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Hybrid system identification for high-performance structural control

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ABSTRACT

Structural systems installed with active or semi-active control devices usually require availability of a high-fidelity model to determine appropriate control designs. Use of traditional system identification techniques has proven to be challenging, primarily due to the fact that such models must be multiple-input and multiple-output (MIMO) systems; the inputs correspond to the excitation and the control commands, while the outputs correspond to the measured responses. Even if a model is identified that can represent well the response of the structure, this model is often a non-minimal realization (i.e., the dynamics of various modes are duplicated in the model); these extra dynamics can degrade the performance of the resulting controller. This paper presents a hybrid system identification approach that can result in minimal (or near-minimal) realizations of the MIMO structure–control system models that are effective for structural control design. The first step in this approach develops a simplified model which can portray adequately the system characteristics found in the experimental data. Using information about the pole–zero relationship of the transfer function in the simplified model, a frequency-domain system identification strategy is employed subsequently to derive multiple single-input and multiple-output (SIMO) models with respect to each system input. The systems are then combined to determine the complete MIMO system model that is accurate over the frequency range of interest for the control applications. To demonstrate this hybrid approach, an example is provided to illustrate a high-fidelity identification result from the experiment of an actively isolated building system. Successful control implementation demonstrates the efficacy of this hybrid system identification approach.Structural systems installed with active or semi-active control devices usually require availability of a high-fidelity model to determine appropriate control designs. Use of traditional system identification techniques has proven to be challenging, primarily due to the fact that such models must be multiple-input and multiple-output (MIMO) systems; the inputs correspond to the excitation and the control commands, while the outputs correspond to the measured responses. Even if a model is identified that can represent well the response of the structure, this model is often a non-minimal realization (i.e., the dynamics of various modes are duplicated in the model); these extra dynamics can degrade the performance of the resulting controller. This paper presents a hybrid system identification approach that can result in minimal (or near-minimal) realizations of the MIMO structure–control system models that are effective for structural control design. The first step in this approach develops a simplified model which can portray adequately the system characteristics found in the experimental data. Using information about the pole–zero relationship of the transfer function in the simplified model, a frequency-domain system identification strategy is employed subsequently to derive multiple single-input and multiple-output (SIMO) models with respect to each system input. The systems are then combined to determine the complete MIMO system model that is accurate over the frequency range of interest for the control applications. To demonstrate this hybrid approach, an example is provided to illustrate a high-fidelity identification result from the experiment of an actively isolated building system. Successful control implementation demonstrates the efficacy of this hybrid system identification approach.

1. Introduction

To achieve high control performance in a structure–control system, a control-oriented mathematical model should be determined for the entire system through appropriate system identification techniques. System identification techniques in most civil engineering applications are parametric in nature, seeking to determine or update physical quantities such as mass, damping, and stiffness. For control purposes, specific values for the physical parameters of the structural system are not required; rather, an effective model that can accurately represent the dynamic relation

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between the various system inputs and the outputs is needed [9,10].

Identifying an appropriate model of structure–control systems is challenging, due in part to the intrinsic interaction between the control system and the structure [11]. Identification methods can determine the model of the system in either the time or frequency domain. A model obtained by a time-domain system approaches (e.g., eigensystem realization algorithm proposed by Juang and Pappa [12] or stochastic subspace system identification proposed by van Overschee and de Moore [26]) may accurately describe the dynamic response of the system, but often cannot replicate detailed frequency domain characteristics such as transfer function zeros. While precise characterization of the zeros may not be significant in terms of response prediction, it is extremely important for control design. For example, the LQG/LTR control algorithm tends to invert the system plant, making the zeros of the plant become poles of the controller; thus, inaccurate identification of the zeros will directly impact achievable control performance [22,24]. To address this problem, researchers have sought to perform identification directly in the frequency domain. Bayard [3] proposed a transfer function curve fitting method to identify a dynamic model. Auweraer et al. [1] modified this method to be more computationally efficient using the total least-squared (LS) algorithm. Kim et al. [13] developed a powerful tool for the frequency-domain system identification that allowed physical information about the number of zeros at the origin to be considered. These methods have proven to be effective for single-input-multi-output (SIMO) system and can be applied to multi-input/multi-output (MIMO) systems by combining the identified SIMO models. Several researchers have proposed approaches to achieve this combination, with the goal of obtaining minimum realizations of the identified system (i.e., redundant dynamics are not present). Dickinson et al. [8] and Chen [6] used a minimal realization method to cancel repeated modes after combining all SIMO systems into a MIMO system. Ober [19], Dyke et al. [9,10] and Chen [6] employed a balanced realization method to combine SIMO systems by reducing the order of the systems and eliminating the noise modes. However, these methods are only effective for systems for which the identified eigenvectors generated for each SIMO system are nearly collinear. These extra dynamics can degrade the performance of the resulting controller.

