# A New Method for Determining Location and Number of MR Dampers in Semi-Active Structural Control

**Arash NIK KHORMIZI**
*Civil Engineering Department, Mashhad Branch, Islamic Azad University, Mashhad, Iran. E-mail: nikkhormizi@yahoo.com*

**Javad ALAMATIAN**
*Civil Engineering Department, Mashhad Branch, Islamic Azad University, Mashhad, Iran. E-mail: alamatian@mshdiau.ac.ir*

**Hamid KAZEMI**
*Civil Engineering Department, Mashhad Branch, Islamic Azad University, Mashhad, Iran. E-mail: kazemi_un@yahoo.com*

*Abstract:* This study presents a new method for determining suitable locations and number of MagnetoRheological dampers in semi active procedures. Here, the first mode of structural oscillation is used and some specific criteria are introduced to classify the structural types. Based on this classification, the structural stories are divided into three categories: very weak, weak, and strong. The best place to install a MR damper is very weak stories. The efficiency of dampers will increase if MR dampers attached to the very weak stories so that the relative displacement of top of structure reduces considerably. Moreover, the number of MR dampers is assumed to be equal to the number of very weak stories as the dampers act by high performance. This method easily provides the necessary information for the structural control designer to use these devices logically and efficiently. By applying this approach, designers can easily determine number and location MR dampers. Moreover, the proposed method could determine number of fully activated dampers; however, MR dampers may not be completely activated in common techniques. Based on the proposed approach, vibrations of four models are controlled by MR dampers and results are compared with conventional techniques. Results show that the suggested method has suitable efficiency and consistency with other well-known studies.

*Keywords:* Semi-active control; MR damper; Modal relative displacement; Seismic load

## 1. INTRODUCTION

There are various systems and devices for structural control against dynamic loads. Considering control forces, these systems can be classified into three categories including the passive, active and semi-active control. With regards to the passive control, the system is designed for specific excitation. This can be assumed as a simple controlling technique with low maintenance costs and no need for any external sources. Besides, the control features are constant in this technique and the system cannot be adjusted to suit other excitation conditions [1]. Tuned mass damper and base isolation are two instances of passive control system. Accordingly, the active control system has been considered since 1989. In the active control system, by measuring with sensors, the actuator is instructed to adjust the appropriate reciprocal force, and this loop continues until the end of the excitation load. Therefore, the system monitors the excitation load intelligently and changes the capacity of the structure, accordingly. The major problems with this control technique are complexity of calculations, uncertainties of the factors, high-force actuators, and the need for a large energy source [2,3]. Hence, by combining the active and passive control, the researchers provided the semi-active control technique. In this type, the sensors measure the excitation and the dampers, proportionally modify the damping of the system, so that the oscillations are eliminated faster. Consequently, the system requires less force and power supply, while maintaining its high intelligence [4,5]. Magnetorheological dampers are modern, robust and powerful devices of dampers that are suitable for structural projects. In this way, one of the most effective factors, which can increase the efficiency of such systems, is the suitable location and number of MR dampers.

Some experimental studies were performed on the behavioral model of the different MR dampers [5-8]. Moreover, the influence of MR dampers on reducing three-story frame oscillations was investigated by experimental research [9]. Another study showed that in a two-story frame with two dampers, the minimum response is obtained when two dampers act with different patterns and currents [10]. Moreover, the efficacy of MR dampers are influenced by their locations [11]. In another study, the cost of steel moment-resisting frames was optimized by the number of MR dampers through direct performance-based design [12]. Moreover, the behavior of a three-story shear frame as well as the system responses and the damper force was studied by installing a variety of dampers on its various stories [13]. Using the MR damper with an external lever system was investigated based on PID control algorithm [14]. Also, uncertainty of semi-active MR dampers was studied [15]. In recent study, a new method was presented for parameter identification of MR damper using the modified Bouc-Wen model [16]. It is worth noting that in all of mentioned studies, the location and number of dampers has been determined based on engineering experiences or trial and error.

In this study, a new simple methodology is presented for suitable location and number of MR dampers. To do this, the structural modal analysis is used and some criteria are suggested for the classification of the stories. Based on this classification, the required criteria are addressed to determine the location and the number of MR dampers in a structure. Based on the proposed approach, vibrations of four numerical examples are controlled subjected to the El-Centro earthquake by MR dampers and the results are compared with common techniques.

## 2. THE MODEL OF MR DAMPER

There are several patterns accessible for modeling of MR dampers. These patterns can be divided into two categories, namely implicit and explicit. In implicit models, the damper force is made accessible by solving complex differential equations.

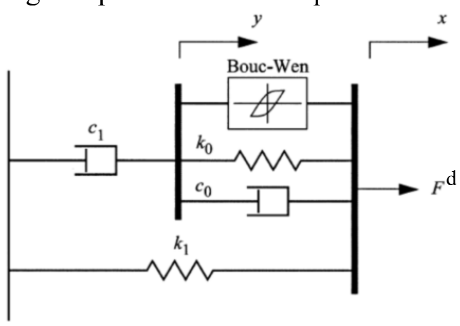


**Figure 1**. The modified Bouc-Wen model

For instance, the modified Bouc-Wen model can be mentioned as a model in which the involved differential equations are solved by numerical methods such as Runge-Kutta 4th order [6]. Fig. 1 shows the modified Bouc-Wen behavioral model. Based on the Fig. 1, following relation can be written for damper force [6]:

$$
\begin{aligned}
F_d &= \left[K_0(x - y) + C_0(\dot{x} - \dot{y}) + \alpha_0 T\right] + K_1(x - x_0) \\
&= C_1\dot{y} + K_1(x - x_0) \\
C_1\dot{y} &= K_0(x - y) + C_0(\dot{x} - \dot{y}) + \alpha_0 T \\
\dot{y} &= \frac{1}{(C_0 + C_1)}\left[K_0(x - y) + C_0\dot{x} + \alpha_0 T\right] \\
\dot{T} &= -\lambda\,|\dot{x} - \dot{y}|T|T|^{\sigma - 1} - \theta\,(\dot{x} - \dot{y})|T|^{\sigma} + A(\dot{x} - \dot{y}) \\
\alpha_0(u) &= \alpha_a + \alpha_b u \\
C_\circ(u) &= C_{\circ a} + C_{\circ b} u \\
C_1(u) &= C_{1a} + C_{1b} u \\
\dot{u} &= -\eta\,(u - v) \;\Rightarrow\; v = u + \frac{\dot{u}}{\eta\eta}
\end{aligned}
\tag{1}
$$

Here, $F_d$ is the damper force, x appertains to the damper's piston head displacement, $\dot{x}$ touches on the damper's piston head velocity, $K_0$ indicates damper stiffness at high velocities, $K_1$ alludes to the accumulator stiffness, $C_0$ pertains to viscous damping at high linear velocities (the effective-voltage linear function with $C_{\circ a}$‘$C_{\circ b}$ coefficients), $C_1$ relates to damping to open the branches of the force-velocity curve at low velocities (the effective-voltage linear function with $C_{1a}$‘$C_{1b}$ coefficients), $x_0$ refers to the primary displacement in accumulator, $\alpha_0$ denotes supplementary coefficient (the effective-voltage linear function with $\alpha_a$‘$\alpha_b$ coefficients), T implies auxiliary variable, y concerns domestic quasi-displacement of the damper, u pertains to the effective voltage, v regards the applied voltage, $\eta$ relates to the post-yield viscosity of the fluid damper, $\dot{u}$ alludes to the velocity of voltage generation, and $A, \sigma, \theta, \lambda$ indicate fixed regulating factors (typically $\lambda = \theta$). Similarly, T, y variables are intertwined with two first order differential equations. The value of Parameter applied in 3000N MR damper are mentioned in Table 1.

In contrast, in explicit models, the estimation of the MR damper force is presented without the need to solve the differential equations and only as a function of the input current. The Yang model is an example of a precise explicit method in which the impacts of hysteresis and friction lag are considered. In this study, the MR damper force obtained from the Yang model is investigated for formulation. In the Yang's explicit model, the MR damper force ($F^d_i$) is obtained as follows [17]:

$$F_i^d = kD_i + C\dot{D}_i + \frac{f_b}{e^{\alpha\dot{D} \pm \beta} + \gamma} + f_0 \tag{2}$$

**Table 1**. The value of parameters in 3000N MR Damper for the modified Bouc-Wen model

| Parameter | Value | Unit | Parameter | Value | Unit |
|---|---|---|---|---|---|
| $C_{\circ a}$ | 21 | N.sec/cm | $\alpha_a$ | 140 | N/cm |
| $C_{\circ b}$ | 3.5 | N.sec/cm.V | $\alpha_b$ | 695 | N/cm.V |
| $K_\circ$ | 46.9 | N/cm | $\lambda$ | 363 | $cm^{-2}$ |
| $C_{1a}$ | 283 | N.sec/cm | $\theta$ | 363 | $cm^{-2}$ |
| $C_{1b}$ | 2.95 | N.sec/cm.V | A | 301 | ----- |
| $K_1$ | 5 | N/cm | $\sigma$ | 2 | ----- |
| $x_\circ$ | 14.3 | Cm | $\eta$ | 190 | $sec^{-1}$ |

Where $D_i, \dot{D}_i$ display the relative displacement and velocity of the i-th floor MR damper's piston head, respectively. Moreover, C, k and $f_0$ parameter refer to the damping, stiffness and primary force, accordingly. Likewise, $f_b$, $\alpha$, $\beta$ and $\gamma$ are assumed as the hysteresis parameters. The parameters of the MR damper in the Yang model, with explicit relationships, are dependent on applied effective current (i). For example, the 100N MR damper parameters are as follows:

$$\begin{aligned} C &= 15.761i^2 - 7.1i + 0.756 \\ k &= -41.382i^2 + 13.582i - 0.095 \\ f_b &= -174.903i + 3.137 \\ \alpha &= -0.0278i + 0.0198 \\ \beta &= -1.841i - 1.464 \\ \gamma &= -0.0227i + 0.954 \cong 1 \\ f_0 &= 85.481i + 0.513 \end{aligned} \tag{3}$$

It should be noted that the maximum current creates the damper's maximum tolerable force [18]. In the case of constant current, the MR damper's parameters will have stable values as well. Thus, Eq. (2) can also be considered with constant coefficients. On the other hand, $D_i$ refers to the displacement of the damper's piston head, which is equal to the relative displacement of the i-th floor ($\Delta D_i$). In addition, $\dot{D}_i$ alludes to the relative velocity of the damper's piston head, that is equivalent to the relative velocity of the i-th floor ($\Delta\dot{D}_i$). Hence, Eq. (2) can be written as follows:

$$F_i^d = k\Delta D_i + C\Delta\dot{D}_i + \frac{f_b}{e^{\alpha\dot{D}\pm\beta} + 1} + f_0 \tag{4}$$

The value of $\Delta D_i$ and $\Delta\dot{D}_i$ can be estimated by the modal analysis as follows:

$$\begin{aligned} D_i &= \langle\varphi_{ij}\rangle\{Z_{j1}\} \Rightarrow \Delta D_i = \langle\Delta\varphi_{ij}\rangle\{Z_{j1}\} \\ \dot{D}_i &= \langle\varphi_{ij}\rangle\{\dot{Z}_{j1}\} \Rightarrow \Delta\dot{D}_i = \langle\Delta\varphi_{ij}\rangle\{\dot{Z}_{j1}\}\ j = 1,2,..,n \end{aligned} \tag{5}$$

## 3.THE CONTROL PROGRAM OF THE MR DAMPER

MR dampers are proper devices for the passive, active, and semi-active structural control. The input, in these devices, is typically voltage (current), and the output is force. If the input voltage is constant or equals to zero, the MR damper will be used as a passive control device. By changing the voltage, the output force of the damper changes momentary, and the active control system will be obtained. If, based on a particular controlling program, a certain amount of voltage is continuously applied to the damper and disconnects (equals to zero), the semi-active control system will be availed. Most controlling programs try to minimize kinetic and potential energy of the system and maximize the energy dissipation of the structure, which is usually evaluated based on the system's responses. Consequently, this process is erroneous in scaled structures. The clipped optimal control program is one of the strongest and perfect programs that have always been considered by researchers. In clipped optimal control, if the damper force of the i-th floor ( $f_i$ ) does not reach the optimal force $(f_{opt})$ and be at the same direction, constant voltage ($v_{max}$) will be applied to the damper so that the damper force will be increased;

$$v_i = v_{max} H[(f_{opt} - f_i)f_i] \tag{6}$$

On the other hand, the voltage will be dropped to zero to prevent the negative effect of the damper force. The program is defined by the Heaviside step function and is schematically displayed in Fig. 2 [5]. This controlling program is used here.

Therefore, by using controlling programs, researchers expect that the responses of the control system will be minimized at any given moment and reduced the kinetic energy of the system. On the other hand, the damper force will reach its maximum capacity to increase the dissipated energy of the system.

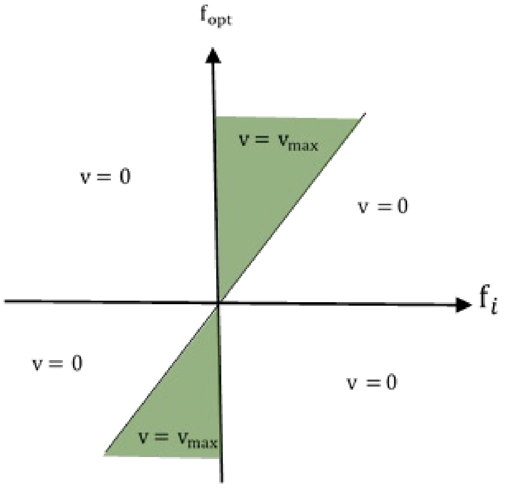


**Figure 2.** Graphical representation of clipped optimal control law

Since the dissipated energy of the damper equals to level below force-displacement diagram, making the dampers reach their maximum capacity is one of the most important goals of the control system [7].

## 4. THE PROPOSED METHOD TO DETERMINE LOCATION AND NUMBER OF MR DAMPERS

The dynamic equilibrium equation with n degree of freedom is as follows:

$$[M]\{\ddot{D}\} + [C]\{\dot{D}\} + [K]\{D\} = \{p(t)\} \quad (7)$$

In Eq. (7), $[K]$ ،$[C]$،$[M]$ and $\{p(t)\}$ are the matrices of mass, damping, stiffness, and the dynamic load vector of the structure, respectively. Also, $\{D\}$ ،$\{\dot{D}\}$ and $\{\ddot{D}\}$ pertain to the vectors of displacement, velocity, and acceleration vectors, respectively. In the modal analysis, the displacement vector is defined as follows:

$$\{D\} = [\varphi]\{Z\} \quad (8)$$

where $[\varphi]$ and $\{Z\}$ are the modal shaped matrix and the modal coordinates vector, respectively. Since the first oscillation mode has the greatest effect on the dynamic response, it can be written as follows [19]:

$$\{D\} \cong \{\varphi_1\}.Z_1 \quad (9)$$

Therefore, the displacement of the i-th degree of freedom of a shear structure ($D_i$) with n degree of freedom is as follows:

$$D_i \cong \varphi_{i1} Z_1 \quad i=1,2,...,n \quad (10)$$

Assuming linear behavior, the maximum displacement of the i-th degree of freedom ($D_{imax}$) is obtained as follows:

$$D_{imax} \cong \varphi_{i1} Z_{1max} \quad (11)$$

Where $Z_{1m\ a}$ is the maximum modal displacement of the first oscillation mode of the structure. Based on Eq. (11), the maximum displacement of each degree of freedom depends on two factors including $Z_{1m\ a}$ and $\varphi_{i1}$.

The parameter $Z_{1m\ a}$ is constant for all degrees of freedom. Therefore, the maximum displacement of i-th degree of freedom is proportional to the i-th element of the first modal shape ($\varphi_{i1}$):

$$D_{imax} \propto \varphi_{i1} \quad (12)$$

Maximum displacement is one of the most significant indicators for evaluating the efficiency of the structural control system. Maximum displacement usually occurs on top of the frame ($D_{nmax}$) and its value is, in accordance with Eq. (13), proportional to the n-th element of the first modal shape ($\varphi_{n1}$):

$$D_{nmax} \propto \varphi_{n1} \quad (13)$$

The n-th element of the first modal shape ($\varphi_{n1}$) can be written as follows:

$$\varphi_{n1} = (\varphi_{n1} - \varphi_{n-1,1}) + (\varphi_{n-1,1} - \varphi_{n-2,1}) + ... + (\varphi_{21} - \varphi_{11}) + (\varphi_{11} - \varphi_{01}) \quad (14)$$

By substituting Eq. (14) into Eq. (13), the maximum displacement will be proportional to:

$$D_{nmax} \propto [(\varphi_{n1} - \varphi_{n-1,1}) + (\varphi_{n-1,1} - \varphi_{n-2,1}) + ... + (\varphi_{21} - \varphi_{11}) + (\varphi_{11} - \varphi_{01})] \quad (15)$$

If there is a Base Isolation, then $\varphi_{01} \neq 0$. Now, the **Modal Relative Displacement** index of the first modal shape in i-th floor ($\Delta\varphi_{i1}$) is defined as:

$$\Delta\varphi_{i1} = \varphi_{i1} - \varphi_{i-1,1} \quad (16)$$

Since only the effect of the first mode is considered, Eq. (16) can be written simply as follows:

$$\Delta\varphi_i = \varphi_i - \varphi_{i-1} \quad (17)$$

Thus, the first modal displacement corresponding to the top floor is simplified as follows:

$$\varphi_n = \Delta\varphi_n + \Delta\varphi_{n-1} + ... + \Delta\varphi_3 + \Delta\varphi_2 + \Delta\varphi_1 \quad (18)$$

By substituting Eq. (18) into Eq. (15), the following result is obtained:

$$D_{nmax} \propto [\Delta\phi_n + \Delta\phi_{n-1} + ... + \Delta\phi_3 + \Delta\phi_2 + \Delta\phi_1] = \sum_{j=1}^{n} \Delta\phi_j \quad (19)$$

Based on Eq. (19), the floor with the maximum modal relative displacement in the first mode ($\Delta\varphi_i$) will have the highest effect on the top floor displacement. This floor has a priority for structural controlling and it is the most suitable place to install a MR damper.

Fig. 3 shows this issue schematically. Based on the proposed method, any floor with the highest $\Delta\varphi_i$ index, has the greatest influence on the top floor displacement. As a result, in order to control the maximum top floor displacement, it is necessary to reduce the displacement of such floors and install MR dampers on there. In the other words, MR dampers can be installed on floors with maximum modal relative displacement. On the other hand, the presence of base isolation leads to the maximum relative displacement at the base of the structure (Fig. 4). Therefore, in such frames, the base is the best place to install MR damper.

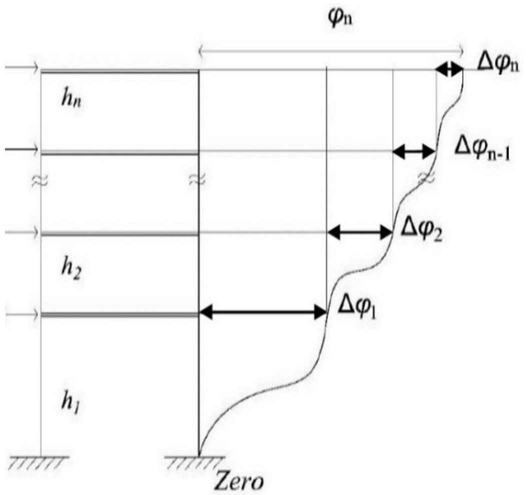


**Figure 3.** The modal displacement of shear frame without base isolation

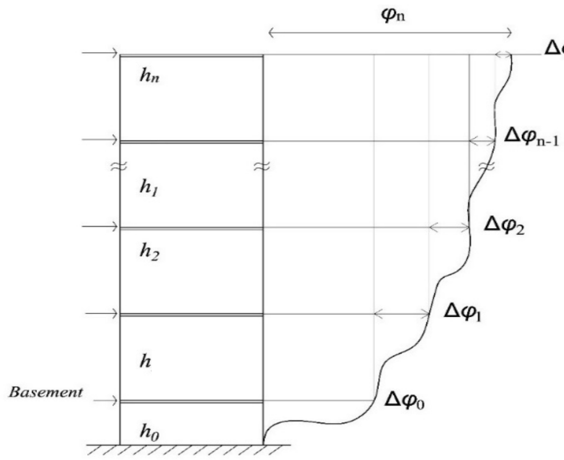


**Figure 4**. The modal displacement of shear frame with base isolation

According to Eq. (10), since the first oscillation mode has the greatest effect on the dynamic response [19], Eq. (5) can be written as follows:

$$\begin{aligned} D_i &\cong \varphi_{i1}\ Z_1 \Rightarrow \Delta D_i \cong \Delta\varphi_{i1} Z_1 \\ \dot{D}_i &\cong \varphi_{i1}\ \dot{Z}_1 \Rightarrow \Delta\dot{D}_i \cong \Delta\varphi_{i1}\dot{Z}_1 \end{aligned} \quad (20)$$

By substituting Eq. (20) into Eq. (4), it is possible to obtain a practical relationship for MR damper force, installed on the i-th floor, as follows:

$$F_i^{\ d} = \Delta\varphi_i (kZ_1 + C\dot{Z}_1) + \frac{f_b}{e^{\alpha\Delta\dot{D}\pm\beta} + 1} + f_0 \quad (21)$$

Eq (21) can be written as follow:

$$F_i^d = \Delta\varphi_i (kZ_1 + C\dot{Z}_1) + L \quad (22)$$

where, L depends on applied effective current (i), only. it can be easily shown that for various MR dampers the L value (the hysteresis and the primary force) is less than 30% of the total force and the first part of the equation (damping and stiffness) provides more than 70% of its value in the maximum force of the MR damper. As a result, most of the damper force was exerted by the $\Delta\varphi_i$ part of the i-th floor.

The maximum efficiency of a MR damper is achieved when it reaches its maximum force [5, 7], so based on Eq. (22) the damper should be installed on floors which have the highest $\Delta\varphi_i$ . As a consequence, the dependent MR damper reaches its highest efficiency and force absorption if it is installed on floors that have the highest modal relative displacement;

$$F_{i\,max}^d = g\ (\Delta\varphi_{i\,max}) \quad (23)$$

In order to employ the proposed method more systematically, it is necessary to categorize the structure's stories. Accordingly, the stories are classified into three groups: very weak, weak, and strong. The main and auxiliary dampers are connected to very weak and weak stories, respectively. In the following, the proposed classification of stories is presented as follows:

### 4.1. Very weak stories

In the event that the displacement is assumed linear in the first oscillation mode of the shear frame, it can be written:

$$\Delta\bar{\varphi}_1 = \Delta\bar{\varphi}_2 = \cdots = \Delta\bar{\varphi}_n \quad (24)$$

$$\varphi_n = n\Delta\bar{\varphi}_1 \quad (25)$$

Therefore, the linear modal relative displacement of each floor ($\Delta\bar{\varphi}$) can be obtained as follows:

$$\Delta\bar{\varphi} = \frac{\varphi_n}{n} \quad (26)$$

It must be underlined that the displacement of a real structure is non-linear. In this case, the modal relative displacement of upper stories is usually decreased and its value is much less than the linear modal relative displacement ($\Delta\bar{\varphi}$). As a result, the modal relative displacement of Eq. (26) can be used as a criterion to recognize very weak stories. Accordingly, if the modal relative displacement of a story ($\Delta\varphi_i$) exceeds the linear modal relative displacement ($\Delta\bar{\varphi}$), this story will be assumed as a very weak one;

$$\Delta\varphi_i \geq \frac{\varphi_n}{n} \quad (27)$$

In the case of satisfaction condition (27), main dampers (those suitable for very weak stories) are installed. It seems economical to use MR dampers on very weak stories. In addition, the maximum frame displacement can be significantly reduced by low cost. The more the modal relative displacement of a story ($\Delta\varphi_i$) exceeds the linear modal relative displacement ($\frac{\varphi_n}{n}$), based on Eq. (23) the damper endures more force and its activity increases as well as its efficiency.

**Table 1**. The mass, stiffness and class of story specifications of F1, F2, F3 three-story frames

| Story i | F1 Mass (N) | F1 Stiffness (N/m) | F1 $\Delta\varphi_i$ | F1 Class of Story | F2 Mass (N) | F2 Stiffness (N/m) | F2 $\Delta\varphi_i$ | F2 Class of Story | F3 Mass (N) | F3 Stiffness (N/m) | F3 $\Delta\varphi_i$ | F3 Class of Story |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **3** | 964 | $6.84*10^5$ | .1199 | **Strong** | 964 | $6.84*10^5$ | .1313 | **Strong** | 964 | $5.16*10^5$ | .1924 | **Weak** |
| **2** | 964 | $6.84*10^5$ | .2196 | **Weak** | 964 | $5.16*10^5$ | .3166 | **Very Weak** | 964 | $6.84*10^5$ | .2541 | **Very Weak** |
| **1** | 964 | $5.16*10^5$ | .3736 | **Very Weak** | 964 | $6.84*10^5$ | .2910 | **Very Weak** | 964 | $6.84*10^5$ | .3141 | **Very Weak** |

### 4.2. Weak stories

Weak stories can be approximately identified as follows;

$$0.7\frac{\varphi_n}{n} < \Delta\varphi_i < \frac{\varphi_n}{n} \quad (28)$$

In case of stories, which conform to condition Eq. (28), auxiliary MR dampers (specified for weak stories) can be installed. It is noteworthy that auxiliary dampers endure less force and are more efficient in reducing the oscillation at top of the frame than the main dampers.

### 4.3. Strong stories

Strong stories can be approximately defined by following condition;

$$\Delta\varphi_i \leq 0.7\frac{\varphi_n}{n} \quad (29)$$

The installation of MR dampers on strong stories is neither economical nor has much effect on reducing the displacement at top of the frame. Besides, the MR dampers installed on strong stories do not withstand much force.

### 4.4. The number of MR dampers

The number of MR dampers required for achieving the proper rate of efficiency and reducing the control costs can be determined based upon the classification provided for the structural stories. The appropriate number of dampers is determined in a way that all MR dampers applied on the story reach their maximum performance. Therefore, it is recommended to install a MR damper on any story, which is very weak. On this account, the number of MR dampers should be equal to the number of very weak stories in each structure. In order to guarantee the stability of the numerical method of the dynamic analysis, the damping matrix must be positive semi-definite. Thus, there must be as many sensors as the dampers, and each sensor should be installed in place of a MR damper [20].

## 5. NUMERICAL EVALUATION OF THE PROPOSED METHOD

In the previous section, a new method was presented for location and number of MR dampers. In order to run a numerical evaluation of the proposed solution, the oscillations of several benchmark shear frames are controlled with MR dampers and the results are compared with conventional techniques. To do so, the required computer program in MATLAB 9-3-0 accompanied by SIMULINK software box have been provided. This program can monitor the oscillations of the shear frame, applying MR dampers.

In this regard, dynamic analysis was performed using the Newmark-β method, with a millisecond time-step. The proposed algorithm, in which MR dampers are installed on very weak stories, is marked with PMR- i~k, and i~k represents very weak stories.

Furthermore, MR-i~k is applied to display other methodologies in which i~k alludes to the degrees of freedom of MR damper's installation. For instance, in MR-1 algorithm, a damper is installed on the first story, in MR-13 algorithm, two dampers are installed on the first and third stories, and in MR-123 algorithm, three MR dampers are set up on the first, second, and third stories.

### 5.1. Three-story frame

As the first step, the efficiency of the proposed method is measured on a three-story shear benchmark frame (F1) excited by El-Centro earthquake [6,5,11,13]. By changing the stiffness specifications, the two other frames, including F2 and F3, will be accessible. It should be pointed out that F2 and F3 frames are designed similar to F1 benchmark frame, and the only soft story in these frames is moved to the second and third stories, respectively. Table 2 shows the mass and stiffness specifications of these frames. Applying the proposed method, the classification of stories in F1, F2, and F3 frames are listed in Table 2.

**Table 3.** The results of different MR damper algorithms for three-story frame

| Frame | Algorithm Of Location Of MRD | $D_{3max}$ Uncontrolled (cm) | $D_{3max}$ (cm) | Displacement Reduction Percentage % | $F^d_{1max}$ (N) | $F^d_{2max}$ (N) | $F^d_{3max}$ (N) |
|---|---|---|---|---|---|---|---|
| F1 | **PMR-1** | 2.567 | **.7707** | **70.0** | **1567** | **----** | **----** |
| | MR-2 | | 1.0844 | 57.0 | ---- | 1434 | ---- |
| | MR-3 | | 1.5023 | 41.5 | ---- | ---- | 1407 |
| | MR-12 | | .6012 | 76.6 | 1436 | 1215 | ---- |
| | MR-13 | | .6618 | 74.2 | 1499 | ---- | 1042 |
| | MR-23 | | .8382 | 67.4 | ---- | 1406 | 1204 |
| | MR-123 | | .5042 | 80.4 | 1425 | 1206 | 977 |
| F2 | MR-1 | 3.103 | .8370 | 73.0 | 1544 | ---- | ---- |
| | MR-2 | | .8046 | 74.1 | ---- | 1511 | ---- |
| | MR-3 | | 1.5804 | 49.1 | ---- | ---- | 1453 |
| | **PMR-12** | | **.5754** | **81.5** | **1338** | **1329** | **----** |
| | MR-13 | | .7338 | 76.4 | 1488 | ---- | 1079 |
| | MR-23 | | .7146 | 77.0 | ---- | 1490 | 1114 |
| | MR-123 | | .4996 | 83.9 | 1321 | 1310 | 1004 |
| F3 | MR-1 | 3.318 | .7932 | 76.1 | 1533 | ---- | ---- |
| | MR-2 | | .8292 | 75.1 | ---- | 1421 | ---- |
| | MR-3 | | 1.8249 | 45.0 | ---- | ---- | 1396 |
| | **PMR-12** | | **.5114** | **84.6** | **1353** | **1311** | **----** |
| | MR-13 | | .6312 | 81.0 | 1432 | ---- | 1139 |
| | MR-23 | | .7062 | 78.7 | ---- | 1407 | 1200 |
| | MR-123 | | .4531 | 86.3 | 1317 | 1308 | 1085 |

As reported by Table 2, there is a very weak story in F1; therefore, the proposed method is performed using one MR damper on the first story (PMR-1). The damping values are represented as $C_1 = 125,\ C_2 = C_3 = 50\ (\frac{N.\sec}{m})$ and in F2 and F3 frames,

by the replacement of the soft story, the maximum damping value was assigned to that floor as well. In all frames, MR dampers of 3000N type, presented in section 2, were used with specified value, using the modified Bouc-Wen model. The clipped optimal control program with maximum applied voltage of 2.25 v is utilized. The maximum displacement at top of the frame, its reduction related to the uncontrolled structure and the maximum values of the MR damper force, for different algorithms are listed in Table 3.
From Table 3 it is concluded that in F1 frame, the PMR-1 decreases the displacement at top of the frame by 70%. However, by placing MR damper on other weak or strong stories (MR-2 and MR-3), the efficiency of structural control method is greatly reduced and the damper endures less force. In the proposed method, the MR damper has reached its maximum performance.

On the other hand, by increasing the number of dampers to two or three (MR-12 and MR-123), the efficiency of the structural control method is slightly improved by 6.6% and 3.8%, respectively. Nevertheless, the dampers, which are installed in strong and weak stories, endure less force and their efficiency does not increase significantly. The location and number of the required dampers are fully consistent with previous studies.

In the case of F2 frame, if a damper is installed in a very weak story (MR-1), the displacement at top of the frame will be reduced by 73%, and if the same damper is installed on the second very weak story, the displacement at top of the frame will be reduced by 74.1%. Here, the efficiency ratio is improved due to the modal relative displacement of the story. This being the case, the displacement is proportional to the modal relative displacement, regardless of the floor's position in the frame.

According to the proposed method, if two MR dampers are installed on the first and second very weak stories (PMR-12), the efficiency of the structural control method will increase by 8.5%. In such circumstances, the second-story damper will have the same rate of force as the first-story damper, and both dampers are completely activated.

Nonetheless, adding third damper (MR-123), the efficiency of the structural control method will be increased by 2.4% so not considerable improvement will be carried out. In the case of three dampers, the first-story and the second-story dampers are fully activated but the third-story damper does not reach its maximum force capacity.

In F3 frame, if a damper is installed on the first very weak story (MR-1), the displacement at top of the frame will be reduced by 76.1%, and if the same damper is installed on the third weak story (MR-3), the displacement is reduced by 45%. Thus, the installation of a damper on a single weak story seems less influential. According to the proposed method, by installing two dampers on two very weak stories (PMR-12), the displacement at top of the frame decreases by 85% and a significant improvement is achieved. In this case, the second-story damper force is approximately the same of the first-story damper force and gets activated. By installing the third damper on the third weak story (MR-123), only 1.7% improvement is achieved which reduces the damper's influence. Obviously, the third-story damper is not fully activated.

## 5.2 Six-story frame

In order to evaluate the efficiency of the proposed method, a six-story benchmark frame with the same mass $m_i = 222\,(N)$ and stiffness $k_i = 29700(\frac{N}{m})$ at all stories was examined. Applying the proposed method, the classification of stories is listed in Table 4. Here, The damping coefficient is ξ =0.5% and the dampers of 30 N are used. This frame is subjected to the ten percent of El-Centro ground acceleration record. The dampers were modeled by the Bouc-Wen model and the clipped optimal control program, considering 5 voltages. The rest of the data are provided in references [7].

**Table 4.** The classification of stories in six-story benchmark frame

| ***Story (i)*** | *1* | *2* | *3* | *4* | *5* | *6* |
|---|---|---|---|---|---|---|
| $\varphi_1$ | *.1327* | *.2578* | *.3678* | *.4565* | *.5187* | *.5507* |
| $\Delta\varphi_1$ | *.1327* | *0.1251* | *.1100* | *.0887* | *.0622* | *.0320* |
| ***Class of Story*** | *Very Weak* | *Very Weak* | *Very Weak* | *Weak* | *Strong* | *Strong* |

The frame was analyzed in different cases including three modes with single damper (MR-1, MR-4 and MR-6), three dampers (MR-456), four dampers (MR-1~4) and with six dampers (MR-1~6). Here, the proposed control method is PMR-123 because there are three very weak story in this frame (Table 4). The results of these analyses, including the maximum displacement, reduction related to the uncontrolled frame and maximum MR damper forces are listed in Table 5.

Based on Table 5, it can be concluded that by installing a MR damper on the first very weak story (MR-1), the displacement at top of the frame will be reduced by 32.5%. If the same damper is installed on the fourth weak story (MR-4) or the sixth strong story (MR-6), the displacement at top of the frame will be reduced by 20.8% and 13.4%, respectively and the efficiency of the structural control will be lessened, accordingly.

Table 5. The results of different MR damper algorithms for six-story benchmark frame

| Story | Uncont. | MR-1 | | MR-4 | | MR-6 | | PMR-123 | | MR-456 | | MR-1~4 | | MR-1~6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Displ. (cm) | Displ. (cm) | Red. % | Displ. (cm) | Red. % | Displ. (cm) | Red. % | Displ. (cm) | Red. % | Displ. (cm) | Red. % | Displ. (cm) | Red. % | Displ. (cm) | Red. % |
| **6** | 1.3131 | .8866 | 33 | 1.040 | 21 | 1.137 | 13 | .4989 | 62 | .8123 | 38 | .4089 | 69 | .282 | 79 |
| **5** | 1.1990 | .8512 | 29 | .9601 | 20 | 1.045 | 13 | .4348 | 64 | .7804 | 35 | .2753 | 77 | .229 | 81 |
| **4** | 1.0407 | .7580 | 27 | .7921 | 24 | .8921 | 14 | .3574 | 66 | .7125 | 32 | .1879 | 82 | .166 | 84 |
| **3** | .8272 | .5860 | 29 | .6358 | 23 | .6945 | 16 | .2283 | 72 | .5472 | 34 | .1437 | 83 | .132 | 84 |
| **2** | .5948 | .3946 | 34 | .4930 | 17 | .5421 | 9 | .1558 | 74 | .3963 | 34 | .1080 | 82 | .100 | 83 |
| **1** | .3163 | .1817 | 43 | .2672 | 16 | .2917 | 8 | .0968 | 69 | .1821 | 42 | .0635 | 80 | .063 | 80 |
| $F^d_{imax}(N)$ | ---- | 23.78 | | 23.74 | | 23.53 | | 23.72,23.72 23.70 | | 22.88,22.69 21.61 | | 23.71,23.71 23.70 | | 23.71,23.71 23.70,19.23 17.32,15.21 | |

Since more than one damper is required to control the frame, the dampers force is the same in all these three cases. Based on the proposed method, by using three dampers in very weak stories (PMR-123), the placement at top of the frame will decrease by 62% that is a significant improvement, compared to the single damper algorithms. The location and number of the required dampers are fully consistent with previous studies. In the proposed method, all three dampers reach their maximum force capacity and are fully activated. If three dampers are installed on the fourth, fifth, and sixth story (MR-456), the displacement at top of the frame will be reduced by 38.1%. In this case, the dampers will be less influential. In such circumstances, the dampers do not endure much force and will not be activated, accordingly. On the other hand, the displacement reduction in the case of three dampers is approximately the same of using single damper. It is observed that the damper force, installed on the sixth story, has been reduced to 21.61 (N) and has not improved much in controlling the frame. By installing four dampers (MR-1~4) and six dampers (MR-1~6), the structural control efficiency increases by 7% and 9%, respectively, which cannot be regarded as a significant improvement. In such cases, the dampers do not endure much force and they are not activated.

## 6. CONCLUSION

In this study, a new method was proposed to determine the suitable location and number of MR dampers in the semi-active structural control. This method was provided based on the relative displacement of the first structural oscillation mode. For this purpose, the stories were divided into three groups including very weak, weak, and strong. The suitable locations of dampers, in compliance with the proposed theory, are very weak stories of the structure. The proposed method has been able to determine the number of dampers in a way that all of them are activated. Nonetheless, in similar studies, the dampers are not typically activated. The results obtained from the proposed method are fully consistent with the results of the previous studies. Therefore, the suitable number of MR dampers is equal to the number of very weak stories. Dampers are quite forceful in very weak stories and reach their force capacity thoroughly. However, having said that, dampers are not activated on weak and strong stories. On the other hand, the installation of dampers on strong stories has been found uninfluential, and on weak stories has much less effect than on very weak stories. As a result, it is concluded that the location and number of dampers in structural control only depends on controlling very weak stories.

## REFERENCES


[1] Huang X., Evaluation of genetic algorithms for the optimum distribution of viscous dampers in steel frames under strong earthquakes, *Earthquakes and Structures*, 14(3), 2018, pp. 215-227. https://doi.org/10.12989/eas.2018.14.3.215.

[2] Alamatian J., Rezaeepazhand J., A simple approach for determination of actuator and sensor locations in smart structures subjected to the dynamic loads, *International Journal of Engineering Transactions, A: Basics*, 24(4), 2011, pp. 341-349.

[3] Karimpour B., Keyhani A., Alamatian, J., New active control method based on using multiactuators and sensors considering uncertainly of parameters, *Journal of Advances in Civil Engineering*, 2014, pp. 1-10. https://doi.org/10.1155/2014/180673.

[4] Spencer Jr.B.F., Nagarajaial S., State of the art of structural control, *ASCE Journal of structural Engineering*, 129(7), 2003, pp. 845-856. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:7(845).

[5] Dyke S.J., Spencer Jr.B.F., Sain M.K, Carlson J.D. Modeling and control of magnetorheological dampers for seismic response reduction, *Smart Materials and Structures*, 5, 1996,pp565-575.https://doi.org/10.1088/0964-1726/5/5/006.

[6] Spencer Jr.B.F., Dyke S.J., Sain, M.K., Carlson, J.D., Phenomenological model of a Magnetorheological damper”, *ASCE Journal of Engineering Mechanics*, 1997, pp. 1-23. https://doi.org/10.1061/(ASCE)0733-9399(1997)123:3(230).

[7] Jansen L.M., Dyke, S.J., Semi-active control strategies for MR dampers: Comparative study, *ASCE Journal of Engineering Mechanics*, 126(8), 2000, pp. 795–803. https://doi.org/10.1061/(ASCE)0733-9399(2000)126:8(795).

[8] Yang, G., Spencer Jr.B.F., Carlson J.D., Sain M.K. Large-scale MR fluid dampers: modeling and dynamic performance consideration, *Engineering Structures*,24,2002, pp. 304-323.https://doi.org/10.1016/S0141-0296(01)000979.
[9] Tsang H.H., Su R.K.L., Chandler A.M., Simplified inverse dynamics models for MR fluid dampers, *Engineering Structures*, 28, 2005, pp. 327-341. https://doi.org/10.1016/j.engstruct.2005.06.013.
[10] Liu Y., Matsuhisa H., Utsuno H., Park J.G., Vibration control by a variable damping and stiffness system with MR dampers, *JSME International Journal*, 49, 2006, pp. 411-417. https://doi.org/10.1299/jsmec.49.411.
[11] Das D., Datta T.K., Madan, A., Seismic control of building frames using MR dampers, *Proceedings of the 14th World Conference on Earthquake Engineering*,2008Beijing, China.
[12] Cha Y.J., Agrawal A.K., Philips B.M., Spencer Jr.B.F., Direct performance-based design with 200KN MR dampers using multi-objective cost effective optimization for steel MRFs, *Engineering Structures*, 71, 2014, pp. 60-72. https://doi.org/10.1016/j.engstruct.2014.04.023.
[13] Elmeligy O.M.M., Hasan M.H.M., Optimum allocation of MR dampers within semi-active control strategies of 3DOF systems, *International Journal of Recent Contributions from Engineering, Science & IT*, 4, 2016, pp. 45-49. https://doi.org/10.3991/ijes.v4i4.6546.
[14] Takin K., Hosseini Hashemi B., Nekooei M., Controlling the lateral displacement of building with external lever by using of MR damper", *Earthquakes and Structures*, 13(1), 2017, pp. 1-8. https://doi.org/10.12989/eas.2017.13.1.001.
[15] Hadidi A., Farahmand Azar B., Shirgir S., Reliability assessment of semi-active control of structures with MR damper, *Earthquakes and Structures*, 17(2), 2019, pp. 131-141. https://doi.org/10.12989/eas.2019.17.2.131.
[16] Shirgir S., Farahmand Azar B., Hadidi, A., Opposition based charged system search for parameter identification problem in a simplified Bouc-Wen model, *Earthquakes and Structures*, 18(4), 2020, pp. 493-506. http://dx.doi.org/10.12989/eas.2020.18.4.493 .
[17] Yang M.G., Li C.Y., Chen Z.Q., A new simple non-linear hysteretic model for MR damper and verification of seismic response reduction experiment", *Engineering Structures*, 52, 2013, pp.434-45. https://doi.org/10.1016/j.engstruct.2013.03.006 .
[18] Sapinski B., Filus J., Analysis of parametric models of MR damper, *Journal of Theoretical and Applied Mechanics*, 41(2), 2003, pp. 215-240.
[19] Clough R.W., Penzien J., *Dynamics of structures*, John Willey & Sons, New York, N.Y, USA, 1997.
[20] Alamatian J., Davtalab H., A new active control process based on applying critical damping theor, *Romanian Journal of Acoustics and Vibration*, XIV, 2017, pp. 115-124.