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A STFT semiactive controller for base isolated buildings with variable stiffness isolation systems

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Abstract

A new short time Fourier transformation (STFT) control algorithm is developed for reducing the response of base isolated buildings with variable stiffness isolation systems in near fault earthquakes. The central idea of STFT is to break up the signal into small time segments and Fourier analyze each time segment to ascertain the frequencies that exist in it. For each different time a different spectrum is obtained and the totality of these spectra is the time–frequency distribution. STFT is used to determine the energy spectrum and time–frequency distribution of the earthquake excitation signal. Of particular importance is the tracking of the energy of the earthquake excitation corresponding to the fundamental period of the base isolated building. When the energy of the excitation exceeds a predetermined threshold value the STFT controller varies the stiffness of the isolation system smoothly between minimum and maximum values to achieve response reduction. The main reason for the response reduction is the variation of the fundamental frequency of the base isolated building. Additionally, the STFT control algorithm ensures passivity and energy dissipation during the smooth variation of the stiffness. The STFT algorithm is implemented analytically on a five-story base isolated reinforced concrete building with linear elastomeric isolation bearings and a variable stiffness system located at the isolation level. Several recent near fault earthquakes are considered. It is shown that the controller is effective in reducing the base displacements and interstory drifts without increasing floor accelerations. The novelty of the STFT controller lies in its effective variation of stiffness only a few times to achieve response reduction, which makes it suitable for practical implementation.

Keywords: Semiactive control; STFT; Variable stiffness; Base isolated buildings

1. Introduction

The application of semiactive variable stiffness and damping devices has been investigated and demonstrated to be effective by many researchers (e.g., [16]). Passive structural control methods such as base isolation [3], supplemental fluid dampers, tuned mass dampers are widely accepted. For the case of base isolation systems with sliding or elastomeric bearings, the addition of passive damping at the isolation level to reduce the base displacements in near fault earthquakes may lead to increased interstory drifts and floor accelerations [7,4]. An attractive alternative is the use of semiactive systems. The primary goal of this study is to develop a new control algorithm for the semiactive variable stiffness (SAIVS) system to achieve response reductions in base isolated buildings subjected to near fault earthquakes.

Semiactive control of linear and nonlinear structures using novel devices such as variable stiffness systems, magnetorheological (MR) dampers and electrorheological (ER) dampers has gained significant attention in recent years [5–7,12–15,17,20,21]. The effectiveness of structural control strategies and different control algorithms has been demonstrated, by many researchers, experimentally and

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analytically [16]. The primary advantage of variable stiffness systems is their ability to avoid resonance [5,10]. The active variable stiffness system [5] has performed successfully in several earthquakes; however, the on–off device can switch stiffness between on–off states and may in some cases lead to increased accelerations. To overcome the limitation of abrupt switching, a new semiactive independently variable stiffness (SAIVS) device has been developed [10,9]. The SAIVS device is capable of switching the stiffness smoothly. The control algorithm proposed by Kobori et al. [5] is based on estimation of the response in each stiffness state and selection of the state which results in the least response. The controller developed by Yang et al. [19] is a sliding mode controller. The resetting algorithms [2,18] are effective primarily due to energy dissipation with constant stiffness. The tuned interaction damper [22] is based on Lyapunov theory. The aforementioned studies do not estimate the energy spectrum and time–frequency distribution of the ground excitation needed for developing a variable stiffness control strategy for response reduction.

In this paper the use of short time Fourier transformation (STFT) to track the energy spectrum and the time–frequency distribution of the earthquake for response control is proposed. Of particular importance is the proposed tracking of energy of the earthquake excitation, corresponding to the fundamental period of the base isolated building, used in developing the variable stiffness control algorithm. When the energy of the excitation exceeds a certain threshold value the STFT controller varies the stiffness of the isolation system smoothly between minimum and maximum values to achieve response reduction. The STFT algorithm is implemented analytically on a five-story base isolated reinforced concrete building with linear elastomeric isolation bearings and a variable stiffness system located at the isolation level. Several recent near fault earthquakes are considered. It is shown that the controller is effective in reducing the base displacements and interstory drifts without increasing floor accelerations.

