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Nonlinear signal-based control with an error feedback action for nonlinear substructuring control

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ABSTRACT

A nonlinear signal-based control (NSBC) method utilises the 'nonlinear signal' that is obtained from the outputs of a controlled system and its linear model under the same input signal. Although this method has been examined in numerical simulations of nonlinear systems, its application in physical experiments has not been studied. In this paper, we study an application of NSBC in physical experiments and incorporate an error feedback action into the method to minimise the error and enhance the feasibility in practice. Focusing on NSBC in substructure testing methods, we propose nonlinear substructuring control (NLSC), that is a more general form of linear substructuring control (LSC) developed for dynamical substructured systems.

In this study, we experimentally and numerically verified the proposed NLSC via substructuring tests on a rubber bearing used in base-isolated structures. In the examinations, NLSC succeeded in gaining accurate results despite significant nonlinear hysteresis and unknown parameters in the substructures. The nonlinear signal feedback action in NLSC was found to be notably effective in minimising the error caused by nonlinearity or unknown properties in the controlled system. In addition, the error feedback action in NLSC was found to be essential for maintaining stability. A stability analysis based on the Nyquist criterion, which is used particularly for linear systems, was also found to be efficient for predicting the instability conditions of substructuring tests with NLSC and useful for the error feedback controller design.

1. Introduction

The nonlinear signal-based control (NSBC) method [1] proposed recently achieves accurate control of nonlinear systems, relying on the 'nonlinear signal'; this signal is obtained as an error of the outputs of a controlled system and its linear model subjected to the same input signal. The NSBC controllers are currently composed of two transfer functions $\{K_r, K_\sigma\}$ associated with the reference and nonlinear signals $\{r, \sigma\}$, respectively. These controllers are basically designed by an inverse transfer function of a linear model of the controlled system. However, this controller design is not flexible for the enhancement of the robustness for a pure time delay, which inevitably exists in the transfer system and causes the instability of the controlled system. Therefore, in order to enhance the flexibility of the design and robustness of the system, we incorporate an error feedback controller, K_e, into NSBC. In this study, for the first application in the physical experiments, the NSBC method

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with the error feedback action is employed in a dynamical substructuring method.

Dynamical substructure testing, whereby a dynamical experiment is conducted upon a critical part (referred to as the *physical substructure*) of an emulated system with real-time simulations of the other parts (referred to as the *numerical substructure*) of the system, has become a key experimental method in a wide range of engineering fields. The purpose of substructure tests is to study the properties of the critical part, such as its nonlinear characteristics, instead of conducting experiments on the entire emulated system. Many engineering fields require the effects of nonlinearities to be minimised for ease of control of the system, but, in structural and earthquake engineering, nonlinearity is positively utilised to increase the energy dissipation or change the natural frequency of the structures under earthquakes. Therefore, the dynamical substructuring methodology is required to maintain robustness for systems with nonlinearities or unknown parameters.

Hybrid system (HS) testing is probably the most intuitive execution of this technique, since this method directly uses feedback of the numerical substructure output as an input to the physical substructure via an actuation system [2–9]. The actuation system is regarded as the system to be controlled. This basic HS realises perfect control of the systems only in an ideal situation where the actuator dynamics are perfectly modelled, and there is no pure time delay. However, in practice, there is always a pure time delay and modelling error for the actuator dynamics in substructured systems. In this case, the basic HS suffers from a significant lack of robustness, in particular, for a low damped system [10–12]. To enhance the robustness, a series of advanced HS methods have been proposed to compensate for pure time delays [2–9] and dynamics changes in the actuation system [10,13–15].

Controllers developed within the dynamically substructured system (DSS) framework are proposed from the perspective of automatic control system design [16] to generate an input signal to the transfer system (a combination of actuators, inner-loop controllers and signal-conditioning hardware) that drives the physical substructure output so that it closely matches that of the corresponding output of the numerical substructure. In this method, knowledge of the parameters of the substructures, as well as the transfer system, is required in the formulation of the DSS using a linear substructuring controller (LSC). The advantage of the DSS-LSC strategy is the resultant separation of the emulated system dynamics from those of the closed-loop error dynamics. This enables the representation of even very lightly damped emulated systems using a DSS configuration with large stability margins that are designed into the system. However, the applicability of LSC is limited to relatively well-known systems because it is designed on the basis of a nominal knowledge of the dynamics of the substructures. As a result, adaptive minimal control synthesis (MCS) [17] is typically required in the DSS scheme when system parameters are unknown or poorly known [16,18,19]. In this study, in order to enhance the robustness of DSS for poorly known and highly nonlinear systems, we propose a nonlinear substructuring control (NLSC) method as a generalised form of LSC by incorporating the NSBC method with the error feedback action into DSS.

The use of discrete-time computational elements in the transfer system inevitably results in a pure time delay, which tends to destabilise experimental substructure test systems. Therefore, the stability of DSS with NLSC is also discussed in this study, with the critical pure time delay given by the Nyquist criterion, i.e., the value of delay that causes instability, which can therefore be utilised as an index of relative stability [20]. Associated experiments were conducted for the substructure test of a rubber bearing demonstrating a base-isolated structure under a seismic excitation in the Advanced Control and Test Laboratory (ACTLab), at the University of Bristol.

In Section 2, NSBC with an error feedback action is discussed together with the details of NLSC and its stability analysis for a pure time delay. In Section 3, NLSC is examined in numerical simulations of substructuring tests for rubber bearings. In Section 4, the real implementation of substructured experiments for the rubber bearing is reported.

2. Nonlinear substructuring control

In the physical experiments, transfer systems are crucially important to excite controlled systems, based on the control signal generated at computation. However, the transfer system has certain dynamics and a pure time delay, mainly caused by the discrete-time computational elements. In this study, the transfer system and its model are expressed by:

$$\begin{cases} G_{TS}(s) = G_{ts}(s)e^{-\tau s} \\ \bar{G}_{TS}(s) = \bar{G}_{ts}(s)e^{-\tau s} \end{cases} \tag{1}$$

where s is the Laplace operator, $\{G_{TS}, G_{ts}\}$ represents the transfer system dynamics including a pure time delay τ, and the undelayed component of the transfer system dynamics, respectively, and $\left\{\bar{G}_{TS}, \bar{G}_{ts}\right\}$ represents the linear models. Although dynamics in the transfer system is influenced by a controlled system due to the interaction, the error feedback action, in general, can compensate the error caused by the change of dynamics. Thus, for the simplification, our controller design is based on the separation of the transfer system and controlled system. The controller designs of the NSBC and NLSC methods are discussed in Sections 2.1 and 2.2, together with the transfer system including the pure time delay term.

2.1. Nonlinear signal-based control

NSBC relies on a nonlinear signal obtained from the output signals of a nonlinear system and its linear model under the same input signal [1], as shown in Fig. 1. In NLSC, the nonlinear system is equivalently expressed, as follows: