ACTIVE ISOLATION OF STRUCTURES UNDER SEISMIC VIBRATIONS

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Seismic isolation of structures is very important to prevent serious damage in buildings due to earthquake, and to protect equipment during transportation. Several passive or semi-active devices exist for protecting structures from secondary seismic waves, but few solutions are present to avoid damage due to primary waves. Usually, primary waves are considered less dangerous than secondary waves, nonetheless they can produce serious damage close to the epicentre.

In order to protect structures from vertical oscillations, in this paper an active vibration control system is proposed. In the present formulation, active vibration control is based upon varying foundation stiffness during the seismic movement. In the paper, it will be shown how such kind of vibration control is effective in suppressing vibrations for the case of a measured earthquake signal.

Keywords: Active vibration control

1. Introduction

The problem of seismic wave isolation has been faced by many authors, both using passive and active control methods [1]. Seismic waves act on a building as a transient external forcing, so that they can be very dangerous if the harmonic content of the seismic forcing matches one of the system natural frequencies [2]. Passive isolation methods include Base Isolators (BI) [3], which are low-pass filters designed in order to cut out the frequencies containing most of the seismic energy. Another approach is to reduce the amplitude of oscillations in the structure by means of Tuned Mass Damper (TMD). The archetype of TMD has been described by Den Hartog [4] and is capable to cancel a resonance of the system. More recently, Non-linear Energy Sinks (NES) [5] and Tuned Liquid Dampers (TLD) [6] have been proposed as passive as passive seismic energy absorbers. Mohtat et al. [7] developed an active Tuned Mass Damper for controlling a seismically excited beam.

The recent literature include many papers about active isolation methods. In 2011, Fujita et al. [8] proposed a method for activating an air bearing isolating support upon earthquake occurrence. Recently, some works [9] have shown, by numerical simulations, the effectiveness of an active switch of the stiffness of the base in seismic isolation. In the present paper, the active stiffness control of a system under seismic excitation is investigated.
2. Dynamic model

In the present work, a simple 2 dof model is considered, see Figure 1(a). The model consists of a mass \( m_1 \), which represents the base of the building, and of a suspended mass \( m_2 \), connected to the base by a spring having constant stiffness \( k_2 \), and by a viscous damper \( c_2 \). The base is connected to the ground by means of a spring having time varying stiffness \( k_1 \) and a viscous damper \( c_1 \). The maximum value of the varying stiffness is \( \bar{k}_1 \). The system is under the effect of the weight force, and of the seismic base forcing \( y_1 \). The motion equations are the following:

\[
\begin{align*}
    m_1 \ddot{x}_1 + k_1 (x_1 - y_1) + k_2 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{y}_1) + c_2 (\dot{x}_1 - \dot{x}_2) &= -m_1 g \\
    m_2 \ddot{x}_2 + k_2 (x_2 - x_1) + c_2 (\dot{x}_2 - \dot{x}_1) &= -m_2 g
\end{align*}
\]

The forcing displacement \( y_1 \) is a sine function of frequency \( f \) and maximum acceleration amplitude \( a_g \) enveloped by a half sine wave having duration \( T \), see eq. (2).

\[
y_1(t) = \frac{a_g \sin (2\pi ft) \sin \left( \frac{\pi t}{T} \right)}{(2\pi f)^2}
\]

The simple model proposed can simulate the dynamic behavior of a building or an equipment or a shipping container. In these three cases, the model parameters and the exciting base vibration are different. In the present paper, simulations are performed referring to a seismic loading of a building: Table 1 collects the equivalent parameters used in numerical computations.

<table>
<thead>
<tr>
<th>( m_1 (kg) )</th>
<th>( m_2 (kg) )</th>
<th>( \bar{k}_1 (N/m) )</th>
<th>( k_1 (N/m) )</th>
<th>( T (s) )</th>
<th>( a_g (g) )</th>
<th>( f_c (Hz) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 8.0 \cdot 10^3 )</td>
<td>( 8.0 \cdot 10^3 )</td>
<td>( 1.05 \cdot 10^9 )</td>
<td>( 1.05 \cdot 10^9 )</td>
<td>( 30 )</td>
<td>( 0.2 )</td>
<td>( 100 )</td>
</tr>
</tbody>
</table>

Table 1: Parameters used in the numerical simulations

\( k_1 \) is time varying due to the control activation: it changes during the simulation according to the following control strategy:

1. the control is activated if the overall base vibration (i.e. maximum base acceleration within a period of the exciting oscillation) exceeds a certain fraction of \( g \), namely \( \psi \)
2. when the control is activated, base velocity is checked at control frequency \( f_c \): if the system base has positive velocity at the \( k-th \) control instant \( t_{c,k} \), then the stiffness \( k_1 \) is reduced of a fraction \( \phi \).