2. Structure with a variable stiffness system: formulation

The equations of motion for the base isolated structure are developed on the basis of a three-dimensional formulation consisting of two lateral degrees of freedom and one rotational degree of freedom at the center of mass of each floor and the base. The state space equations for the superstructure and the base are formulated as follows:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{E}\mathbf{a}_g(t) = \mathbf{g}(\mathbf{x}, \mathbf{u}, \mathbf{a}_g) \tag{1}$$

where $\mathbf{X} = \{\mathbf{U}^T \quad \mathbf{U}_b^T \quad \dot{\mathbf{U}}^T \quad \dot{\mathbf{U}}_b^T\}^T$,

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\overline{\mathbf{M}}^{-1}\overline{\mathbf{K}} & -\overline{\mathbf{M}}^{-1}\overline{\mathbf{C}} \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ -\overline{\mathbf{M}}^{-1} \end{bmatrix},$$

$$\mathbf{E} = \begin{bmatrix} \mathbf{0} \\ -\overline{\mathbf{M}}^{-1} \begin{Bmatrix} \mathbf{MR} \\ \mathbf{R}^T\mathbf{MR} + \mathbf{M}_b \end{Bmatrix} \end{bmatrix},$$

$$\overline{\mathbf{M}} = \begin{bmatrix} \mathbf{M} & \mathbf{MR} \\ \mathbf{R}^T\mathbf{M} & \mathbf{R}^T\mathbf{MR} + \mathbf{M}_b \end{bmatrix}, \qquad \overline{\mathbf{C}} = \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_b \end{bmatrix},$$

$$\overline{\mathbf{K}} = \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_b \end{bmatrix}, \qquad \mathbf{u} = \begin{bmatrix} \mathbf{0} \\ \mathbf{f}_d \end{bmatrix}.$$

In the above equations, $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{E}$ are system matrices. $\mathbf{M}$ is the superstructure mass matrix, $\mathbf{C}$ is the superstructure damping matrix in the fixed base case, $\mathbf{K}$ is the superstructure stiffness matrix in the fixed base case, $\mathbf{M}_b$ is the mass of the rigid base, $\mathbf{C}_b$ is the damping of isolation system, $\mathbf{K}_b$ is the total stiffness of elastic isolation elements and $\mathbf{f}_d$ is the vector of force from the control devices. $\mathbf{R}$ is the matrix of earthquake influence coefficients consisting of zeros corresponding to rotational degree of freedom and ones corresponding to the two lateral degrees of freedom. Furthermore, $\ddot{\mathbf{U}}$, $\dot{\mathbf{U}}$ and $\mathbf{U}$ represent the floor acceleration, velocity and displacement vectors relative to the base, $\ddot{\mathbf{U}}_b$ is the base acceleration relative to the ground and $\mathbf{a}_g$ is the ground acceleration in two perpendicular directions (x and y). The evaluation and measured output equations are

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} + \mathbf{Ea}_g \tag{2}$$

$$\mathbf{z} = \mathbf{Cx} + \mathbf{Du} \tag{3}$$

$$\mathbf{y}_m = \mathbf{C}_m\mathbf{x} + \mathbf{D}_m\mathbf{u} + \mathbf{Ea}_g + \mathbf{v} \tag{4}$$

where $\mathbf{z}$ is the evaluation output vector which is obtained by choosing the appropriate mapping matrices, $\mathbf{C}$ and $\mathbf{D}$. The evaluation output vector, $\mathbf{z}$, consists of the base displacement, floor accelerations and interstory drifts. $\mathbf{y}_m$ is the measurement vector consisting of the relative velocity at the device connection points, force in the devices and ground acceleration. These can be obtained by choosing appropriate mapping matrices $\mathbf{C}_m$ and $\mathbf{D}_m$. $\mathbf{v}$ is the measurement noise vector which is assumed to be white noise. The $\mathbf{E}$ matrix is chosen to include the measured ground acceleration.

2.1. Sensor model

The sensors are modeled as follows:

$$\dot{\mathbf{X}}^s = \mathbf{g}_1(\mathbf{X}^s, \mathbf{y}_m, \mathbf{f}_d, t) \tag{5}$$

$$\mathbf{y}_s = \mathbf{g}_2(\mathbf{X}^s, \mathbf{y}_m, \mathbf{f}_d, \mathbf{v}, t) \tag{6}$$

where $\mathbf{X}^s$ are the states of the sensor, $\mathbf{v}$ is the measurement noise vector, $\mathbf{f}_d$ is the vector of device forces and $\mathbf{y}_s$ is the output of the sensor in volts. $\mathbf{y}_m$ consists of the relative velocity at the location of the devices that is needed for feedback into the controller and ground accelerations.

2.2. The control algorithm

The control algorithm is implemented in the discrete domain as follows: