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# CONTROL OF BUILDING SEISMIC RESPONSE BY MEANS OF THREE SEMI-ACTIVE FRICTION DAMPERS

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A study has been made of the use of three semi-active friction devices, herein referred to as dampers, to control the seismic response of a building modelled as three masses. With a pseudo-random earthquake input, peak lateral accelerations, inter-storey drift and base displacement relative to ground can be reduced by up to 50% of the values in the passive case. The relative effectiveness of each damper is assessed. The damper between the base and the ground is, as anticipated, the most useful.



## 1. INTRODUCTION

The protection of buildings from seismic and wind inputs has received increasing attention in recent years. Methods studied include active tendons, moving mass absorbers and piezo-electrically powered actuators [1].

Another approach is to utilize friction forces. Feng [2, 3] examined the use of controlled normal force on sliding bearings positioned between the base of the building and the ground. The normal force (and hence the friction force generated by the damper) was controlled by a hydraulic actuator. For small ground inputs, friction forces are kept low, allowing the building to slide easily. For larger ground inputs, friction is increased sufficiently to keep relative base displacements to a safe level, while keeping building accelerations to an acceptable level. With the use of one semi-active device only, a compromise has to be made between displacements and accelerations.

Fujita studied a system in which a friction damper is positioned between the base and the ground [4]. A copper-based alloy was pressed against a stainless-steel bar. The friction force was controlled by a hydraulic actuator, with the pressure developed assumed to be governed by a first order equation. The building had two freedoms but in the control logic, the building is considered to be one lumped mass. Fuzzy logic was employed. Satisfactory displacement response was reported.

The use of term "*damper*" for the devices being developed by the authors is purely a matter of convention. In fact, these devices can be used for the production of *anti-spring forces*, which result in dynamic de-tuning of the system—the effective natural frequencies of the system are reduced in the dynamic condition. The static strength of the structure is

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unchanged. Some pseudo-viscous damping is found useful, particularly in the control of drift (inter-storey displacements) but the device can operate without employing damping at all. Nevertheless, the widespread use of the term damper as a control device is followed here.

The authors have studied systems employing one semi-active damper [5], the major application in view being the control of vibrations in machines and also motor vehicles, where the friction damper has to be located between the sprung mass and the unsprung mass. Since discomfort correlates with acceleration, it is desirable to reduce this. For sinusoidal road inputs and a single mass, a reduction of 50% in acceleration relative to the passive case is predicted. For a double-mass system typical of a quarter car, and random road input, the reduction is around 30%.

Passive sliding base elements have been used in over 200 bridges worldwide. Active or semi-active applications have also been considered. Yang *et al.* [6] studied a bridge with adjustable viscous dampers, a system which is similar in principle to that employed in some vehicle semi-active suspensions. Nagarajaiah *et al.* [7] have used sliding bearings with actuators employed in parallel with rubber bearings.

A particular interest of the authors, and one germane to the reduction of building vibrations, is the type of control logic employed. The original logic employed in road vehicles was "skyhook", in which the damping force is related to absolute velocity. This logic limits relative deflections (rattle space in the case of vehicles and inter-storey drift in the case of buildings) but increases accelerations, which is particularly undesirable in the case of buildings, where equipment and services (gas, water) could be damaged. Indeed some deaths in the 1999 Izmit (Turkey) earthquake were reportedly due to televisions falling on to people sleeping below. Accordingly accelerations should be kept below 3 $m/s^2$.

Large relative movements within a building (drift) are also liable to fracture pipes and may result in walls actually falling out of the building. For this reason it is desirable to keep drift below 0.5% storey height.

The authors have considered a logic, first advanced by Alony and Sankar [8] and also by Subramamian *et al.* [9], which cancels or reduces the absolute acceleration. The strategy is to reduce or cancel spring forces, which is equivalent to reducing the effective natural frequency of the structure without affecting its static strength.

In order to control drift as well as accelerations, a hybrid logic, a blend of stiffness reduction and pseudo-viscous structural damping, was advanced by one of the authors [10] for a single semi-active damper. This logic is employed here, the main objective of the work being a study of the isolation achievable in buildings by *three* semi-active friction dampers, one between base and ground and the other two positioned higher up the building. The performance of a two-block building controlled by two dampers [11] has been presented by the authors elsewhere. This study was sufficiently encouraging to warrant the extension of the building and control model.

Given that a building will have many storey (20 has been suggested as a basis for comparative studies) it is not possible to place dampers at every location. The study of optimal positioning of *passive* dampers has been examined by a number of workers. Gorgoze and Muller [12] studied the positioning of one viscous damper. Hahn and Sathiavageeswaran [13] concluded that for a uniform building, dampers should be placed in the lower part of the building. Takewaki and Uetani [14] proposed a search algorithm. The performance with three semi-active dampers (acting primarily as de-tuning devices) is examined here.

## 2. THEORY

### 2.1. BUILDING MODEL

Although an $N$ storey building is envisaged, the model adopted employs only three masses, each block representing several stories, the aim being to approximate the vibration of the building in the range of its lower modes. The objective is to discover the type of performance produced by three semi-active dampers controlled by a hybrid logic.

