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Model reduction and optimal parameters of mid-story isolation systems

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ABSTRACT

The paper presents a modal synthesis-based approach to develop a reduced two, three, or higher order model to represent a mid-story isolated building structure. Herein, the approach is utilized to obtain a simple two-degree of freedom model which can effectively capture the response characteristics of the full system well. This reduced order model is used to formulate analytical approaches for calculating the optimal parameters of a mid-story isolation system that either minimize the (a) maximum base shear force amplitudes for harmonic base excitations or (b) base shear force variance for a band-limited white noise random base excitation. Numerical examples are, then, presented to study the influence of the placement of an optimal mid-story isolation system at different levels in a building as well as to show the structural response reducing effects of the isolators.

1. Introduction

Base isolation is now a very well-recognized and accepted seismic response reduction approach used in the design of building and bridge structures in the seismic areas around the world. Its effectiveness has been demonstrated in several past earthquakes and effective design guidelines are available in building codes in several different countries. The most common and effective practice is to place seismic isolators at the base of a structures to deflect the seismic energy. However, the placement of isolation systems at levels higher than the base, called as the "mid-story isolation" has also attracted interest in building designs to take advantage of the seismic isolation effectiveness in special building constructions and applications. It can be used with advantage to improve the performance of buildings where base isolation may have some issues such as congested urban areas and near-sea structures. It can also be used with specific advantages in structures that need to have vertical irregularity or discontinuities, in multistory buildings with structural transfer stories, and in structures in which addition of more stories are anticipated or planned. Although tall building structures being relatively less stiff may not be very good candidates for base isolation, their seismic performance can also be enhanced by incorporating an optimally placed mid-story isolation system to reduce deformation responses of both upper and lower stories.

Several studies on this topic have appeared in the seismic design literature. Tsuneki et al. [1], Tasaka et al. [2] and Murakami et al. [3] discuss some building designs that incorporate the mid-story isolation systems in Japan and its impact on structural response. Several numerical as well as experimental studies [3–8,16,17] analyzing the effectiveness and limitations of such isolation systems have also appeared. The effect of nonlinearity of the system (Shirayama, et al. [4]; Hu et al. [5]), the impact of the placement of isolators at different story levels and other isolator parameters on the isolation effectiveness (Huang, et al., [6]; Zhou et al. [7]) and the effect of modal coupling on response amplification of isolated upper structure (Kobayashi and Koh 8) have been reported. Villaverde's studies [9–11] on the design of vibration absorbers and on utilizing the roof as a large tuned mass damper to improve the performance of multistory buildings with properly designed isolation system and the study by Sadek et al. [12] could be considered as a mid-story isolation near the top. Chey et al. [13] essentially utilize a similar concept to propose the "added stories isolation" which takes the advantage of added stories as a large tuned mass damper to reduce the structural response. Charmpis et al. [14] develop an algorithm to design optimal isolation systems at multiple levels primarily with the objective of minimizing the maximum building floor acceleration using genetic algorithm.

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To accurately evaluate the effect of a mid-story isolation system on a multistory building structure, it is necessary that a complete model of the system accurately incorporating the detail of the building properties as well as the isolation system is considered. Some researchers, including Murakami et al. [1–3], Shirayama et al. [4] and Hu et al. [5], use multi-degree-of-freedom lumped-mass computational model with nonlinear restoring force model of isolator to investigate the mid-story isolation system. However, such a complete and comprehensive model can become cumbersome to use to study the impact of major system parameters on the effectiveness of a planned isolation system, and thus simpler models that capture the fundamental characteristics of the complete system are very useful. The studies with such simple models can be very helpful in preparing and planning an initial design approach the effectiveness of which can be finally evaluated by a more thorough analysis of a more detailed model. The major parameters that are of interest in such initial design studies are the structural and isolator frequencies, isolator damping, the mass ratio of the isolated building parts which depends on the story level at which an isolator is placed, etc.

To examine the impact of some of these parameters, reduced but representative two- and three-lumped mass models have been commonly used in the literature on the subject of the base isolation [15], roof isolation [11,12] and mid-story isolation [7,16,17] to demonstrate the effectiveness and impact of the proposed schemes. The two-lumped mass models of mid-story isolation system are often based on the premise that the isolated part of the building above the level at which a soft isolator is inserted behaves as a rigid body under earthquake excitations. This suggest lumping of the mass of the upper structure and isolation story mass as one lumped mass supported by the isolator. The lower part of the structure below the isolation story is represented by another lumped mass. For example, Zhou et al. [7] and Qi et al. [16] utilize the total masses of the lower part of the isolated structure as the bottom mass of the two-mass model. Villaverde [11], Sadek et al. [12], and Chey et al. [13] have also used two-mass models, however, they incorporate the modal characteristics of the lower part to determine the bottom mass to study the impact of the roof and mid-story isolation systems. To capture the effect of the flexibility of the upper part of the isolated structure on the system response, the isolator and the upper stories have also been modeled as two lumped mass models by Kelly [15]. In a mid-story isolation system, this flexible representation of the upper part leads to a three-lumped mass model. Such three-lumped mass models have been used by Kobayashi and Koh [8] and Wang et al. [17], to study the impact of modal interaction on the lower substructure and isolated superstructure response. In fact Wang et al. [17] have used such a model to identify the range of sub and super structure frequencies where modal interaction can adversely affect the performance of the isolation system.

