase margin of only $\sim 5^{\circ}$. This lack of robustness would probably lead to unstable behaviour. In contrast, a DSS controller for the same emulated system would typically be designed to have a phase margin greater than 70°, far exceeding the robustness offered by HS. Hence, one of the principal objectives of this paper is to highlight this difference in achievable robustness between the two schemes, using a simple practical example taken from the fields of structural and earthquake engineering: vibration mitigation via the use of base isolating natural rubber bearings. Fig. 1 shows a schematic representation of such a system. Further details on the structure of the DSS and its control are given in Section 3 and Figs. 7 and 8.

The first published DSS control design method, called linear substructuring control (LSC), appeared in 2006 [18]. LSC, which is based upon a knowledge of the DSS dynamics, is used as a simple benchmark control policy for the purposes introduced in this paper. However, it should be noted that a knowledge of the DSS dynamics is not required in the more general case. For example, the adaptive minimal control synthesis (MCS), [19], has been applied to the DSS scheme when system parameter values are completely unknown [18,20,21]. These controllers were found to be robust to parameter variations, in both the physical substructure and transfer system. Although discrete-time computational elements certainly resulted in pure time delays being present in the reported experiments the effects of these delays were not evident in the results, due to the high level of robustness provided by the controller. As a consequence, the effect of delays was not examined in any explicit way. Nevertheless, pure time delay in the transfer system, see Fig. 2, is an important factor that will tend to destabilise an experimental substructure test system. In particular, the distinct possibility for low relative stability within the HS has resulted in a number of pure time delay compensation methods being developed for such schemes [7–17].

Therefore the focus in this paper is the stability of the basic HS and DSS as measured by the critical pure time delay, i.e. the value of delay that causes instability, which can therefore be used as an index of relative stability [17]. Hence, the delay term (τ) is the principal parameter of variation in this work, with its nominal value for design taken as $\tau = 0$ ms in the HS compensator and DSS controller synthesis procedures. However, stability analyses and experimental tests are then conducted under the assumption of a non-zero delay. In order to achieve an objective comparison in these studies, basic HS and DSS–LSC configurations were used without any additional embellishments such as pure time delay compensation,

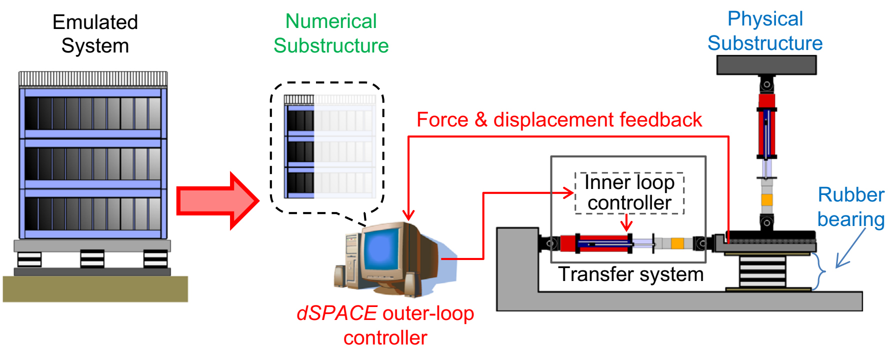

Fig. 1. Dynamical substructuring test for a rubber bearing.

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