EQUIVALENT PASSIVE SYSTEMS FOR SEMI-ACTIVE VISCOS FLUID DAMPERS

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Abstract
In this paper, the capabilities of passive control of structures using hydraulic fluid dampers are compared to those of semi-active control. It is demonstrated that, in most cases, the performance achieved by a properly designed passive control system can be comparable to that of semi-active systems that use the state-of-the-art control algorithms. It is also shown that the optimum damping coefficients for passive control may be much smaller than the maximum values considered in semi-active control. These conclusions are supported by numerical simulations of several structures, including a case of actual implementation of semi-active control in a building structure.

Introduction
Control strategies based on semi-active devices have received close attention in recent years, due to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources. In addition, semi-active systems do not have the potential to destabilize the structural system (Soong and Spencer 2002). This study focuses on the use of the passive and semi-active hydraulic fluid dampers utilized in a structural bracing system for supplemental energy dissipation.

In semi-active structural control using hydraulic fluid dampers, a controllable, electromechanical, variable orifice valve is added to a conventional damper to alter the resistance to flow of the fluid, and thus the damping provided by the device. Depending on the control objective and algorithm, a control force is determined at any instant, and then, the damping coefficient of the device is modified in such a way that the resulting force is as close as possible to the calculated control force.

However, the fact that the value of the damping coefficient is limited between its minimum and maximum values implies that i) the damper cannot add energy to the system by performing work on the structure (Symans and Constantinou 1995), and ii) the amount of generated force cannot be greater than that of a passive damper with the maximum damping coefficient. These considerations may lead to an optimally designed passive structural control system that is able to perform as well as the semi-active system, which if possible, can be an important achievement in terms of implementation convenience and economical feasibility.

Several years after a semi-active structural control scheme was proposed by Hrovat (Hrovat, Barak et al. 1983), semi-active control of structures has become the subject of vast research publications (Symans and Constantinou 1995; Symans and Constantinou 1997; Symans and Constantinou 1997; Kurata, Kobori et al. 1999; Niwa, Kobori et al. 2000; Nasu, Kobori et al. 2001; Spencer and Nagarajaiah 2003; Iemura, Igarashi et al. 2006). Many of them cover the identification of the characteristics of semi-active systems and devices through experimental studies, along with proposition of analytical models. Others focus on control algorithms and the advantages that can be achieved by making dampers act in a semi-active way. The majority of these publications demonstrate the advantage of semi-active systems compared to the cases where the damping coefficients of the devices are kept at their minimum or maximum.

Utilization of semi-active dampers in tuned-mass vibration absorbers has been studied by several authors (Hrovat, Barak et al. 1983; Abe 1996; Ricciardelli, Occhiuzzi et al. 2000; Pinkaew and Fujino 2001). The
comparisons among passive and semi-active tuned mass systems have revealed that a better performance can be achieved by using a semi-active system with relatively low power requirement. Their superior performance has been demonstrated in improved earthquake or steady-state response, in the reduced amount of tuned mass stroke, or in the reduction of the effects of uncertainties or variations associated with the estimates of structural properties that are important in the design of tuned mass dampers.

By referring to the available literature on semi-active control systems, a lack of comparative studies among passive energy dissipation systems using fluid dampers in the bracing system and their semi-active equivalents can be observed. Such a study can reveal the advantages and disadvantages of the semi-active system, which has recently been of considerable interest for vibration control of buildings.

**Damper Model**

A typical braced story equipped with a linear hydraulic fluid damper, along with its numerical model, is shown in Figure 1. In this figure, \( k_s \) and \( c_s \) represent the stiffness and damping of the unbraced story, \( k_b \) is stiffness of the bracing system, and \( k_d \) and \( c_d \) are stiffness and damping coefficient of the device.

The damping coefficient can be constant (passive device) or variable (semi-active damper). The stiffness of the device, \( k_d \), acts in parallel with device damping, and can be either constant or variable, if a stiffness variable device is sought. If the damper shaft cannot be considered rigid, its stiffness can be taken into account by properly modifying the brace stiffness in the analytical model.

The equivalent stiffness \( k \) and damping \( c \) of the story can be calculated using the following relations (Hanson and Soong 2001):

\[
k = k_s + \frac{k_b k_s (k_b + k_d) + k_b c_s^2 \omega^2}{(k_b + k_d)^2 + c_s^2 \omega^2}
\]

(1)

\[
c = c_s + \frac{k_b^2 c_d}{(k_b + k_d)^2 + c_s^2 \omega^2}
\]

(2)

When the stiffness of the device is set to zero (linear viscous damping device) and the brace is stiff enough to be considered rigid, the equivalent mechanical properties reduce to:

\[
k = \lim_{k_b \to \infty} \left( k_s + \frac{k_b k_s (k_b + k_d) + k_b c_s^2 \omega^2}{(k_b + k_d)^2 + c_s^2 \omega^2} \right) = k_s
\]

(3)

\[
c = \lim_{k_b \to \infty} \left( c_s + \frac{k_b^2 c_d}{(k_b + k_d)^2 + c_s^2 \omega^2} \right) = c_s + c_d
\]

(4)

It can be observed that, with this assumption, the structure can be thought as an unbraced frame, with increased damping, which is very desirable as larger values of damping coefficient will result in a better performance in terms of story drift and absolute acceleration. However, this condition cannot be achieved in practice, and stiffness of the brace plays an important role in the response of the system. When this stiffness is taken into account, the equivalent stiffness and damping constant of the system for large device damping will be different, as demonstrated by the following equations:
Controlled Seismic Response Spectra

In this section, the results of a parametric study on a single-degree-of-freedom system as shown in Figure 2 are presented. The natural period of the system ranges from 0.25 s to 1.25 s. With a mass of 200,000 kg, the appropriate stiffness \( k_s \) has been selected for each natural period. The uncontrolled system is assumed to have a damping of 2% of critical.

The device damping coefficient, \( c_d \), is allowed to range from 0 to \( \frac{100}{kN \cdot s \cdot \text{mm}} \), with the maximum produced force being limited to 700 kN. Three ratios of the brace stiffness to the story stiffness, namely 2, 4, and 6, have been considered.

For each set of the periods and brace stiffnesses, the peak drift and absolute acceleration of the uncontrolled system when subjected to 1940 El Centro earthquake are first determined, which are simply the linear displacement and absolute acceleration response spectra for a SDOF structure with 2% damping. Then, an optimal passive control system is chosen, whose damping coefficient is within the above-mentioned range. In order to select the optimal damping coefficients, a structural performance index is defined as:

\[
I_{sp} = w_a d_{max} + w_d a_{max}
\]

whose minimum value implies the best performance. In the above equation, \( a_{max} \) is the peak absolute acceleration, \( d_{max} \) is the maximum displacement or drift, and \( w_a \) and \( w_d \) are weighting coefficients for acceleration and displacement, respectively. It should be noted that this equation is not dimensionally consistent, which has to be considered in the selection of the weights. Finally, using the same structural performance index, a semi-active system is designed based on an LQR algorithm, and the results are plotted against the natural period of the system.

As illustrated in Figure 3, both control strategies significantly reduce peak drift and absolute acceleration of the mass, with the semi-active system being more successful in drift reduction, but not for accelerations. On average, the drift reduction resulted from the passive system is 87%, while this reduction resulted from the semi-active system is about 91%. In terms of absolute acceleration, the results
show average reductions of 44% and 36% for passive and semi-active systems, respectively. From these simulations, one can observe that the semi-active system does not demonstrate significant improvement over the optimum passive system.

When the brace is assumed to be infinitely rigid, a passive control with the maximum damping coefficient gives the best performance. On average, peak drift and peak absolute acceleration are reduced by 99% and 53%, respectively, when the maximum available damping coefficient is used with a rigid brace. It should be noted that based on the selected structural properties, the damping coefficient of $10 \, kN/s/\text{mm}$ results in an overdamped system for the entire period range. When damping is increased to $100 \, kN/s/\text{mm}$, the system is highly overdamped. In the design of passive systems, the optimum damping coefficients are less than $7 \, kN/s/\text{mm}$ in all cases. In most of the semi-active systems, however, the entire range of available damping coefficients has been utilized. When the response spectra with added damping are considered in comparison to the controlled response spectra, one can observe that both control strategies produce a response which is close to the response of the original building with more than 50% added damping.

By comparing the above plots, it can be observed that, while the semi-active control approach significantly reduces the effect of brace stiffness in the response, the resulting performance is not as good as a passive system with a very stiff brace. The fact that a rigid brace makes the device and interstory velocities identical suggests that a viable variation of the damping coefficient can be in such a way that the resulting force will be equal to the multiplication of interstory velocity by a constant damping coefficient. The device damping coefficient should then be of the form:

$$c(t) = c_0 \frac{v_{\text{interstory}}}{v_{\text{device}}}$$

which, of course, is limited between its minimum and maximum values. There are also limitations on the amount of resulting force in the variable damping device. The controlled seismic response spectra of the system when the damping coefficient is determined based on equation (8) is shown in Figure 4. As illustrated, the average reductions of peak drift and peak absolute acceleration are 88% and 53%, respectively. They show a better performance than a passive or a semi-active system, especially in terms of absolute acceleration. In comparison to the response spectra with added damping, the equivalent additional damping is around 60% of critical. The performance, however, is not as good as that can be achieved by a passive system with rigid braces.
The fact that the calculated velocity ratio has an inherent delay (even in a realistic numerical simulation), and the generated force and applicable damping coefficients are limited, prevents the achievement of a perfect rigid-brace-like behavior in the preceding series of simulations. In addition, there are cases in which velocity of the device and interstory velocity are not of the same sign. It is worthwhile to mention that, because of these limitations, a selection of the highest damping coefficient for $c_o$ does not necessarily result in the best performance, as it does not allow sufficient variation of damping coefficient.

**Case Study**

Among the control algorithms studied by Symans and Constantinou (Symans and Constantinou 1995), LQR was shown to give better results than others, including the Sliding Mode Control. However, they have already demonstrated that keeping the maximum damping coefficient results in a performance close to a semi-active system, in which the damping coefficient is variable based on an LQR algorithm.

In this section, we consider the first actual application of semi-active fluid dampers in a building (Kurata, Kobori et al. 1999). The structural properties of the building are listed in Table 1. The maximum damping force is limited to $1000 \text{kN}$, and maximum damping coefficient is about $200 \text{kN} - \text{s/mm}$ for each of the devices. However, a relief load less than $900 \text{kN}$ has been selected for the devices. The minimum damping coefficient is close to zero, and the maximum velocity capacity of the devices is $250 \text{mm/s}$. Two devices are installed in each of the first four stories of the building.

Since the stiffnesses of the brace and device are in series, the equivalent stiffness column of Table 1 is determined by:

$$k_{eq} = \frac{k_b k_d}{k_b + k_d} \tag{9}$$

<table>
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<th>Floor</th>
<th>Mass (Kg)</th>
<th>Frame Stiffness $k_f$ ($\text{kN/mm}$)</th>
<th>Brace Stiffness $k_b$ ($\text{kN/mm}$)</th>
<th>Device Stiffness $k_d$ ($\text{kN/mm}$)</th>
<th>Equivalent Stiffness $k_{eq}$ ($\text{kN/mm}$)</th>
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</tr>
<tr>
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<td>147</td>
<td>438×2</td>
<td>400×2</td>
<td>209.1×2</td>
</tr>
</tbody>
</table>

Table 1. Structural properties of structure 2.

An inherent damping of 2% is assumed for the structure. The first mode period of the uncontrolled structure is 0.992 seconds. The semi-active controller has been designed by Kurata et al (Kurata, Kobori et al. 1999), using an LQR approach (Soong 1990). The weighting matrices $Q$ and $R$ have been selected to be:
where $r$ ranges from 0.01 to 0.4. The displacement gains in the feedback gain matrix, $G$, have been observed to be insignificant compared to the velocity gains, and are ignored, thus eliminating the need for measuring displacements. After the control force is determined at each step, the damping coefficient of each device is selected based on the following strategy:

$$c(t) = \begin{cases} 
    f_{max} / |v_i|, & u_i \times v_i > 0, |u_i| > f_{max} \\
    c_{max}, & u_i \times v_i > 0, |u_i| \leq f_{max} \\
    u_i / v_i, & u_i \times v_i < 0, |u_i| / |v_i| \leq c_{max} \\
    0, & u_i \times v_i \leq 0, |u_i| \leq f_{max}
\end{cases}$$

(11)

in which $v_i$ is the device velocity, and $u_i$ is the desired control force. Then, the actual control force can be determined by multiplying the device velocity by the damping coefficient.