The identification problem can be exacerbated by the phenomena of control–structure interaction [11], which tightly couples together the dynamics of the structure and the control actuators These additional dynamics are usually associated with real eigenvalues (overdamped modes), which are challenging to accurately identify [20]. Moreover, these eigenvalues may be at high frequencies (i.e., outside the frequency range of interest in the system identification); nonetheless, their effect is present in the phase of the transfer functions, and as a result, in the eigenvectors. When multiple control devices are employed in the system, these effects are compounded.

This study develops a hybrid system identification approach to obtain a high-fidelity model for structural control applications that is comprised of the following steps: (i) determine the pole–zero arrangement for the respective transfer functions through analytical modeling of the structure–control system, (ii) identify accurate SIMO systems with respect to all inputs, assuming the pole–zero configurations determined in the previous step, and (iii) combine the identified SIMO systems to derive a minimal (or near-minimal) realization of the MIMO model. Detailed description of each of these steps will be described in the subsequent sections. Finally, to demonstrate the efficacy of this approach, a six-story, actively-isolated building in the Smart Structures Technology Laboratory at the University of Illinois at Urbana–Champaign is considered. The resulting model is shown to accurately predicts the dynamic behavior of the system in both time and frequency domains and to be effective in producing high-quality control designs.

2. Analytical modeling of actively controlled structures

Active structural control for civil engineering applications typically uses either servo-hydraulic actuators or servo-electric motors as the primary active control device. Both offer high power-to-weight ratios, allowing them to generate sufficiently large forces for control of massive civil structures [21,18]. In the remainder of this section, an approach for modeling the structure–control system with an arbitrary number of actuators is presented. This model is then used to determine the pole–zero arrangement for the system. The structure–control system considered herein employs servo-hydraulic actuators; however, the equations governing servo-electric motors are similar in nature [2].

The dynamics of servo-hydraulic actuators have been discussed in previous studies [11,4]. The dynamics of the actuator and structure are shown to be tightly coupled together (a phenomenon known as control–structure interaction). This coupling indicates that the dynamics of the servo-hydraulic actuators will vary depending on the dynamics of the structure to which they are attached. Thus, the effects of control–structure interaction need to be discussed to facilitate the development of the proposed system identification approach.

Consider the equation of motion of a structural system given in the state space representation by

$$\begin{aligned}\dot{\mathbf{x}}_s &= \mathbf{A}_s\mathbf{x}_s + \mathbf{B}_s\mathbf{f} + \mathbf{E}_s\mathbf{w} \\ \mathbf{y} &= \mathbf{C}_s\mathbf{x}_s + \mathbf{D}_s\mathbf{f} + \mathbf{F}_s\mathbf{w} + \mathbf{v}\end{aligned} \tag{1}$$

where

$$\mathbf{A}_s = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}, \quad \mathbf{B}_s = \begin{bmatrix} \mathbf{b}_1 & \cdots & \mathbf{b}_j & \cdots & \mathbf{b}_n \end{bmatrix}$$

$\mathbf{x}_s$ is the structural state in terms of displacements and velocities; $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the $N \times N$ mass, damping, and stiffness matrices of the structure with N degrees of freedom, respectively; $\mathbf{B}_s$ and $\mathbf{E}_s$ are the influence matrices with respect to the control force and external disturbance (e.g., the ground excitations or wind loads); $\mathbf{b}_j$ is an influence vector corresponding to the jth control actuators; n is the total number of control actuators; $\mathbf{y}$ is the structural response with respect to the sensor locations; $\mathbf{C}_s$, $\mathbf{D}_s$, and $\mathbf{F}_s$ are the matrices related to the structural response; $\mathbf{f}$ is an $n \times 1$ vector of forces generated by the control actuators; n is equal to $2N$ due to the fact that a state vector contains both displacement and velocity terms; $\mathbf{w}$ is a vector of disturbances; and $\mathbf{v}$ is a vector that represents the noise.

In previous studies, many models for servo-hydraulic actuators have been developed by researchers. For example, DeSilva [7] and Dyke et al. [11] proposed a 1st-oder model which considers the natural velocity feedback from the structure in the control–structure interaction. Carrion and Spencer [4] introduced the servo dynamics in the modeling, resulting in a 2nd-order model. These two models linearize the actuator behavior as the piston displacement remains small. Due to the complexity of structural systems, higher-order models may need to be developed, even considering system nonlinearity in the modeling [17,28]. This paper considers a 3rd-order model that accounts for the differential behavior between the two piston chambers in a servo-hydraulic actuator [16]. The 3rd-order actuator model is given by