Active viscous damping system for control of MDOF structures

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SUMMARY

The development and applications of a supplemental viscous damping device with active capacity are described. The system of the dampers defined as active viscous damping system (AVDS) is presented herein. Structural control principles defined here as active control theory (ACT) are used to obtain the control forces at each time step during an excitation. Control of the damping forces is possible due to a mechanical structure of the proposed AVDS and do not require the input of large power and energy. This system can be efficiently used to enhance the damping of a structure without adding in stiffness and strength. The added damping forces can be adjusted in a wide range. Its efficiency is demonstrated by a numerical simulation of a seven-storey building subjected to earthquakes. The simulation shows that the behaviour of the damped structure with the AVDS is significantly improved compared to that of an uncontrolled system. Moreover, the response is better than that of adding either passive viscous dampers or electrorheological damping devices. Copyright © 2001 John Wiley & Sons, Ltd.

1. INTRODUCTION

Passive energy dissipating systems such as viscous dampers, tuned mass dampers and base isolation systems have been installed in new or existing buildings resulting in improved structural response to earthquakes. However, passive systems are not always efficient in reducing response of random vibrations. Active systems have wider ranges of operation as shown in recent research outlines in state-of-the-art publications [1, 2].

Soong [3], and Agrawal et al. [4] indicate that new devices using external energy and algorithmic logic can produce more optimal reductions than passive systems. Recently, Kobori et al. [5] proposed an active variable stiffness system consisting of stand-by braces

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and locking devices. The bracing system may be locked or unlocked at a particular time instant of the occurring earthquake. Locking or unlocking of the bracing system during the earthquake according to a control algorithm enables to change the stiffness of the structure and improves its dynamic response, in particular to shock type excitations.

Yang et al. [6] presented control methods for buildings equipped with such variable stiffness systems. These methods are based on the sliding mode control theory [7, 8]. Yang et al. [6] demonstrated that active variable stiffness systems are effective in reducing the interstorey drifts. However, they may yield to significantly increased floor accelerations. More recently, Gavin et al. [9], and Makris et al. [10] developed electrorheological (ER) fluid dampers and their theory and suggested their use as semi-active systems. The authors showed in earlier publications [11] that several active control systems, including ER dampers, designed according to the instantaneous optimal control theory [12] significantly improve the behaviour of building structures during earthquake motions.

The alternative device proposed in this study is an active viscous damped system (AVDS). The damping forces in the proposed system are both independent of the displacement, (similar with ER dampers), and also do not change instantaneously when the velocity changes sign (like friction dampers).

This work describes the proposed devices, and the use of such devices, placed between chevron braces and the rigid floor diaphragm at various locations in the structure (Figure 1(b)). The paper presents a method for design of structures with the above dampers which can be used in new structures or in old constructions for their improvement.
2. ACTIVE VISCOUS DAMPING SYSTEM (AVDS)

An AVDS (Figure 2) consists of a cylinder (1), an activating bar (2), two independent bearings (3), two viscous dampers (4), and a control device (5). The viscous dampers are connected at one end to the bearing through a connector (6), and at the other end to the activating bar. A hydraulic piston is used as the control device, that changes the angle, \( \theta \), between the viscous devices and the plane perpendicular to the activating bar. Thus, the damping force can be set to a specified controlled value at each time step.

The device may be installed in the structure by connecting the cylinder to chevron braces, which are fixed to the lower floor, and the activating bar fixed to the upper floor diaphragm. The force developed by the device, \( F_D(x) \), is given by

\[
F_D(x) = 2F_{VD} \sin \theta
\]

(1)
where $F_{VD}$ is the force developed by each viscous damper, and $\theta$ is the angle between the damper and the plane perpendicular to the activating bar (Figure 2). $\theta$ is determined as shown in the next section.

The force in a linear fluid viscous device is proportional to the velocity of the piston in a viscous environment [13]:

$$F_{VD} = C_{VD}|\dot{u}(t)|^alpha \text{sgn}(\dot{u}(t))$$  \hspace{1cm} (2)

where $F_{VD}$ is the force in the device, $C_{VD}$ is the viscous characteristic of the device, $\dot{u}(t)$ is the velocity of the piston in the fluid viscous medium, $\alpha$ is a power between 0.5 and 2. This study is limited to linear damper ($\alpha = 1$ in Equation (2)). Optimal passive viscous characteristics of the dampers to be used in the AVDS can be obtained using the design technique that have been presented by Gluck et al. [14].

The idea examined in this study is to obtain at each time instant the required optimal forces in the AVDS devices by using the active control theory (ACT). Using the control device, the necessary position of the internal dampers can be adjusted to obtain a resulting force in the AVDS that is equal to the optimal value.

3. OPTIMAL CONTROL ALGORITHMS

Yang et al. [12] had developed instantaneous control algorithms, which are presented in detail by Soong [3]. According to these algorithms, the base excitation record available up to a “real-time” instant, $t$, is measured on-line by sensors installed at the base level. This record is then utilized in the calculation of the optimal control forces. The closed-loop instantaneous optimum algorithm is adopted for control in this study and is outlined below with necessary adjustments for the AVDS.

The response of a structure provided with supplemental dissipating devices can be described by the following dynamic equilibrium equation [3]:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Lf_c(t) + Du_c(t)$$  \hspace{1cm} (3)

where $M$, $C$, $K$ are the mass, the damping, and the stiffness matrices, respectively, $x(t)$, $\dot{x}(t)$, $\ddot{x}(t)$ are the displacement, the velocity and the acceleration vectors, respectively, $u_c$ is the vector of control forces in the supplemental devices, $f_c$ is the external excitation, and $D$ and $L$ are the location matrices of the control and excitation forces, respectively.

According to the instantaneous control rules, a performance index is minimized at each instance, $t$ [12]. The performance index, $J(t)$, is time-dependent and is defined by the following equation:

$$J(t) = z^T(t)Qz(t) + u_c^T(t)Ru_c(t)$$  \hspace{1cm} (4)

where $R$ and $Q$ are weighting matrices which define the priorities between the energies dissipated in the structural elements and in the dampers. In this study the matrices $R$ and $Q$ are assumed to be

$$R = 10^{-m}I, \hspace{1cm} Q = I_{2n \times 2n}$$  \hspace{1cm} (5)
where \( I \) is a \( 2n \times 2n \) unit diagonal matrix, and \( m \) is a parameter which keeps the damping forces within the dampers’ practical capacity.

This second-order differential equation (Equation (3)) may be simplified by a transformation into the space-state form as follows:

\[
\dot{z}(t) = Az(t) + Bu_c(t) + Hf_e(t)
\]  \hspace{1cm} (6)

where \( z(t) = [x(t), \dot{x}(t)]^T \) is the \( 2n \) space state vector of the displacements and velocities for each of the \( n \) degrees of freedom of the structure, \( A \) is a system matrix, \( B \) defines the control location, and \( H \) is the excitation forces location matrix:

\[
A = \begin{bmatrix}
0 & 1 \\
-1^{-1}K & -1^{-1}C
\end{bmatrix}, \quad B = \begin{bmatrix}
0 \\
1^{-1}D
\end{bmatrix}, \quad H = \begin{bmatrix}
0 \\
1^{-1}L
\end{bmatrix}
\]  \hspace{1cm} (7)

The solution in modal space can be formulated [3]:

\[
z(t) = Ty(t)
\]  \hspace{1cm} (8)

where \( T \) is a \( 2n \times 2n \) modal matrix whose columns are eigenvectors of \( A \).

Upon substituting Equation (8) into Equation (6), the decoupled state-space equations governing \( y(t) \) has the form

\[
\dot{y}(t) = \Lambda y(t) + q(t), \quad y(0) = 0
\]  \hspace{1cm} (9)

where \( \Lambda \) is a diagonal matrix whose diagonal elements are the complex eigenvalues of the matrix \( A \), and the vector \( q(t) \) is given by

\[
q(t) = T^{-1}[Bu_c(t) + Hf_e(t)]
\]  \hspace{1cm} (10)

Over a small time interval \( \Delta t \), the vector \( y(t) \) becomes:

\[
y(t) = \int_0^{t-\Delta t} \exp[\Lambda(t-\tau)]q(\tau) \, d\tau + \int_{t-\Delta t}^t \exp[\Lambda(t-\tau)]q(\tau) \, d\tau \\
\approx \exp \Lambda \Delta t \times y(t-\Delta t) + \frac{\Delta t}{2} [\exp \Lambda \Delta t q(t-\Delta t) + q(t)]
\]  \hspace{1cm} (11)

For the response state vector, \( z(t) \), Equations (8), (10) and (11) lead to

\[
z(t) = Td(t-\Delta t) + \frac{\Delta t}{2} [Bu_c(t-\Delta t) + Hf_e(t)]
\]  \hspace{1cm} (12)

where

\[
d(t-\Delta t) = \exp(\Lambda \Delta t)T^{-1} \left\{ z(t-\Delta t) + \frac{\Delta t}{2} [Bu_c(t-\Delta t) + Hf_e(t-\Delta t)] \right\}
\]  \hspace{1cm} (13)
The total control force in the AVDS

\[ u_c(t) = -\frac{\Delta t}{2} R^{-1}B^TQz(t) \]  

(14)

where the measured response state vector, \( z(t) \), can be obtained also analytically as follows:

\[ z(t) = \left[ I + \frac{\Delta t^2}{4}BR^{-1}B^T \right]^{-1} \left[ Td(t - \Delta t) + \frac{\Delta t}{2}Hf_c(t) \right] \]  

(15)

The force produced by the AVDS depends on the angle, \( \theta \), between the dampers and the plane perpendicular to the activating bar. To obtain the force the angle can be changed according to the rule:

\[ \sin^2 \theta = \frac{u_{R,i}(t)}{2C_{VD,i}(\dot{u}_i(t) - \dot{u}_{i-1}(t))} \]  

(16)

where

\[ u_{R,i}(t) = \min[u_{c,i}(t), 2C_{VD,i}(\dot{u}_i(t) - \dot{u}_{i-1}(t))] \]  

(17)

and \( u_{c,i} \) is obtained from Equation (14) and is continuously adjusted.

4. NUMERICAL EXAMPLE

In order to examine the efficiency of the proposed AVDS the ACT was applied in a numerical simulation of a seven-storey building provided with these supplemental systems. The response of a shear framed structure with stiff beams (Figure 1(a)) was analyzed under different earthquakes. The following matrices characterize the structure:

\[
M = 8.75 \times 10^4 \begin{bmatrix} I_7 & \cdots & 0 \end{bmatrix} (\text{kg-mass})
\]

\[
K = \begin{bmatrix}
29.28 & -14.64 & 0 \\
-14.64 & 31.59 & -16.95 \\
-16.95 & 30.96 & -14.01 \\
-14.01 & 28.02 & -14.01 \\
-14.01 & 25.13 & -11.12 \\
-11.12 & 22.24 & -11.12 \\
0 & -11.12 & 11.12 \\
\end{bmatrix} \times 10^7 \text{ (N/m)}
\]

where \( M \) is the mass matrix of the structure, and \( K \) is the structural stiffness matrix. An initial damping ratio of 2% was assumed for the first vibration mode of the uncontrolled structure. First, the response of an uncontrolled structure was obtained. Next, an analysis of an optimally designed viscous damped passive controlled structure was performed, with the technique presented by Gluck et al. [14] in order to obtain the viscous coefficients of
Table I. Peak values of displacements and base shear forces in the structure under the El-Centro earthquake.

