Intelligent Base Isolation Systems

Erik A. Johnson,1 Juan C. Ramallo,1 Billie F. Spencer, Jr.1 and Michael K. Sain2

1 Dept. of Civil Engineering and Geo. Sciences, University of Notre Dame, Notre Dame, IN 46556, USA
2 Dept. of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA

ABSTRACT

An intelligent base-isolation system, comprised of low damping isolation bearings and controllable fluid dampers, is studied in this paper. The damper employs a magnetorheological (MR) fluid that change its properties in the presence of a magnetic field, resulting in a damper whose characteristics may be modified in real time to adapt to changing excitations in a stable and cost-effective manner. A model of a five-story building is used to study and compare the efficacy of a passive base-isolation alone, with the addition of an active control device, and with a semi-active MR damper. A preliminary study of active $H_2$/LQG designs shows that mostly dissipative designs exist, which may be implemented using far less power in an approximate manner with an MR damper. Simulations of the semi-active system demonstrate that the ‘smart’ damper can achieve most of the decrease in base displacement and peak acceleration typical of an active device.

1. INTRODUCTION

Base isolation systems are one of the most successful and widely-applied methods of mitigating structural vibration and damage during seismic events. Base isolation systems have been installed in numerous full-scale structures (Kelly, 1981, 1996; Buckle and Mayes, 1990; Soong and Constantinou, 1994; Skinner et al., 1993). However, consideration of near-fault, high-velocity, long-period seismic pulses, as were recorded during the Northridge and Kobe earthquakes, has taught engineers and researchers that ground motion due to such earthquakes can be difficult to accommodate. For example, a base isolated structure in one region of Los Angeles that readily survived the 1994 Northridge earthquake, may well have been destroyed if it were located elsewhere in the region (Makris, 1997). A base isolation system that can adapt to, and protect against, seismic excitation of differing characteristics may help mitigate these problems.

Current design codes for seismic isolation (UBC, 1997) have quite conservative requirements, which can lead to large isolators, costly flexible utility connections, and expensive loss of space for the seismic gap. To alleviate these effects, isolators have been augmented with
supplemental damping devices (e.g., Asher et al., 1996); the effect, however, is to decrease base drift at the expense of increasing floor acceleration and structure interstory drifts. Furthermore, when designed for a maximum capable earthquake (MCE), extremely low-probability events, little isolation effect may be realized in more probable moderate earthquakes (Elsesser, 1997).

Several active base control systems have been proposed and studied (e.g., Reinhorn et al., 1987; Kelly et al., 1987; Yoshida et al., 1994; Schmitendorf et al., 1994; Yang et al., 1996), with the goal of supplementing passive base-isolation with active control devices to limit base drift. Several small-scale experiments (e.g., Reinhorn and Riley, 1994) have been performed to verify the effectiveness found in the simulation studies. Active control devices, however, have yet to be fully embraced by engineers, in large part due to the challenges of large power supplies (that will not be interrupted during an earthquake), concerns about stability, and so forth.

In this paper, a preliminary study of an intelligent base isolation system is presented, using controllable fluid dampers to improve the performance over that of purely passive isolation systems. The proposed system is comprised of low damping isolation bearings and controllable fluid dampers employing magnetorheological (MR) fluid. While controllable isolation systems have been suggested by other authors and shown to be promising, the proposed system employing the MR damper overcomes many of the expenses and technical difficulties of these systems. The focus of this current study is to demonstrate the potential of such 'smart' dampers in comparison with active control devices. A model of a five-story building is used as a testbed for this analytical and simulation study. The efficacy of three isolation systems is studied and compared: passive base-isolation alone, augmented by an active control device, and augmented by a semi-active MR damper. It is shown that one may design an active control that is largely dissipative in nature. Using a clipped-optimal form of these control designs and an MR damper performs as well as the active control in constraining base displacements; peak accelerations remain smaller than with the passive isolation system alone, but somewhat increased over the active system in these preliminary results.

2. PROBLEM FORMULATION

2.1. System Model

The structure used in this study is a five-story building model, based on that given by Kelly et al. (1987). The model, shown in both fixed-base and base-isolated configurations in Figure 1, is a lumped-parameter model that assumes the motion of the structure is sufficiently moderate that nonlinearities have minimal effect on the system dynamics. Letting \( x \) denote the displacements of the floor slabs relative to the ground, the equation of motion of the base-isolated system may be written

\[
M \ddot{x} + C \dot{x} + K x = A f - M \dot{1} g
\]

where \( \Lambda = [1 \, 0]^T \) gives the position of the MR damper, \( f \) is the force exerted by the damper, and \( 1 \) is a vector whose elements are all unity. Rewriting in state-space form, with sensors measuring interstory displacements and absolute floor accelerations, gives
\[
\begin{align*}
\dot{z} &= Az + Bf + E\ddot{x}_g \\
Y &= Cz + Df + v
\end{align*}
\] (2)

where
\[
A = \begin{bmatrix} 0 & 1 \\ -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M_s^{-1}A \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ -1 \end{bmatrix}
\] (3)

and \( \Delta \) is a matrix giving interstory displacements (ones on the diagonal and negative ones on the subdiagonal). An additional filter state is added to model the relatively, but not infinitely, fast dynamics of the actuator; this also has the benefit of zeroing the \( D \) matrix, which simplifies subsequent control design.

The fixed-base structure is chosen to have the same parameters and dynamic characteristics as in Kelly et al. (1987), with a fixed-base fundamental period of 0.3 seconds and 2% damping in the first mode. The base mass is chosen to be \( m_0 = 6800 \text{ kg} \) as in Kelley et al. (1987). The base stiffness \( k_0 \) is chosen such that the fundamental period of the base-isolated structure is 2.5 seconds. The base isolator is assumed to be low damping isolation bearings such as laminated-rubber bearings, which falls in the ‘Class (ii): lightly damped, linear isolation system’ category of Skinner et al. (1993). It is assumed here that the isolation bearings are indeed linear, with an isolation mode damping ratio of 4%; \( c_0 \) is chosen accordingly. The parameters of the structure and passive base isolation are given in Table 1.

2.2. MR Damper Model

The MR damper may be modeled using a simple Bingham viscoplastic model (Shames and Cozzarelli, 1992; Spencer et al., 1997), with a viscous damping term in parallel with a controllable yield force

\[
f_{\text{damper}} = f_{\text{yield}}(u) \, \text{sgn} \dot{x} + c_{\text{MR}} \ddot{x}
\] (4)
where $c_{\text{MR}}$ is the viscous damping coefficient and $f_{\text{yield}} \geq 0$ is the yield force which is related to the fluid yielding stress. The yield force is controllable by sending a voltage signal $u$ to the electromagnets in the MR device. The time constant of a full scale device is on the order of 100 ms, which is fast in comparison with the fundamental natural frequencies of the base-isolated structure.

The viscous damping factor and maximum yield force for the MR device are dependent on the size and configuration of the device; for this preliminary study, these properties are assumed to be $c_{\text{MR}} = 3000 \text{ Ns/m}$ and $f_{\text{yieldmax}} = 12.5 \text{ kN}$.

### 3. CONTROL STRATEGIES

#### 3.1. Passive Base Isolation Augmented by an Active Control Device

Several studies have focused on the use of active control devices in parallel with a base-isolation system. For example, Kelly et al. (1987) proposed a Lyapunov control design for an active control device installed between the base of a building and the ground. They demonstrated that significant reduction in base displacement could be achieved with this active control.

In this preliminary study, an $H_2/LQG$ control design is used, assuming in the control design that the ground motion is Gaussian white noise. (A more realistic approach would be to incorporate a shaping filter, such as one corresponding to a Kanai-Tajimi spectrum (Soong and Grigoriu, 1993), into an $H_2$ control design (Spencer et al., 1998; Zhou et al., 1996), so as to more closely match typical earthquake spectra.) The ground excitation and measurement noises are assumed to be independent, and the measurement noises are identically distributed; the ratio of the power spectral density magnitudes is taken to be

$$
\gamma = \frac{S_{x_x}}{S_{v_v}} = 49
$$

The system outputs, absolute accelerations and interstory drifts, are weighted so as to minimize floor accelerations and the base drift. It was observed that decreasing floor accelerations had the side effect of similar decreases in interstory drifts, so the drifts (other than the base) need not be weighted in the control design. In particular, the cost function

$$
J = \lim_{\tau \to \infty} \frac{1}{\tau} \left[ \int_0^\tau \left( (y^TQy + rf^2) dt \right) \right] = \lim_{\tau \to \infty} \frac{1}{\tau} \left[ \int_0^\tau \left( (Cz)^TQ(Cz) + rf^2 \right) dt \right]
$$

is used with a diagonal $Q$ weighting matrix with elements $q_{\text{base drift}} = 0_{1\times5}$ and $q_{\text{accel}} = 1_{1\times6}$ and a weight on the force $r = 10^{-10}$ (which is small due to the large magnitude of the force

<table>
<thead>
<tr>
<th>Floor Masses [kg]</th>
<th>Stiffness Coefficients [kN/m]</th>
<th>Damping Coefficients [kNs/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0 = 6800$</td>
<td>$k_0 = 231.5$</td>
<td>$c_0 = 7.45$</td>
</tr>
<tr>
<td>$m_1 = 5897$</td>
<td>$k_1 = 33732$</td>
<td>$c_1 = 67$</td>
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<tr>
<td>$m_2 = 5897$</td>
<td>$k_2 = 29093$</td>
<td>$c_2 = 58$</td>
</tr>
<tr>
<td>$m_3 = 5897$</td>
<td>$k_3 = 28621$</td>
<td>$c_3 = 57$</td>
</tr>
<tr>
<td>$m_4 = 5897$</td>
<td>$k_4 = 24954$</td>
<td>$c_4 = 50$</td>
</tr>
<tr>
<td>$m_5 = 5897$</td>
<td>$k_5 = 19059$</td>
<td>$c_5 = 38$</td>
</tr>
</tbody>
</table>

Table 1. Structural model parameters (Kelley et al, 1987).
relative to the drifts and accelerations in $\mathbf{z}$). An $H_\infty$/LQG control may then be designed using one of several convenient tools (e.g., the Control Toolbox in MATLAB®) to solve two Riccati equations. The resulting optimal compensator $\mathbf{K}(s)$ is dynamic and of order equal to that of the original plant.

### 3.2. Passive Base Isolation Augmented by a Semi-Active Control Device

In previous studies of MR dampers in seismic protection systems (e.g., Dyke et al., 1996a,b), one control strategy that performed well, a clipped-optimal control, was to assume an ‘ideal’ active control device, use $H_\infty$/LQG control theory to design an appropriate controller for this active device, and then, using a secondary bang-bang-type controller, try to make the MR damper replicate the same forces the active device would have exerted on the structure. Since the force generated by the MR damper is dependent on the structure and its motion, it is not always possible to produce the ‘desired’ force. In reality, only the voltage to the electromagnets may be commanded. The secondary control law that Dyke et al. (1996a,b) used is given by

$$u = u_{\text{max}}H(f_{\text{actual}}[f_{\text{desired}} - f_{\text{actual}}])$$  \hspace{2cm} (7)

where $H(\cdot)$ is the Heaviside function. Effectively, this law turns the voltage on full when the desired force is dissipative and larger than the measured force.

Since the MR damper is an energy dissipation device and cannot add mechanical energy to the structural system, care must be taken in the design of the primary controller (here, the $H_\infty$/LQG design) so that the ‘desired’ force is dissipative the majority of the time history of a seismic event. Thus, the first test for the efficacy of an MR damper in such a system for base isolation is to check the rate of energy dissipation, which may be given by

$$\text{rate of energy dissipation} = -f_{\text{actual}}v$$  \hspace{2cm} (8)

where $v$ is the velocity across the damper, which, in this case, is the base velocity $\dot{x}_0$.

### 4. NUMERICAL RESULTS

#### 4.1. Active Control

In order to determine appropriate $H_\infty$/LQG weighting matrices, an in-depth parameter study was performed. A family of controllers that best decrease base drift or absolute accelerations or some balance of the two were obtained. Three representative controllers were designed with $q_{\text{base drift}} = 60$ and $q_{\text{accels}} = 20$ for the balanced case, and setting one or the other to zero to weight either base drift or acceleration more heavily.

Figure 2 shows, for a N-S 1940 El Centro ground excitation, the resulting base drift and the roof acceleration (which was observed to be the peak acceleration for nearly all cases) for the fixed-base, passive, and three actively-controlled cases. The passive system decreases the peak acceleration by 84% over the fixed-base system, but at the cost of 28.3 cm peak base drift. The active control with balanced weights cuts both the peak base drift and peak roof acceleration...
by 57% and 77%, respectively, over the passive system alone. Weighting the accelerations more gives less decrease in peak base drift over the passive case, but with an 81% decrease in peak acceleration. On the other hand, weighting the base drift tends closer to the fixed-base structure, decreasing peak base drift by 79% over the passive case, but with accelerations larger than the passive case.