The uncontrolled peak response of the structure under 1940 El Centro earthquake is illustrated in Figure 5. The maximum drift, slightly less than 5cm, can be observed at the second floor, and the maximum acceleration at the top floor is about 0.9g.

Simulations show that selecting $r = 0.05$ results in an optimal performance under this earthquake. The maximum drifts and accelerations are demonstrated in Figure 6. As shown, the reductions of drifts are very significant, while peak accelerations are also considerably reduced, and are very close to the peak ground acceleration.

As mentioned earlier, selecting high damping is not always a good solution, as with very high damping, the role of the braces becomes more important, and the resulting change in the structural properties can be detrimental to the building performance. In this case, the drifts are observed to be almost double of those of semi-actively controlled building, and the accelerations are very large, even compared to the uncontrolled building. It should be mentioned that the maximum device force here is limited to 900 kN, which can be implemented by a pressure valve without any power requirement.

This phenomenon is expected since, with large damping, the building behaves like a braced one, and its dynamic properties of the building become less dependent on the damping provided by the devices. In the extreme case of very large damping coefficient, the first mode period reduces to 0.610s, which is closer to the dominant period of most earthquakes.

However, the optimal passive damping coefficient was found to be a constant damping of $8 \text{kN} - \text{s/mm}$ for all of the devices, or about 4% of the maximum available damping coefficient. The peak response as illustrated in Figure 7 shows very small difference to that of semi-active system, except for the last floor, where no device is present. This can be considered as an advantage of the semi-active system, which can take advantage of the data collected in the last story to modify the response, while the passive devices only produce a controlling force based on their local excitation.
The semi-active control based on interstory velocities (equation (8)) results in the peak response illustrated in Figure 8. Again, a comparable response to the passive system can be observed, with small reductions in all quantities.

Simulations using stronger earthquakes have also shown that the same conclusion can be drawn from structural performance standpoint. For example, 1995 Kobe earthquake results in the structural response shown in Figure 9, which demonstrates that the passive system and the semi-active systems perform similarly under this earthquake. Again, as a result of the absence of any controlling device in the last floor, the maximum acceleration detected in the last floor is higher by about 0.2g in the passive control case. The first floor control force history of the passive and LQR semi-active control systems are shown in Figure 10. It is evident that the difference between these two strategies is very small, implying that the optimal LQR semi-active controller tends to resemble a force history similar to that of an optimal passive system.

Conclusions

Several parametric analyses and case studies have shown that the limitations on the force produced by a semi-active damping device, along with its dependency on local excitation, significantly limit its ability to control structural response. As a result, it has been demonstrated that, in most cases, an optimum passive control system can be designed, whose resulting performance is comparable to what can be achieved by a semi-active system that uses state-of-the-art active control algorithms. In addition, implementation issues such as delay and control and measurement spillovers will degrade the performance of semi-active systems, while these issues do not exist in passive systems. The selection of a semi-active system over a more cost-effective and easier-to-implement passive control system should then be made carefully.

As an advantage for a semi-active system, when the full state feedback is available, a semi-active system may improve the response quantities in the places that control force cannot be directly applied. In addition, it has been shown in other studies that semi-active systems offer adaptability that can be useful...
when uncertainties or alterations of the structural properties make the design of optimum passive control systems difficult. It has been observed that semi-active control systems slightly improve the performance over the passive systems, partially by reducing the effect of brace stiffness in the response. Nonetheless, in no case the performance can be as good as a passive system with a rigid brace. For this reason, another semi-active control strategy that tends to remove the effect of bracing flexibility is studied and shown to be as effective as LQR.

In order for a semi-active control system to perform acceptably, a wide range of damping coefficients should be available. As a result, the maximum available damping is in general significantly larger than an optimal passive damping coefficient. Hence, the use of fail-safe strategies in semi-active systems that automatically switch to the maximum damping coefficient in case of power failure should be carried out with care.

Finally, it is important to note that the above-mentioned conclusions are derived based on comparisons of passive systems with semi-active systems that utilize LQR algorithm. While these conclusions should be carefully extended to other control algorithms, the above-mentioned limitations of semi-active fluid damping devices exist regardless of the utilized control algorithm. In any case, it is strongly recommended to compare the performance of the semi-active control system with the optimally designed passive system for any building, before the final selection of the control system.

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