Computer-Aided Design of Anti-earthquake Semiactive Control of Structures Using Magnetorheological Dampers

Grigory Agranovich¹,a, Gily Levy²,b

¹Prof. of Dep. Electricity and Electronics Engineering, Ariel University Center, Israel
²B.Sc.Stud. of Dep. Electricity and Electronics Engineering, Ariel University Center, Israel

¹agr@ariel.ac.il ²gili.levy1@gmail.com

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ABSTRACT

The work is devoted to the problem of strengthening of civil structures against earthquakes. As the main equipment for this purpose the well-known magnetorheological dampers are selected, as an affective and relatively low price means. Because these devices are essentially nonlinear, the design of the damping system is a complicated problem, which requires the use of modern computers’ software. In the present study design of the damping system is accomplished by methods of control theory using MATLAB for engineering calculations and simulations of the structure under earthquake excitations. The most important problems that are solved in this study are: the computer-aided selection of optimal parameters of the damping system and effective placing of dampers in the structure.

1. Introduction

The magnetorheological (MR) dampers [1–3, 6-7] are used in vibration control applications and known as a damper with attractive characteristics over the last few decades. The MR damper consist a fluid that developed in 1940’s by Winslow and Rainbow. This fluid consists of a suspension of iron particles in a carrier medium such as oil. Via magnetic field, it is possible to increase the resistance of the fluid and turning the fluid into a semi-solid. So his operational parameters are available to adjustment under the influence of the control voltage. More attractive characteristics include its small power requirements, reliability, and stability. This MR damper needs 20-50 watt of control and can operate with battery. At the same time he is able to develop forces up to several tens of tons.

Spencer and Dyke et al. [1], Yang, Spencer et al. [2] developed a phenomenological model for an MR damper based on the Bouc-Wen hysteresis model. In particular, the model was verified by Spencer et al. [1] based on a 20-ton MR damper at the University of Notre Dame. This model was subsequently used to demonstrate the capabilities of MR dampers to structures' control, including control of multistory civil engineering structures.

A variety of control algorithms have been proposed for seismic control using semi-active dampers [3–10]. This problem is solved, or in a wider class viscoelastic dampers [5,7,8,10] or directly in the class of MR dampers [5,6,9]. Lee et al. [8] compared various analysis methods for building structures with added VE dampers. Dyke and Spencer [8] explore an evaluation of MR control strategies with MR dampers.

The purpose of this study is to optimize the location and the values of control parameters of MR dampers in a structure design. The three-stage procedure for such design is developed and verified. The first two stages are performed based on a linear model, and at the last stage the linear viscoelastic damper is approximated by a nonlinear MR damper. At the first stage the optimal location of dampers is defined using frequency responses analysis of the floor displacements. The comparison is done using the resonance peak points of the frequency responses and calculation of criterion, which indicate the effectiveness of the analyzed location. At the next stage for chosen
location optimal parameters of viscoelastic damper are found. At the last stage the nonlinear MR
damper control parameters are calculated for optimal approximation of the viscoelastic damper.

2. **Viscoelastic dampers optimal design of base of linear model of structure**

The response of a structure provided with supplemental dissipating devices is described by the
following dynamic equation

\[ M \ddot{Z}(t) + C \dot{Z}(t) + K Z(t) = G\ddot{u}_e(t) + P F(t) \]  

(1)

where \( M, C, \) and \( K \) are the structure mass, damping, and stiffness matrices, respectively; \( Z(t), \) \( \dot{Z}(t), \) and \( \ddot{Z}(t) \) are the displacement, velocity and acceleration vectors, respectively; \( F \) is the vector of forces in the supplemental devices, \( \ddot{u}_e(t) \) is the earthquake acceleration; \( G \) and \( P \) are the excitation and control forces location matrices, respectively. For horizontal motion model of a civil structure, \( G = \begin{bmatrix} 1 & 1 & \ldots & 1 \end{bmatrix}^T \) and for dampers, located on all floors,

\[ P = \begin{bmatrix}
1 & -1 & 0 & \cdots & 0 \\
0 & 1 & -1 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & -1
\end{bmatrix}. \]

In order to analyze the frequency response of structure the linear state space equations of the structure are used

\[ \begin{cases}
\dot{X}(t) = AX(t) + B_f \ddot{u}_e(t) + B_u F(t) \\
Y(t) = CX(t)
\end{cases} \]

(2)

where state vector \( X \) includes the displacement (\( Z \)) and velocity (\( \dot{Z} \)) vectors of the model (1),

\[ A = \begin{bmatrix} 0 & I \\ -M_s^{-1} K_s & -M_s^{-1} C_s \end{bmatrix}, \quad B_f = \begin{bmatrix} 0 \\ -G \end{bmatrix}, \quad B_u = \begin{bmatrix} 0 & M_s^{-1} P \end{bmatrix} \]

(3)

In civil engineering, the difference between the displacements of two adjacent floors is usually
denoted as story drift. Story drifts are the main issue for many design problems, where the design
goal is to reduce drifts in the earthquake excited structure. Since the presented research is devoted
to this problem, the matrix \( C \) in the construction of the frequency response is chosen in the form

\[ C = (C_I \quad 0), \quad C_I = \begin{bmatrix}
1 & 0 & 0 & \cdots & 0 \\
-1 & 1 & 0 & \cdots & 0 \\
0 & -I & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & -1 & 1
\end{bmatrix}. \]

The proposed algorithm is a set of successive improving steps. Initially the structure is
supposed to be uncontrolled. At each of step a new one damper sequentially embedded on the any
of still uncontrolled floor. Its efficiency is evaluated by calculating the gain of Bode characteristics
and its comparative analysis with the previous dampers distribution is performed. The variations in
the resonance gain values is calculated using the following criterion

\[ J_m = \left( \sum_k G_{m,\text{uncontr}}(\omega_{rk}) - G_{m,\text{contr}}(\omega_{rk}) \right) / \max_k G_{m,\text{uncontr}}(\omega_{rk}) \cdot 100 \]

(4)

where \( m \) is the floor number, \( \omega_{rk} \) are the resonant frequencies of the structure, \( G_{m,\text{uncontr}} \) and
\( G_{m,\text{contr}} \) are the gains of uncontrolled and controlled structure, respectively.

The algorithm stops when adding a new damper does not lead to significant improvement in the
efficiency criterion. An example of application of the algorithm is given in Section 4.
At the second stage of the proposed method parameters of viscoelastic dampers’ are found using numerical optimization procedure.

3. Parametric design of magnetorheological damper

In order to calculate and reproduce the force $F_m(t)$ of the damper on third stage of proposed method phenomenological model of MR damper, suggested by Spencer [1,2] was used:

$$F_m(t) = \alpha z_m(t) + c_{0m}(x_m(t) - y_m(t)) + k_{0m}(x_m(t) - y_m(t)) + k_{1m}(x_m(t) - x_0)$$

$$\hat{z}_m(t) = -\gamma[\dot{x}_m(t) - y_m(t)]z_m(t) + [\gamma(t) - \beta(\dot{x}_m(t) - \dot{y}_m(t))]z_m(t) + A(\dot{x}_m(t) - \dot{y}_m(t))$$

$$\dot{y}_m = \frac{1}{c_{0m} + c_{1m}}\{\alpha z_m + c_{0m}\dot{x}_m + k_{0m}(x_m - y_m)\}$$

where $m$ is the number of floor the damper is embedded, $z_m(t)$ and $y_m(t)$ are the damper internal states. The damper parameters $\alpha(i_m)$, $c_{0m}(i_m)$, $\alpha(i_m)$ are functions of its control current $i_m$:

$$\alpha(i_m) = 16566i_m^3 - 87071i_m^2 + 168326i_m + 15114$$

$$c_{0m}(i_m) = 437097i_m^3 - 1545407i_m^2 + 1641376i_m + 457741$$

$$c_{1m}(i_m) = -9363108i_m^3 + 5334183i_m^2 + 48788640i_m - 2791630$$

Other model (4) parameters values identified for the large-scale 20-ton MR damper in [2]: $A = 2679.0$ m$^{-1}$, $g = b = 647.46$ m$^{-1}$, $k_0 = 137,810$ N/m, $n = 10$, $x_0 = 0.18$ m, $k_1 = 617.31$ N/m. The current $i_m$ values have to be chosen to minimize the criteria

$$J_m = \int_0^{T_f} (F_{m,viscoelastic} - F_{m,MR})^2 dt.$$  

These calculations were performed using mean-quadratic Gaussian optimization numerical procedure. The results of such calculations are shown in the example of Section 4.

4. Example of design for six-floors structure

In order to demonstrate the affectivity and to verify the proposed optimization procedure, MATLAB programs were developed. Using these programs optimum parameters searches and simulations were carried out. A typical six-story steel office building (Fig. 1) has been chosen for the analysis.

Figure 1: A six-story structure used for numerical example

An initial damping ratio of 2% was assumed for the first vibration mode of the uncontrolled structure. The natural frequencies of the chosen structure are 1.09, 2.95, 4.87, 6.65, 8.15, and 9.50 Hz. Its structural parameters are presented in the table 1.
Table 1. Structural parameters of the six-story building

<table>
<thead>
<tr>
<th>Floor number</th>
<th>Floor mass ($10^5$ kg)</th>
<th>Stiffness coefficient ($10^5$ kg/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.75</td>
<td>3.434</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>0.865</td>
</tr>
<tr>
<td>3</td>
<td>1.75</td>
<td>3.009</td>
</tr>
<tr>
<td>4</td>
<td>1.75</td>
<td>2.596</td>
</tr>
<tr>
<td>5</td>
<td>1.75</td>
<td>2.183</td>
</tr>
<tr>
<td>6</td>
<td>1.75</td>
<td>1.092</td>
</tr>
</tbody>
</table>

Based on the stages 1 and 2 of proposed method the viscoelastic dampers optimal displacement and the optimal parameters were obtained. The effective displacement for the structure is two dampers located on 1st and 3rd floors.