The rate of energy dissipation (rate of work done by the structure on the active control) is shown in Figure 3 for the balanced-weighting case (and the MR controlled case discussed below); the cumulative energy dissipated by the active device is 10.6 kNm, and the cumulative energy added to the structure is 4.9 kNm, for a net energy dissipation of 5.8 kNm. The fact that the active control is energy dissipative for a majority portion of the time record suggests that this system is a good candidate for implementing an MR damper.

4.2. MR Damper in Isolation System

The base isolated system augmented by the MR damper was simulated using SIMULINK®. Figure 4 shows a comparison of the base drift and roof accelerations for the fixed-base, passive isolated, active control, and MR damper control systems. The MR damper is able to constrain the base drifts quite well, about 16% smaller than the active case; while it does increase the
peak acceleration somewhat over that of the active control case, it is still 41% below the peak accelerations of the passive isolation system alone. Table 2 lists the peak responses for each of the control strategies for several earthquake excitations.

The MR damper isolation system does not perform quite as well for the near-field earthquakes studied herein, as may also be seen in Figure 5, which gives the base drifts and roof displacements.
Table 2. Maximum base drift, absolute accelerations, and applied force.

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>El Centro</th>
<th>Hachinohe</th>
<th>Kobe</th>
<th>Northridge</th>
<th>El Centro*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Base Drift [m]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive Isolation</td>
<td>0.283</td>
<td>0.426</td>
<td>0.366</td>
<td>0.822</td>
<td>0.344</td>
</tr>
<tr>
<td>Active Control</td>
<td>0.123</td>
<td>0.146</td>
<td>0.183</td>
<td>0.365</td>
<td>0.127</td>
</tr>
<tr>
<td>MR damper</td>
<td>0.103</td>
<td>0.096</td>
<td>0.282</td>
<td>0.534</td>
<td>0.115</td>
</tr>
<tr>
<td><strong>Peak Absolute Acceleration [g]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed base</td>
<td>1.197</td>
<td>1.054</td>
<td>2.954</td>
<td>4.005</td>
<td>1.197</td>
</tr>
<tr>
<td>Passive Isolation</td>
<td>0.190</td>
<td>0.282</td>
<td>0.247</td>
<td>0.544</td>
<td>0.227</td>
</tr>
<tr>
<td>Active Control</td>
<td>0.043</td>
<td>0.043</td>
<td>0.107</td>
<td>0.161</td>
<td>0.040</td>
</tr>
<tr>
<td>MR damper</td>
<td>0.112</td>
<td>0.101</td>
<td>0.205</td>
<td>0.382</td>
<td>0.123</td>
</tr>
<tr>
<td><strong>Peak Applied Force [N]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Control</td>
<td>25269</td>
<td>29969</td>
<td>37353</td>
<td>74023</td>
<td>26099</td>
</tr>
<tr>
<td>MR damper</td>
<td>12819</td>
<td>12555</td>
<td>14071</td>
<td>15561</td>
<td>13022</td>
</tr>
</tbody>
</table>

* using 0.56% isolation-mode damping as per Kelly et al. (1987) instead of the 4% used elsewhere herein

Figure 5. Comparison of base drifts and peak accelerations for the MR controlled system under a Kobe excitation.
accelerations due to 1995 N-S Kobe ground excitation. Here, the base drift and peak acceleration of the MR system are smaller than the passive system but only about 20% less, in contrast with the active control at 50-60% less than the passive results. Part of the reason for this decreased efficacy is undoubtedly that the control parameters were tuned to perform well during an El Centro excitation. Additionally, the energy dissipation by the MR device, which was double that of the active control for the El Centro earthquake, is not much more than the active control in the Kobe earthquake (see Figure 6).

5. CONCLUSIONS

A comparison study covering two possible types of ‘intelligent’ base isolation systems, ideal fully active and semi-active via MR damper, was performed. The response to several earthquake excitations were computed. This preliminary study suggests that MR dampers show significant promise in base isolation applications with greatly reduced power requirements.

Several important items remain for future study. First, although the control strategy used herein has been shown to be effective, there are a number of other viable contenders (Dyke and Spencer, 1997) that should be considered. Second, as base isolation systems are designed based on the so-called Maximum Capable Earthquake (MCE), the control algorithms used herein should be tuned to the strong, near-field earthquakes (e.g., Kobe and Northridge) and, then, their performance under more moderate earthquakes (e.g., El Centro and Hachinohe) gauged.

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