Only lateral motion is considered, the building being treated as a shear structure. The building (see Figure 1) is modelled as three masses $M_1$, $M_2$, $M_3$, connected by linear springs to represent structural stiffness for displacements in the elastic region. The lateral stiffness to ground $K_1$ is governed by the flexibility of the structure and also of the soil. The latter is a function of the type of soil, which can be characterized by the speed $v_s$ of shear waves. For a building of height $h$ and base area $b \times b$ in plan, and fundamental period $T_\infty$ in rigid soil, the fundamental period is taken to be [15]

$$T^2 = T_\infty^2 + 1{\cdot}47Jb^2(1 + 1{\cdot}65J^2)/v_s^2,$$

where $J$ is the building aspect ratio $h/b$.

The influence of soil conditions is indicated in Figure 2 where $T$ is plotted as a function of shear wave velocity $v_s$ for three different buildings, each of aspect ratio 4. The building is assumed to be rigid ($T_\infty$ zero) so that the graph shows the behaviour of the second term in the above equation. The difference between a rock foundation and sand foundation is a profound one in terms of dynamic response as well as static strength. However, since the frequency content of earthquakes varies it is not easy to make a choice of a desirable fundamental period. However, it is worth noting that for passive isolation systems [16], designs having a natural period in the range 2–4 s have been chosen.

A base isolation system, in which the building is placed on laterally flexible mounts and soil removed from around the base, can be represented by an appropriate choice of $v_s$.

Denoting by $K_{1\infty}$ the purely structural stiffness at the base, the values of $K_{1\infty}$, $K_2$ and $K_3$ are chosen so that the fundamental frequency of the three mass systems is that of the $N$th

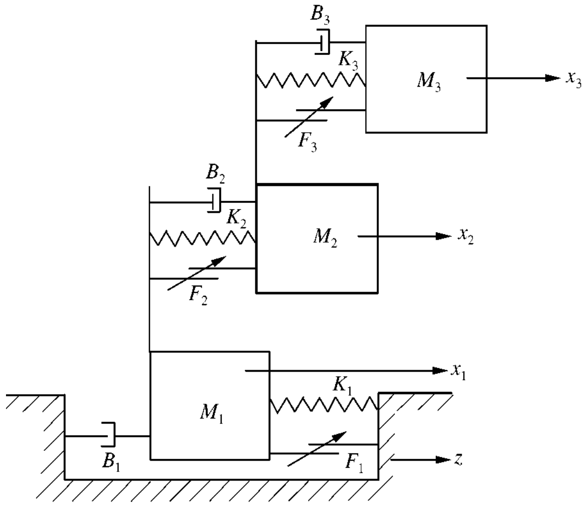


Figure 1. Analytical model.

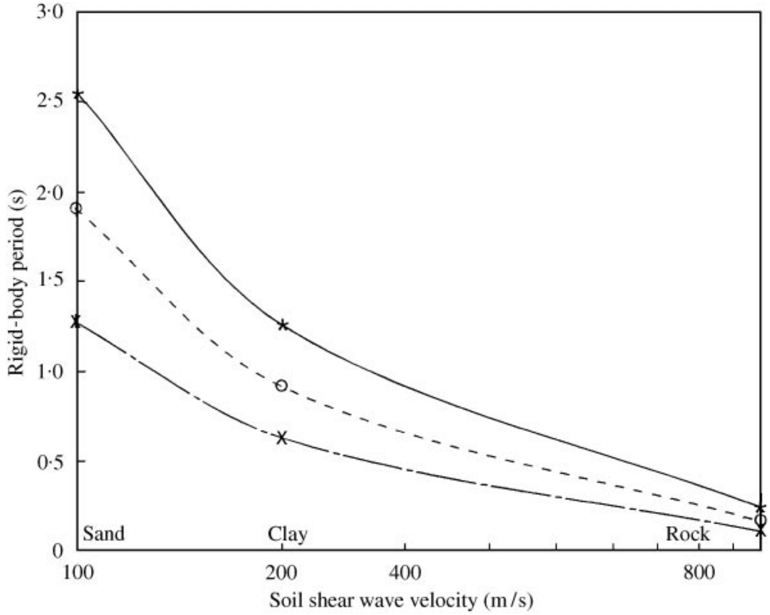


Figure 2. Influence of soil on building rigid-body period (building aspect ratio 4): —∗— height 80 m; – – ○– – height 60 m; —— × —— height 40 m.

storey building considered when soil flexibility is negligible. The period $T_\infty$ in this case is assumed, for a square plan building, to be of the form $T_\infty = h/c$ where $h$ is the height of the building and $c$ is a constant (having the dimensions of velocity) which depends on the type of construction.

For a uniform three mass body, the fundamental frequency is $0{\cdot}445\omega$, where $\omega$ is the frequency $(K_j/M_j)^{0{\cdot}5}$ of each of the three sub-systems. Hence given a uniform building of a known height, the natural frequency of the three subsystems can be deduced. Soil and structural damping are assumed, as is usual, to be viscous in nature.

The equations of motion are

$$M_1 \mathrm{d}^2x_1/\mathrm{d}t^2 = -M_2\mathrm{d}^2x_2/\mathrm{d}t^2 - M_3\mathrm{d}^2x_3/\mathrm{d}t^2 - K_1(x_1 - z) - B_1(v_1 - v_0) + F_1, \quad (1)$$

$$M_2 \mathrm{d}^2x_2/\mathrm{d}t^2 = -M_3\mathrm{d}^2x_3/\mathrm{d}t^2 - K_2(x_2 - x_1) - B_2(v_2 - v_1) + F_2, \quad (2)$$

$$M_3 \mathrm{d}^2x_3/\mathrm{d}t^2 = -K_3(x_3 - x_2) - B_3(v_3 - v_2) + F_3, \quad (3)$$

where

$$v_0 = \mathrm{d}z/\mathrm{d}t, \qquad v_j = \mathrm{d}x_j/\mathrm{d}t \quad (j = 1, 3), \qquad \omega_i^2 = K_i/M_i$$

and

$$B_1 = 2\zeta_{soil}\omega_1 M_1, \qquad B_2 = 2\zeta_{str}\omega_2 M_2, \qquad B_3 = 2\zeta_{str}\omega_3 M_3.$$

Since soil damping is in general low (5% or less), in order to generate the required control forces it appears necessary to take the damper down to bedrock or very compacted soil. Hence, the friction device is assumed to act in parallel with soil damping rather than in series.

Setting

$$q_j = F_j/M_j \quad (j = 1, 3),$$

it is assumed that the response of the hydraulic system controlling the normal force on the friction plate is governed by a first order equation

$$t_c \mathrm{d}q_j/\mathrm{d}t + q_j = q_{j,dem},$$

where $t_c$ is the time constant of the control system, assumed to be the same for all three dampers.

The (lateral) earth movement $z$ is represented as the sum of a number of sinusoids of random phase and frequency

$$0{\cdot}25k + \pi/100, \qquad k = 1, 40.$$

The $\pi/100$ term is added to the frequencies to prevent gross beating effects. The frequency range employed was thus approximately 0·28–4·03 Hz. The amplitude of each component is chosen to given constant peak velocity in the frequency range 0·2–3 Hz, with constant displacement below 0·2 Hz and constant acceleration above 3 Hz. The waveform is finally shaped by a rooftop envelope $(t_1, t_2)$:

$$\mathrm{e} = \begin{cases} t/t_1, & t < t_1, \\ 1, & t_1 < t < t_2, \\ (t_3 - t)/(t_3 - t_2), & t > t_2, \end{cases}$$

where $t_3$ is the duration of the earthquake.

### 2.2. CONTROL LOGIC

Recalling that $q_j = F_j/M_j$ $(j = 1, 3)$ since the friction force must oppose the relative velocity, it is necessary that

$$q_1(v_1 - v_0) < 0, \qquad q_2(v_2 - v_1) < 0, \qquad q_3(v_3 - v_2) < 0, \tag{4–6}$$

where $v_0$ is the ground lateral velocity $\mathrm{d}z/\mathrm{d}t$,

#### 2.2.1. *Balance logic* (*cancellation of acceleration*)

For the top damper to cancel the acceleration $a_3$, equation (3) indicates that

$$q_3 = \omega_3^2(x_3 - x_2) + 2\zeta_3\omega_3(v_3 - v_2)$$

provided that

$$q_3(v_3 - v_2) < 0,$$

i.e.,

$$\omega_3(\omega_3 u + 2\zeta_3 v_u)v_u < 0,$$

where $u$ is the relative displacement

$$x_3 - x_2 \quad \text{and} \quad v_u = \mathrm{d}u/\mathrm{d}t,$$

i.e.,

$$uv_u < -2\zeta_3 v_u^2/\omega_3$$

for the damper to be on, the conditions are

$$\text{if } v_u > 0, \quad u < -b_3 v_u, \qquad \text{if } v_u < 0, \quad u > b_3 v_u,$$

where

$$b_3 = 2\zeta_{str}/\omega_3, \tag{7}$$

The ON region in the phase plane is indicated in Figure 3(a).

The angle $\theta$ in Figure 3 is given by

$$\tan\theta = \omega_3/2\zeta_{str} = 1/b_3.$$

Hence, the greater the damping in the structure, the smaller the region in which the damper is on.

2.2.2. *Shear reduction logic*

Inter-storey drift can be controlled by the addition of pseudo-viscous damping generated by the device. However, the increase in damping reduces the available switching region as is indicated above, and so reduces the capability for acceleration cancellation.

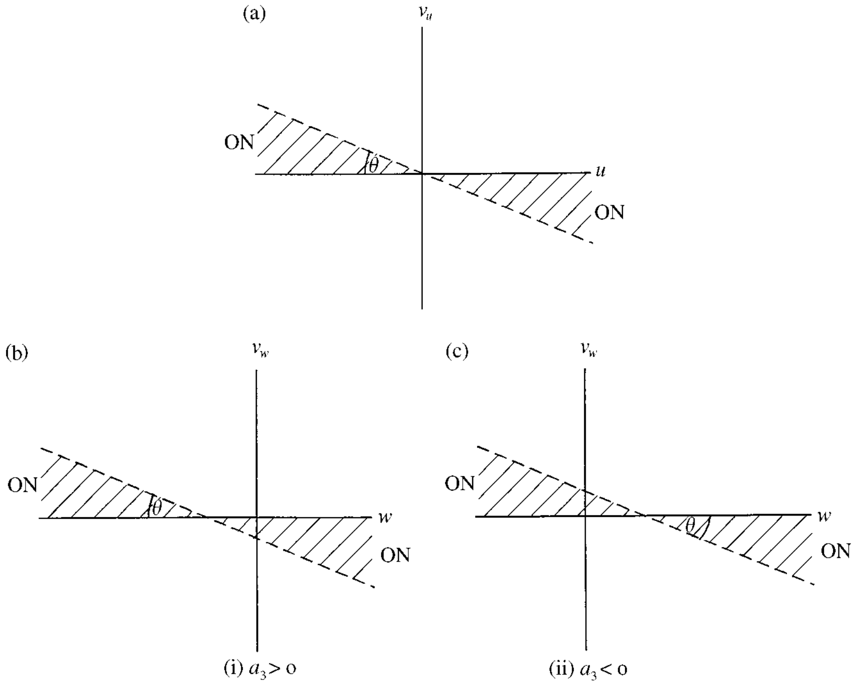


Figure 3. Switching zones, 2 masses, 2 dampers.