Provided that the first condition is matched, at the \( k-th \) control instant, \( k_1 \) is switched as follows:

\[
    k_1 = \begin{cases} 
    \varphi \bar{k}_1 & \text{if } \dot{x}_1(t_{c,k}) > 0 \\
    \bar{k}_1 & \text{otherwise}
    \end{cases}
\]

Figure 1: (a) Model of the two dof system; (b) external forcing \( y_1 \)
3. Results and Discussion

3.1 Control effectiveness

In order to show how the proposed method can be effective in controlling seismic vibrations, Figure 2(a) displays the results of a run without control (case A) along with a run having velocity control activated (case B). In both cases, the external forcing frequency $f$ matches the fundamental frequency of the system $f_1$. The control parameters are $\varphi = 0.5$ and $\psi = 0.01$, i.e. stiffness is reduced by one half for positive base velocity and the control works only if the overall vibration exceeds $0.01g$. The control is capable to reduce by 88% the maximum acceleration of the suspended mass $m_2$: from $1.9g$ to $0.2g$. In the same picture, case D represents the solution obtained using the same control parameters, but for a system which is not loaded by any weight force ($g = 0$ in eq. (1)). For case D, the maximum acceleration is cut by 44% only, thus suggesting that an important role in the proposed active control method is played by the weight force. Indeed, reducing the stiffness when the base is going upwards (positive $\dot{x}_1$) means having a longer stroke for the weight force, when it is doing negative work over the system.

Figure 2(b) shows what happens if no check of the overall vibration is performed (case C, $\psi = 0$). The static equilibrium position is unstable, and the controlled system presents a limit cycle in the aftershock, oscillating around a new equilibrium position. In order to overcome such limit cycle arising, numerical simulations have proven that $\psi = 0.01$ is sufficient; moreover, an higher value of $\psi$ would introduce higher vibrations when the control activates, due to the abrupt change in the system when it is already oscillating.

Figure 2: Effectiveness of the control: (a) A – no control, B – controlled, D – controlled without gravity; (b) A – no control; C – control with $\psi = 0$

3.2 Optimal parameters

In this section, a parametric analysis is performed: the maximum acceleration of the top mass $a_2$ is chosen as the objective function, and its relationship with the forcing frequency $f$ and the stiffness parameter $\varphi$ is investigated (Figure 3). If the stiffness $k_1$ is reduced by a small amount, the acceleration is still high; if $k_1$ is reduced a lot, then the varying stiffness excites the system more than the seismic load itself. The best value for $\varphi$ is 0.5: for such value the proposed control strategy is effective broadband, both below and over the fundamental frequency of the system.

Figures 4 and 5 clarify the behavior of the system with/without control. Control activation changes the center around which the system oscillates: this is due to the reduced average stiffness. In terms of acceleration, when the control is active the top mass acceleration is much lower than in the no control case, nonetheless the base presents a certain acceleration for all the seismic duration. Figure 5(b)
clarifies this feature: each time the velocity $v_1$ reaches a zero, the corresponding acceleration $a_2$ has a jump, which is due to the sudden stiffness variation. The energy for this change, which cannot be instantaneous in the real application, must be provided by the control actuator. Figure 6(b) shows the isolation effect due to the control: the total energy of the system has a maximum of 4700 J without control, 1040 J with optimal control.

Figure 3: Maximum top mass acceleration for varying control parameters

4. Conclusions

A control method for seismic isolation of buildings or equipments has been theoretically investigated. The control consists in changing the stiffness of the building base when its velocity has opposite sign with respect to the weight force. The role of the weight force has been pointed out by means of numerical simulations, as well as the importance of setting a further control condition in terms of the overall acceleration, so that instabilities are prevented. A parametrical study has shown that the best control for all the forcing frequencies can be obtained for a base stiffness reduction of one half. For such value, the top mass acceleration is cut by 88% with respect to the uncontrolled case, nonetheless the base vibrates at constant amplitude for a longer time, due to effect of the actuator.

Figure 4: Positions of the oscillating masses: case A — without control, case B — with $\varphi = 0.5$
Figure 5: Accelerations of the oscillating masses: case A — without control, case B — with $\varphi = 0.5$

Figure 6: (a) Total energy: case A — no control, case B — with $\varphi = 0.5$; stiffness fluctuation during seismic control

REFERENCES