Examples of Bode graphs to frequency responses of two structure floors are depicted in the figure 2.

![Bode magnitude plot for frequency response](image)

Fig. 2. Bode magnitude plot for frequency responses of controlled and uncontrolled structure: (a) 1st floor frequency response, (a) 3rd floor frequency response

In the Tables 2-5 the results of calculations of resonance gains and evaluation of their variations are shown. Based on the change evaluations the most effective dampers number and their distribution on the floors were obtained.

Table 2. Resonance peaks of frequency response gain for the 1st floor of uncontrolled and controlled structure (Controller in 1st floor)

<table>
<thead>
<tr>
<th>Uncontrolled Structure</th>
<th>Controlled Structure</th>
<th>Rel. Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res. Freq, Hz</td>
<td>Peak Gain</td>
<td>Res. Freq, Hz</td>
</tr>
<tr>
<td>1.09</td>
<td>0.216</td>
<td>1.09</td>
</tr>
<tr>
<td>2.95</td>
<td>0.0225</td>
<td>2.95</td>
</tr>
<tr>
<td>4.87</td>
<td>0.0034</td>
<td>4.90</td>
</tr>
<tr>
<td>6.65</td>
<td>0.0008</td>
<td>6.57</td>
</tr>
<tr>
<td>8.15</td>
<td>0.0005</td>
<td>8.19</td>
</tr>
</tbody>
</table>

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<tr>
<td>6.65</td>
<td>0.0008</td>
<td>6.67</td>
</tr>
<tr>
<td>8.15</td>
<td>0.0005</td>
<td>8.18</td>
</tr>
</tbody>
</table>
Table 3. Resonance peaks of frequency response gain for the 1st floor of uncontrolled and controlled structure (Controller in 1st and 3rd floors)

<table>
<thead>
<tr>
<th>Uncontrolled Structure</th>
<th>Controlled Structure</th>
<th>Rel. Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res. Freq, Hz</td>
<td>Peak Gain</td>
<td>Res. Freq, Hz</td>
</tr>
<tr>
<td>1.09</td>
<td>0.126</td>
<td>1.09</td>
</tr>
<tr>
<td>2.93</td>
<td>0.0041</td>
<td>2.91</td>
</tr>
<tr>
<td>4.83</td>
<td>0.0038</td>
<td>4.82</td>
</tr>
<tr>
<td>6.58</td>
<td>0.0006</td>
<td>6.59</td>
</tr>
<tr>
<td>8.20</td>
<td>0.0003</td>
<td>8.24</td>
</tr>
</tbody>
</table>

Table 4. Resonance peaks of frequency response gain for the 3rd floor of uncontrolled and controlled structure (Controller in 1st floor)

<table>
<thead>
<tr>
<th>Uncontrolled Structure</th>
<th>Controlled Structure</th>
<th>Rel. Variation (%)</th>
</tr>
</thead>
<tbody>
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<td>Res. Freq, Hz</td>
<td>Peak Gain</td>
<td>Res. Freq, Hz</td>
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<tr>
<td>4.83</td>
<td>0.0038</td>
<td>4.80</td>
</tr>
<tr>
<td>6.58</td>
<td>0.0006</td>
<td>6.62</td>
</tr>
<tr>
<td>8.20</td>
<td>0.0003</td>
<td>8.27</td>
</tr>
</tbody>
</table>

Table 5. Resonance peaks of frequency response gain for the 3rd floor of uncontrolled and controlled structure (Controller in 1st and 3rd floors)

The time histories of inter-floor displacements for uncontrolled and controlled by viscoelastic dampers are depicted in figures 3a, 4a. At the third stage of the proposed method, optimal according to criterion (7) MR dampers parameters were obtained. Deviations in forces developed by viscoelastic and equivalent MR dampers were 7.2% on the 1st floor and 0.92% on the 3rd one. From the figures 3b, 4b it can be seen that differences in inter-floor displacements using these dampers are negligible.

![Fig. 3. Comparison of 1st floor displacement for: (a) uncontrolled and linear-controlled structure, (b) viscoelastic and MR-controlled structure](image-url)
The time histories of controller forces for viscoelastic and MR-controlled structure are depicted in figures 5a, 5b.

5. Conclusions

Three-stage method is presented for optimal design of parameters and locations of MR dampers for earthquake exited structure. The method is realized by MATLAB programs for optimization and simulation of an exited structure. Verification of the method using the programs was performed. It demonstrates the high efficiency of the developed method.

6. References