2.2.3. *General strategy*

A more general strategy is to demand not a zero acceleration, but an acceptable non-zero acceleration $a_3$ of block 3. Then from equation (3), for the damper to be on it is necessary that

$$uv_u < -b_3 v_u^2 - a_3 v_u/\omega_3^2. \tag{8}$$

The switching zone is shown in Figures 3(b) and 3(c) for the case of $a_3$ (i) positive and (ii) negative. The zone is moved to one side, the direction depending on the sign of $a_3$, but remains the same size as in the case of zero acceleration $a_3$.

From equation (2), the condition for eliminating the acceleration of block 2 is

$$wv_w < -b_2 v_w^2 + R_{32} a_3 v_w/\omega_2^2, \tag{9}$$

where

$$b_2 = 2\zeta_{str}/\omega_2.$$

Setting $w = x_2 - x_1$, $v_w = v_2 - v_1$ and $R_{32} = M_3/M_2$ expression (9) is of the same form as equation (8) above and the switching zones are of the form indicated in Figures 3(b) and 3(c).

2.3. DAMPER STATES

In the subsequent analysis, the acceleration of block $j$ will be written as $a_j$. Considering a pair of semi-active dampers, there are four possible states. Consider the top pair in Figure 1 (with block 1 ignored at this point).

If $q_{j,des}$ is the desired friction “force”, $F_j/M_j$, the four possibilities are ON/OFF (damper 3 ON, damper 2 OFF).

This means that

$$q_{3,des} v_u < 0, \qquad q_{2,des} v_w > 0.$$

The top damper can be chosen to given zero $a_3$ if desired. However, the acceleration $a_2$ of the lower mass may be undesirable. It is possible to choose $a_3$ to be a desirable non-zero value so as to reduce the acceleration of the lower mass.

The maximum absolute acceleration is minimized when

$$\text{abs}(a_3) = \text{abs}(a_2).$$

Returning to the equation of motion for the lower mass 2, since the lower damper is off, $q_2 = 0$ in this case. Assuming that both accelerations are of the same sign, i.e., $a_2 = a_3$, the equation for the lower mass becomes

$$(1 + R_{32})a_2 = -\omega_2^2 w - 2\zeta_2\omega_2 v_w$$

giving

$$a_2 = a_{20} = -(\omega_2^2 w + 2\zeta_2\omega_2 v_w)/(1 + R_{32}).$$

If the accelerations $a_2$ and $a_3$ have opposite sign, the denominator becomes $(1 - R_{32})$ which produces a lower absolute value of $a_{20}$ only when $R_{32} > 2$. The mass ratio is known and hence the appropriate selection for $a_{20}$ can be made.

ON/ON:

$$q_{3,des} v_u < 0, \qquad q_{2,des} v_w < 0.$$

Both accelerations can be cancelled.

OFF/ON:

$$q_{3,des} v_u > 0, \qquad q_{2,des} v_w < 0.$$

$q_3$ has to be set to zero and $a_3$ is found to be

$$-\omega_3^2 u - 2\zeta_3 \omega_3 v_u.$$

It is possible by a suitable choice of $q_2$ to make $a_2$ zero.

OFF/OFF:

$$q_{3,des} v_u > 0, \qquad q_{2,des} v_w > 0.$$

In this case $q_3$ and $q_2$ have both to be set to zero.

Adding a third damper—in this case at position 1—introduces a new pair of configurations. Since $a_2$ is known, $q_{1,des}$ is known for a given instantaneous ground input, and hence the state of the damper is determined.

## 2.4. HYBRID CONTROL LAW

A more general strategy is to employ a proportion of the control force required to cancel the acceleration of the mass and to add a certain level $\zeta_{j,add}$ of pseudo-viscous damping. The required control force is assumed to be of the form

$$\begin{aligned} q_{3,dem} &= \delta q_{30} - 2\zeta_{3,add} \omega_3 v_u, \\ q_{2,dem} &= \beta q_{20} - 2\zeta_{2,add} \omega_2 v_w, \\ q_{1,dem} &= \gamma q_{10} - 2\zeta_{1,add} \omega_1 (v_1 - v_0), \end{aligned} \tag{10}$$

where $q_{30}$ is the value of control "force" required to achieve $a_3 = 0$, $q_{20}$ that to achieve $a_2 = 0$, and $q_{10}$ that to produce $a_1 = 0$.

$$q_{30} = \omega_3^2 u + 2\zeta_{str} \omega_3 v_u,$$

$$q_{20} = \omega_2^2 w + 2\zeta_{str} \omega_2 v_w + R_{32} a_3.$$

The friction force must oppose the relative velocity. Hence,

$$\text{if } q_{1,dem}(v_1 - v_0) > 0, \quad \text{set } q_{1,dem} = 0,$$

$$\text{if } q_{2,dem} v_w > 0, \quad \text{set } q_{2,dem} = 0,$$

$$\text{if } q_{3,dem} v_u > 0, \quad \text{set } q_{3,dem} = 0.$$

In the case of a motor vehicle or a stationary machine, the running time is long enough for a continuous revision of the parameters to be made. In the case of an earthquake this approach is not possible since the earthquake is a brief and non-stationary event. The values of $\delta$, $\beta$ and $\gamma$ need to be set by current displacements and accelerations.

## 3. RESULTS AND CONCLUSIONS

The input chosen was 40 sinusoids of frequency $k/40 + \pi/100$ Hz ($k = 1, 40$), the phases of which were randomly assigned at the beginning of the run. A shaping factor (see section 2.1) with $t_1 = 5$ s and $t_2 = 20$ s was used. The length $t_3$ of the earthquake was taken to be 40 s. The input had a maximum displacement of 148 mm and a peak acceleration of 0·23$g$.

The building considered was one of 40 m height and 10 metres square base section. Equal masses were assumed for each block, which was assumed to represent three storeys. The fundamental period for rigid soil (drawing on data from Dowrick [15]) was taken to be 0·9 s. For a uniform building this corresponds to sub-system natural frequencies $f_1$, $f_2$ and $f_3$ equal to 2·4 Hz. The effect of soil conditions or a base isolation system was modelled by reducing $f_1$. Values of $f_1$ were chosen to be in the range 0·4–1 Hz. The lower end of the range corresponds to a building fundamental period of around 4 s, and the upper value to a period of about 1·7 s.

The relative merits of each damper were assessed by evaluating the peak lateral acceleration (the highest of the three) when each damper in turn was used alone. The frequencies $f_2$ and $f_3$ of the other sub-systems were taken to be 2·4 Hz, the passive case being included for comparison.

In the semi-active case, full spring cancellation was employed (i.e., for damper 1, $\gamma = 1$; for damper 2, $\beta = 1$, and for damper 3, $\delta = 1$). Structural and soil damping of 5% critical were assumed, with no added (pseudo-viscous) damping for the results shown in Figures 4–7. The peak acceleration was found to be that of the top mass, although when damping was added this was not always the case.

The peak accelerations for the three configurations are shown in Figure 4 as a function of the base natural frequency $f_1$. In each case the peak value falls with $f_1$, indicating the merits of base isolation. When $f_1$ is 0.4 Hz (building fundamental frequency about 0·25 Hz) there is little to choose between the passive and semi-active performance. However, as the base stiffness is increased, the benefits of the semi-active system become apparent.

Damper 1 (between the base and the ground) is the most effective, producing a reduction of 28% in peak acceleration relative to the passive case for a base natural frequency of 0·8 Hz and 32% when the base frequency is 1 Hz.

Damper 2 (between the base and mid-section) offers a modest improvement over the passive case (3% for $f_1 = 0{\cdot}8$ Hz and 5% when $f_1 = 1$ Hz). However, when damper 3 used alone, peak values of acceleration are higher than in the passive case. In the passive case the base frequency has to be below 0·6 Hz (for acceleration less than 3 m/s$^2$).

Figure 5 shows the results when the dampers are used in combination. Adding damper 2 to damper 1 reduces peak acceleration by 38% of the value in the passive case when $f_1 = 0{\cdot}8$ Hz, and by 37% when $f_1 = 1$ Hz. Adding the third (top) damper produces further reductions when the base frequency is in the region 0·6–0·8 Hz, but is of no value when base frequency is 1 Hz.

The corresponding maximum drift (relative displacement between floors) in each case is indicated in Figure 6. Drift is expressed as a percentage of storey height, assuming each block to represent three storeys.

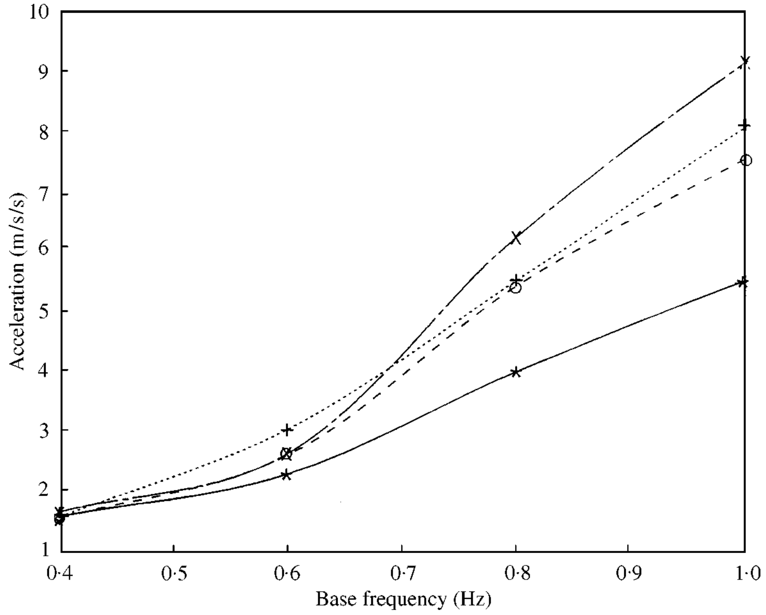


Figure 4. Max lateral acceleration. Effect of each device: ····+···· passive; —⁎— damper 1; – ○ – damper 2; —✕— damper 3.

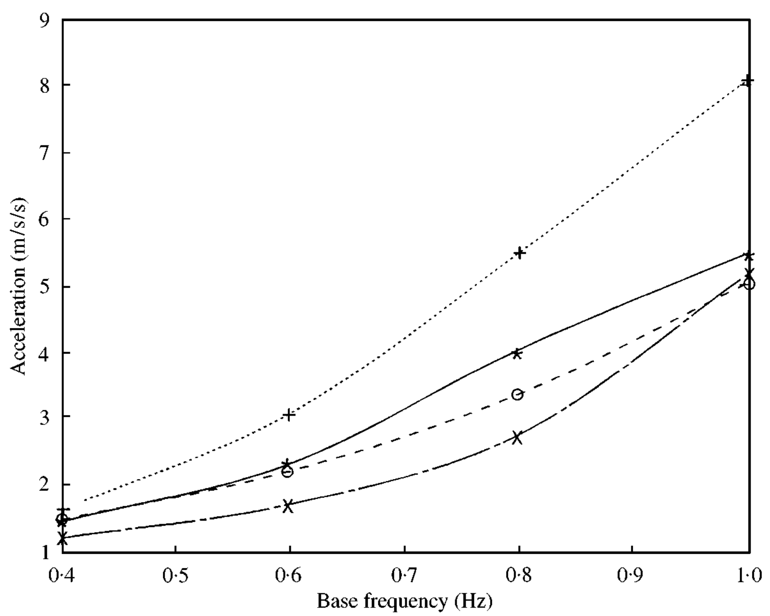


Figure 5. Max lateral acceleration, damper in combination: ····+···· passive; —⁎— damper 1; – ○ – dampers 1 & 2; dampers 1, 2 & 3.

As with acceleration, drift increases with base frequency, and in the passive case exceeds 0·5% storey height when the base frequency exceeds 0·6 Hz (this is the same critical frequency as for accelerations in Figure 5).

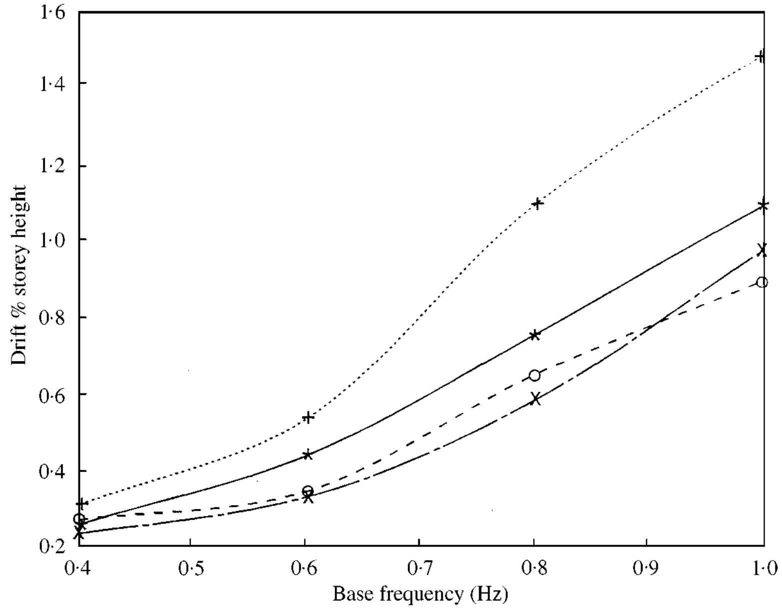


Figure 6. Max drift, dampers in combination: ····+····; passive; —*— damper 1; - -o- - dampers 1 & 2; - -o- - dampers 1, 2 & 3.

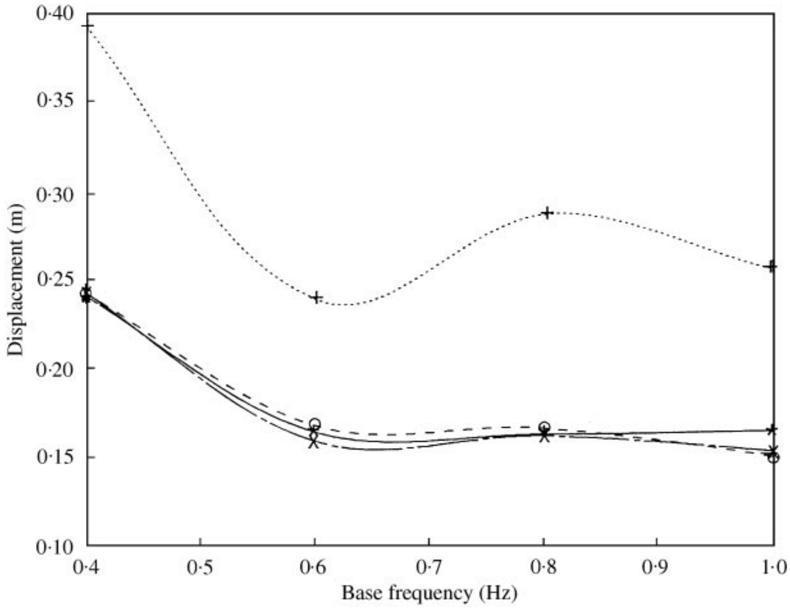


Figure 7. Max base-ground displacement: ····+···· passive; —*— damper 1; - -o- - dampers 1 & 2; —x— dampers 1, 2 & 3.

Damper 1 is again distinctly beneficial. Adding damper 2 is useful, while adding damper 3 to the others produces the least gain. To keep drift below 0·5% storey height, even in the three damper cases a relatively low base frequency is called for, below about 0·75 Hz.

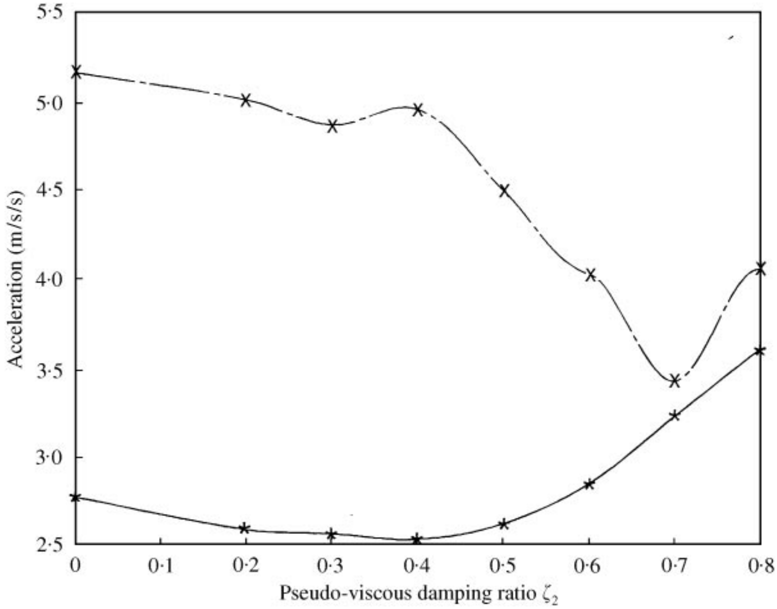


Figure 8. Max lateral acceleration, all three devices used: —✱— base frequency 0·8 Hz; –✱– base frequency 1·0 Hz.

Finally, the peak displacement of the base relative to the ground is shown in Figure 7. In the passive case, the variation with $f_1$ follows a gently oscillating curve. The reason for this is not clear, but the larger displacement at the bottom of the range is as expected. The actual value (0·39 m) is a practical one. Naeim and Kelly [16] quote a moat of width 0·508 m (20 in) for the Oakland City Hall passive isolation system. Damper 1 alone reduces the relative movement by 40%, but adding the other two dampers has little benefit.

The effect of introducing pseudo-viscous damping (see equations (9)) was studied. Adding damping $\zeta_{2,add}$ (between the base and the middle block) was found to be beneficial. In Figure 8 the peak acceleration is plotted as a function of $\zeta_{2,add}$ for two different values of base frequency when all three dampers are used.

The reduction of peak acceleration with increased added damping is evident in the case of $f_1 = 1$ Hz. The fluctuations in the curve are caused by the fact that whereas peak accelerations are generally due to accelerations at the top of the building, when $f_1$ is 0·4 and 0·5 Hz, the peak value is that of the middle block. The optimal damping ratio for $f_1 = 1$ Hz is 0.7. There is a 32% education compared to the zero damping case (three dampers) and 56% relative to the passive case.

However, when $f_1$ is 0·8 Hz, added damping is of little value, and actually increases the peak acceleration when $\zeta_{2,add}$ is greater than 0.6.

Adding pseudo-viscous damping to the other two dampers is undesirable. In the case of damper 1, the base isolation properties are destroyed, and in the case of damper 3 the acceleration of the top increases.

The spring cancellation terms $\delta$, $\beta$ and $\gamma$ were selectively reduced from the value of unity (full spring cancellation case). Two dampers were maintained at full cancellation while the other was varied. The results are shown in Figure 9 for the case of peak acceleration when the base frequency $f_1 = 0{\cdot}8$ Hz. Partial cancellation can produce modest gains (as with damper 1 in this case) but variations from unity may in general be detrimental.

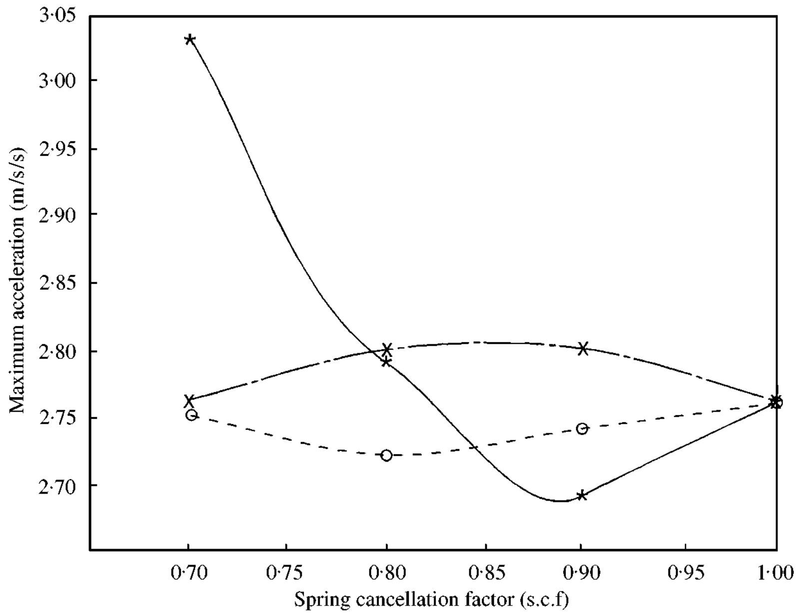


Figure 9. Two dampers set at total cancellation (scf = 1), the third varied. Base frequency 0·8 Hz: —*— damper 1; - -o- - dampers 2; —x— damper 3.

TABLE 1

*Peak acceleration (sa)/peak acceleration (passive) %*

| Building height (m) | Base frequency (Hz) | | | |
|---|---|---|---|---|
| | 0·4 | 0·6 | 0·8 | 1 |
| 30 | 51 | 67 | 42 | 48 |
| 40 | 74 | 56 | 50 | 64 |
| 50 | 62 | 61 | 36 | 56 |

Finally, buildings of height 30 and 50 m (and aspect ratio 4) were modelled to assess the performance of the system more generally. The frequencies of the subsystems were taken to be $f_2 = f_3 = 3{\cdot}3$ Hz for the 30 m building and $f_2 = f_3 = 2$ Hz for the 50 m building.

In Table 1, the peak acceleration in the three damper case with no added damping is compared with the result for the passive case. The same range of values for base frequency was assumed as for the 40 m building.

The results indicate that the semi-active strategy can cope with a variety of building natural frequencies. For the earthquake input chosen, a base natural frequency of 0·8 Hz is about the best (there are no resonances evident in the passive response to give a specious advantage to the semi-active system). Over 50% reduction is possible for the three buildings.

## 4. CONCLUSIONS

- Semi-active friction "dampers" used as spring cancellation devices can reduce lateral accelerations and inter-storey drift to 50% of those in the passive case.

- Damper 1 (between base and ground) is the most effective, and appreciably decreases peak acceleration, drift and relative ground motion compared to the passive case. As the device acts primarily as a soft element, it is most effective at the base of the building.
- Adding damper 2 to damper 1 is beneficial.
- Damper 3 is only useful when used in conjunction with the other two; its omission would not significantly impair system performance. A soft element near the top of the building has little effect on the building's fundamental frequency of the building.
- Full spring cancellation appears to be desirable.
- The logic performs well over a range of base and soil conditions (and hence range of building natural frequencies).

## 5. FURTHER WORK

The question of optimal damper values, i.e., values which minimize some penalty function involving peak acceleration, drift and base—ground displacement, remains unresolved since classical optimal control method are not applicable to switchable systems and the earthquake input is in practice brief and non-stochastic. Adaptive strategems—modifying the damper settings via instantaneous values of acceleration, drift and base relative motion—are being examined, but are not yet resolved.

The authors have shown that the use of fuzzy logic applied to a vehicle suspension with two semi-active dampers [17] can reduce the number of switches without impairing isolation performance unduly. The application of fuzzy logic to the case of three or more dampers appears to be worthy of study.

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## APPENDIX A: NOMENCLATURE

| | |
|---|---|
| $F_1$ | friction force, base damper |
| $F_2$ | friction force, middle damper |
| $F_3$ | friction force, top damper |
| $J$ | building aspect ratio height/width |
| $K_1$ | net stiffness of base to ground connection |
| $K_2$ | lateral stiffness, middle to base |
| $K_3$ | lateral stiffness, top to middle |
| $K_s$ | stiffness of soil |
| $M_1$, $M_2$ | building sub-masses |
| $R_{21}$ | mass ratio $M_2/M_1$ |
| $R_{32}$ | mass ratio $M_3/M_2$ |
| $T$ | fundamental period of building, based fixed (rigid soil) |
| $T^*$ | fundamental period of building |
| $T_q$ | length of earthquake (s) |
| $a_j$ | lateral acceleration of block $j$. |
| $b$ | width of building |
| $e$ | envelope function for ground input |
| $f_j$ | natural frequencies (Hz) of sub-systems of building |
| $h_s$ | storey height |
| $h$ | building height |
| $q_j$ | $= F_j/M_j$ control acceleration, termed "force" |
| $t_c$ | time constant of actuator |
| $u$ | relative displacement $x_3 - x_2$ |
| $v_s$ | soil shear wave velocity |
| $v_u$ | relative velocity $du/dt$ between blocks 3 and 2 |
| $v_w$ | relative velocity $dw/dt$ between top and middle blocks |
| $v_0$, $v_1$, $v_2$, $v_3$ | velocity of ground, base, middle, top respectively |
| $w$ | relative displacement $x_2 - x_1$ |
| $x_1$ | lateral motion of base of building |
| $x_2$ | lateral motion of middle |
| $x_3$ | lateral motion of top |
| $z$ | lateral motion of ground |
| $\delta$ | proportion of "balance" control, top mass |
| $\beta$ | proportion of "balance" control, middle mass |
| $\gamma$ | proportion of "balance" control, base mass |
| $\nu$ | Poisson's ratio, soil |
| $\omega_j$ | natural frequency, sub-system $j$ |
| $\zeta_{soil}$, $\zeta_{str}$ | damping ratio of soil, structure respectively |
| $\zeta_j$, $\zeta_{j,add}$ | damping ratio, added pseudo-viscous damping ($j = 1, 2, 3$) |