<table>
<thead>
<tr>
<th>Storey</th>
<th>Uncontrolled structure</th>
<th>A structure with passive dampers</th>
<th>A structure with electrorheological dampers</th>
<th>A structure with AVDS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>6.68</td>
<td>5.85</td>
<td>4.93</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>12.49</td>
<td>6.26</td>
<td>5.48</td>
</tr>
<tr>
<td>Displ. (cm)</td>
<td>5</td>
<td>10.93</td>
<td>5.45</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>9.14</td>
<td>4.54</td>
<td>4.03</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.96</td>
<td>3.45</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.92</td>
<td>2.44</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.53</td>
<td>1.21</td>
<td>1.09</td>
</tr>
<tr>
<td>BS (kN)</td>
<td></td>
<td>1813.3</td>
<td>1839.0</td>
<td>1828.8</td>
</tr>
</tbody>
</table>

the dampers used in the AVDS which yields the following optimal values:

\[
C_{VD} = \begin{bmatrix} 1.7219 & 1.7219 & 0 \\ 1.9936 & 1.6478 & 1.6478 \\ 0 & 1.3079 & 1.3079 \end{bmatrix} \times 10^6 \frac{Ns}{m}
\]

The matrix represents the optimal solution of a passive controlled structure provided by supplemental viscous dampers. The solution requires different damping levels at each storey. The response of the structure with two standard passive viscous devices \((C_{VD} = 1.07 \times 10^6 Ns/m)\) at each storey was obtained for comparison sake. Then an active controlled structure with ER dampers was analyzed. Finally, a structure with AVDS, which incorporate the same viscous dampers as in the passive controlled one \((C_{VD} = 1.07 \times 10^6 Ns/m)\) was analysed.

The following four seismic excitations were used as an input in order to examine the behaviour of the structure: El-Centro S00E, 1940, Taft N21E, 1952, Loma-Prieta (Santa Cruz) N90E, 1989, and Eilat EL1226NS, 1995. All simulations were performed with routines written in MATLAB [15].

Peak values of displacements and base shear forces in the structure, under the El-Centro, Taft, Loma-Prieta, and Eilat earthquakes are presented in Tables I, II, III and IV, respectively. Note that for all earthquakes the peak response of the structure with the proposed AVDS (column 6 in the tables) is improved compared to that of the passive controlled structure with viscous dampers (column 4) and to the active controlled structure with electrorheological dampers (column 5). Time histories of the top storey displacements and accelerations are shown in Figures 3 and 4, respectively. Typical values of maximal required control forces and force rates in the pistons are presented in Table V. The maximal length change of the piston required for the specified earthquakes was less than 20 cm/s. An important positive feature of the proposed AVDS is that it does not require the input of large power and energy (see Figure 5).
Table II. Peak values of displacements and base shear forces in the structure under the Taft earthquake.

<table>
<thead>
<tr>
<th>Storey</th>
<th>Uncontrolled structure</th>
<th>A structure with passive dampers</th>
<th>A structure with electrorheological dampers</th>
<th>A structure with AVDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>4.91</td>
<td>2.14</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.61</td>
<td>2.00</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4.04</td>
<td>1.74</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.39</td>
<td>1.45</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.60</td>
<td>1.11</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.85</td>
<td>0.79</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.94</td>
<td>0.40</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>BS (kN)</td>
<td>892.5</td>
<td>899.2</td>
<td>897.2</td>
</tr>
</tbody>
</table>

Table III. Peak values of displacements and base shear forces in the structure under the Loma-Prieta earthquake.

<table>
<thead>
<tr>
<th>Storey</th>
<th>Uncontrolled structure</th>
<th>A structure with passive dampers</th>
<th>A structure with electrorheological dampers</th>
<th>A structure with AVDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>1.56</td>
<td>1.37</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.41</td>
<td>1.21</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.17</td>
<td>0.99</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.96</td>
<td>0.79</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.75</td>
<td>0.60</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.57</td>
<td>0.43</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.33</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>BS (kN)</td>
<td>1837.7</td>
<td>1814.0</td>
<td>1814.5</td>
</tr>
</tbody>
</table>

Table IV. Peak values of displacements and base shear forces in the structure under the Eilat earthquake.

<table>
<thead>
<tr>
<th>Storey</th>
<th>Uncontrolled structure</th>
<th>A structure with passive dampers</th>
<th>A structure with electrorheological dampers</th>
<th>A structure with AVDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>4.52</td>
<td>2.21</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.23</td>
<td>2.05</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.69</td>
<td>1.79</td>
<td>1.47</td>
</tr>
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<td></td>
<td>4</td>
<td>3.07</td>
<td>1.51</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.34</td>
<td>1.17</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.71</td>
<td>0.85</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.89</td>
<td>0.44</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>BS (kN)</td>
<td>1837.6</td>
<td>1807.0</td>
<td>1835.7</td>
</tr>
</tbody>
</table>

The reductions of the peak displacements in the structure with AVDS compared to the uncontrolled one varies from 39 to 73%, whereas in a passive controlled vs uncontrolled and in an active controlled structure with electrorheological dampers the reductions varies from 13 to 56% and from 17 to 65%, respectively. There is no significant change, either increase or decrease of the base shear forces in the case when electrorheological dampers were used. Using AVDS produces reduction of base shear forces under some earthquakes (El-Centro 1949 and Taft 1952) or no changes in others (Loma-Prieta 1989 and the Eilat 1995).
Table V. Typical values of control forces and control force rates in the AVDS.\textsuperscript{6}

<table>
<thead>
<tr>
<th>Storey</th>
<th>Control force (kN)</th>
<th>Control force rate (kN/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>62.0</td>
<td>1484</td>
</tr>
<tr>
<td>6</td>
<td>6.7</td>
<td>305</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>151</td>
</tr>
<tr>
<td>4</td>
<td>41.0</td>
<td>737</td>
</tr>
<tr>
<td>3</td>
<td>34.0</td>
<td>827</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>257</td>
</tr>
<tr>
<td>1</td>
<td>12.0</td>
<td>474</td>
</tr>
</tbody>
</table>

\textsuperscript{6} Control was considered at all floors. Based on requirements system may be optimal by eliminating controllers at 2, 5, 6 storeys.
In more moderate motion with lower velocities (such as Loma Prieta, 1989) the AVDS seem to be more effective while the other damping techniques using either active (electrorheological) or passive (viscous dampers) seem less efficient.

5. CONCLUSIONS

The proposed active viscous damping system (AVDS) is examined for the use in active controlled structures. An optimal passive control theory [14] is suggested to be used to obtain the viscous characteristics of the dampers used in the AVDS. The instantaneous optimal control theory is suggested to find the optimal damping forces to be applied for control. These forces...
are developed in the AVDS by varying the angle between two passive viscous dampers and an activating cylinder with commands adjusted at each time step.

The optimal control forces are calculated with feed back of the structure’s displacements and velocities. However, because of the AVDS construction the actual implementation of these forces is independent of the structure displacements and also less sensitive to the changes in velocity direction (compared to the electrorheological dampers).

Numerical simulation of a seven-storey building showed that AVDS installed in the structure yields a displacement reduction without significant increase in the overall base shear forces. The proposed AVDS requires addition of a small power and energy, which makes it suitable for practical implementation.

The results of the numerical example show that energy dissipation in a structure controlled by AVDS occurs mainly in the supplemental system rather than in the structural elements of the
Figure 4. Roof acceleration time history of the structure.
Figure 4. Continued.
Figure 4. Continued.
Figure 4. Continued.
building, causing reduced displacements, and lower damage to the structural elements. Thus, the structure becomes less sensitive to the influence of strong earthquakes.

Further development of the active viscous damped system (AVDS), which would make it more practical, is expected to significantly improve the seismic behaviour of structures. Issues of time delay, although leaving the structure always stable in Liapunov sense, need to be further verified to prevent deterioration of performance during implementation.

REFERENCES


