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Simultaneous parameter and state estimation of shear buildings

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ABSTRACT

This paper proposes an adaptive observer that simultaneously estimates the damping/mass and stiffness/mass ratios, and the state of a seismically excited building. The adaptive observer uses only acceleration measurements of the ground and floors for both parameter and state estimation; it identifies all the parameter ratios, velocities and displacements of the structure if all the floors are instrumented; and it also estimates the state and the damping/mass and stiffness/mass ratios of a reduced model of the building if only some floors are equipped with accelerometers. This observer does not resort to any particular canonical form and employs the Least Squares (LS) algorithm and a Luenberger state estimator. The LS method is combined with a smooth parameter projection technique that provides only positive estimates, which are employed by the state estimator. Boundedness of the estimate produced by the LS algorithm does not depend on the boundedness of the state estimates. Moreover, the LS method uses a parametrization based on Linear Integral Filters that eliminate offsets in the acceleration measurements in finite time and attenuate high-frequency measurement noise. Experimental results obtained using a reduced-scale five-story confirm the effectiveness of the proposed adaptive observer.

1. Introduction

The simultaneous identification of parameters and state in shear building models has been an important topic of research in the last five decades [1] because it allows monitoring structural health and permits designing control techniques that attenuate vibrations of the structure when it is excited by external forces induced by earthquakes or wind. Usually, adaptive observers for civil structures employ acceleration measurements; the reason is that in most cases it is not possible to measure absolute displacements and velocities in a structure, since it is difficult to establish a static reference. References [2–8] present adaptive observers for systems whose models need to be written in special canonical forms obtained through static or dynamic transformations. In the particular case of civil structures, several techniques that estimate their parameters and state composed of displacements and velocities, and that do not resort to canonical transformations have been proposed in [9–28]. Observer/Kalman filter identification (OKID) approaches are presented in [9–11] and they compute the

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Markov parameters of a Kalman filter observer. These methods allow obtaining the natural frequencies and damping factors of a building. On the other hand, the methodologies reported in [12–18] employ adaptive observers based on the Kalman filter; in this case the parameters, displacements and velocities form a extended state to be estimated; the corresponding nonlinear state equation is linearized; however, some poles of the linearized equation may lie on the imaginary axis and, as a consequence, the state estimate may easily become unbounded [19]. In [19–25] adaptive observers that employ the Least Squares method are developed. Yang et al. [19] identify time-varying parameters of civil structures. Nagarajaiah and Li [20] estimate the parameters of base isolated buildings and use a reduced order observer in order to estimate the unknown states. Yang and Huang [21] consider the case in which external excitations and some floor accelerations are not available from measurements, and they developed an adaptive observer for structural health monitoring. Jiménez and Alvarez-Icaza [22] propose a parametrization for a multi-degree-of-freedom (MDOF) building that allows estimating its mass/stiffness and mass/damping ratios. Jiménez and Alvarez-Icaza [23] develop a method that estimates the state and parameters of a building and identify the parameters of a magnetorheological damper employed for attenuating the vibrations of the structure. In [24] a new parametrization of a MDOF building is proposed, which requires less computational effort than the parametrization presented in [22]. Angeles-Cervantes and Alvarez-Icaza [25] developed a technique that identifies the state and parameters of a 3D building model excited through two seismic excitation signals that are horizontal and orthogonal. Waller and Schmidt [26] present an adaptive observer that identifies the eigenfrequencies, damping and the stiffness matrix of a building. Wang et al. [27] propose an adaptive observer for structures whose design employs the Hilbert transform. Moreover, Dion et al. [28] present an adaptive observer that estimates the natural frequencies of structures and that is based on the Optimized Spectral Kurtosis and the Extended Kalman Filter (EKF); this adaptive observer tracks and removes sinusoidal components, which pollute the acceleration measurements and come from engines in operation and from spurious harmonic components of the electric power supply. Finally, references [29–31] propose Sequential Monte Carlo (SMC) methods that are robust against measurement noise, have gained popularity due to their superiority over the EKF, can simultaneously estimate the state and parameters of buildings, and require a discrete-time model of this system; with the SMC methods, the state and parameter identification consist in the computation of a non-Gaussian probability density function $p(x_k, \theta | D_k)$, where x_k is the state, θ contains the parameters of the structure, and D_k is a set that contains the measurements available up to time instant k. It is worth mentioning that most of the references [9–31] consider the presence of measurement noise, but none of them take into account offsets in the acceleration measurements. It is well known that accelerometers usually have a constant voltage disturbance at their output [32]. Therefore, the velocity and displacement of the structure cannot be obtained by simple numerical integration of the acceleration measurements since the integration of biased signals produces a drifting output.

This paper proposes an adaptive observer that simultaneously estimates the state, the damping/mass and stiffness/mass ratios of a seismically excited MDOF shear building model. This type of linear model is preferred as the final goal is to design a semi-active control system for vibration attenuation that helps preserving the building without permanent damage. Acceleration measurements of the ground and floors are employed by the adaptive observer; it is assumed that these measurements have offsets. The adaptive observer identifies all the parameter ratios, velocities and displacements of the structure if all the floors are instrumented, and it also estimates the state and the damping/mass and stiffness/mass ratios of a reduced model of the building if only some floors are equipped with accelerometers. This observer combines the Least Squares (LS) method and a Luenberger state estimator, and uses a parameterization based on Linear Integral Filters (LIF), which eliminates the constant disturbances of the acceleration measurements in finite time and attenuates measurement noise. A novel smooth parameter projection is introduced which produces only positive estimates, does not affect the stability properties of the LS method and allows constructing a stable adaptive observer. A simple technique for designing the state estimator gain, that provides a fast response of this estimator, is also proposed. If the regressor matrix associated to the parametrization fulfills a persistency of excitation condition, then the estimated parameters and state converge to their true values. Unlike the adaptive observers in [22–25], boundedness of the parameter estimates is independent of the state estimator properties; thus, the stability proof of the proposed adaptive observer is simpler than the ones presented in these references. In comparison with [2–8], the proposed adaptive observer has the advantage that it does not resort on a particular canonical form. Moreover, in contrast to the stochastic methods in [29–31], the proposed adaptive observer is completely deterministic, does not require any model transformation from continuous-time to discrete-time, and the parameter estimation does not depend on the state estimation. In order to verify the performance of the proposed methodology, experiments are carried out in a five-story small scale building. Two tests are presented: the first one consists in identifying the state and parameters of all five-stories of the building using acceleration measurements in each floor; in the second test, the state and parameters of a three-story reduced model of the structure are estimated using acceleration measurements in only three floors.

This paper has the following structure. Sections 2 and 3 show, respectively, the building model and its parametrization using the LIF. Section 4 describes the proposed adaptive observer and its convergence. Experimental results obtained using a five-story structure, that allow verifying the performance of the proposed observer, are presented in Section 5. Finally, Section 6 establishes the conclusions of this paper.