In this study also we use a two-lumped mass model to study the response characteristics of mid-story isolation systems. However, the mass and stiffness characteristic of this model are derived based on the modal synthesis approach. By comparing the frequency response functions of structural accelerations and base shear, the mode synthesis-based model is shown to represent the full structure better than some lumped mass models used earlier. The proposed mode synthesis-based model is then used to determine the optimal isolation parameters and to study the impact of using an isolation system on the structural response.

2. Mode synthesis-based reduced order model

Consider a typical multi-degree-of-freedom (MDOF) shear beam building structure shown Fig. 1 divided into two parts by an isolation story. The isolation story is included with the upper structure. Let N_u and N_l be the number of the stories in the upper and lower parts, respectively. Assuming that the structural system remains elastic and the stiffness and damping elements of the isolation system can be described in terms of an equivalent linear elastic spring and a linear viscous damper, the equations of motion under earthquake excitation for the lower part and the upper part, respectively, can be written as follows:

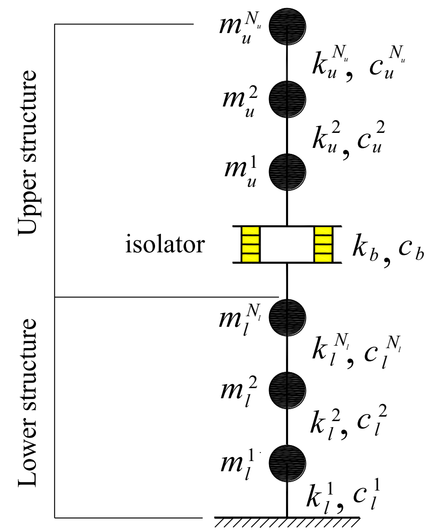

Fig. 1. Full model of mid-story isolation structure.

$$[M_l]\{\ddot{x}_l\} + [M_t]\{\ddot{x}_u\} + [C_l]\{\dot{x}_l\} + [K_l]\{x_l\} = -([M_l]\{1_l\} + [M_t]\{1_u\})\ddot{x}_g \quad (1)$$

$$[M_u]\{\ddot{x}_u\} + [C_u]\{\dot{x}_u\} + [K_u]\{x_u\} + \{F_t\} = -[M_u]\{1_u\}\ddot{x}_g \quad (2)$$

Wherein, the $N_l \times N_l$ mass, damping and stiffness matrices of the lower structure are associated with subscript l and $N_u \times N_u$ matrices of the upper structure are associated with subscript u; $\{x_l\}$ and $\{x_u\}$, respectively, are the N_l- and N_u-dimensional displacement vectors of the lower and upper structure relative to the ground; $\{1_l\}$ and $\{1_u\}$ are the $N_l \times 1$ and $N_u \times 1$ vectors with all their elements equal to 1; and $\ddot{x}_g$ is the ground acceleration. The elements of the mass, stiffness and damping matrices of the upper part are defined in usual way in terms of the floor masses, damping coefficients and story stiffness values (m_u^j, c_u^j and k_u^j, $j = 2$ *to* N_u) as well as the mass, equivalent damping and stiffness value of the isolation story (m_u^1, c_b and k_b), and likewise these matrices for the lower part are defined in terms of the floor masses, damping coefficients and story stiffness values (m_l^j, c_l^j and k_l^j, $j = 1$ to N_l) of the lower part. The matrix $[M_t]$ is a $N_l \times N_u$ mass matrix and $\{F_t\}$ is a N_u-dimensional force vector defined as follows:

$$[M_t] = \begin{bmatrix} [0]_{(N_l-1)\times N_u} \\ \{1_u\}^T[M_u] \end{bmatrix}, \quad \{F_t\} = \begin{Bmatrix} -c_b\dot{x}_l^{N_l} - k_b x_l^{N_l} \\ \{0\}_{(N_u-1)\times 1} \end{Bmatrix} \quad (3)$$

Next, we express the displacement vector $\{x_u\}$ of the upper structure in terms of its displacement $\{\tilde{x}_u\}$ with respect to its base and the displacement of the top floor of the lower structure $x_l^{N_l}$ on which the isolation system is placed as,

$$\{x_u\} = \{1_u\}x_l^{N_l} + \{\tilde{x}_u\} \quad (4)$$

Substituting Eq. (4) into Eqs. (1) and (2) we obtain the following: