Seismic Response Control of Building using Magneto-rhelogical (MR) Damper

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Abstract-- **Recent trends in civil engineering construction have been to build taller buildings and more flexible structures. The inherent damping in these structures that can mitigate large vibration response under severe environmental loading (e.g. Earthquake, Wind etc.) is small. In recent years, efforts have been undertaken to develop the concept of energy dissipation or supplemental damping into a workable technology and a number of these devices have been installed in structures throughout the world. This paper discusses the passive mode of enhancing damping of the building using Magneto-rhelogical (MR) damper device. It has been shown that, seismic responses of the building undertaken are controlled substantially.**

***Index Terms*—Magneto-rhelogical (MR) Fluid, Magento-rhelogical (MR) Damper, Modified Bouc-wen Model, The State Space Method**

I. INTRODUCTION

Civil engineering structures must withstand ever-changing environmental loads, such as earthquake, wind etc., over the span of their design life. All vibrating structures dissipate energy due to internal stressing, rubbing, cracking, plastic deformations, and so on; the larger the energy dissipation capacity the smaller the amplitude of vibration. Some structures have very low damping on the order of 1% of critical damping and consequently experience large amplitudes of vibration even for moderately strong earthquakes. Methods of increasing the energy dissipation capacity are very effective in reducing the amplitude of vibration. Many methods of increasing damping have been utilized and many others have been proposed. The various types of passive damping devices include, Metallic Yield Damper, Friction Damper, Visco-elastic Damper, Viscous Fluid Damper, Tuned Mass Damper, Tuned Liquid Damper and Liquid Column Damper [1],[2]. However, due to advent of smart materials in recent past, many new promising devices have been developed, like Controllable Fluid Dampers. The advantage of controllable fluid devices is that they contain no moving parts other than piston unlike to other passive devices, which makes them more reliable. The essential characteristic of controllable fluid is their ability to reversely change from a free flowing, linear viscous fluid to a semi-solid with controllable yield strength in milliseconds when exposed to electric or magnetic field [3]. Two fluids that are viable contender for development of controllable dampers are (I) Electro-rhelogical (ER) Fluid and (II) Magneto-rhelogical (MR) Fluid. Both Electro-rhelogical (ER) and Magneto-rhelogical (MR) fluids have similar zero-field viscosity of the order of 0.1 to 1.0 Pa-s, but they differ markedly in the maximum yield stress they can support. Typical maximum value of τ_y for ER fluids are in the range of 2 to 5 kPa, while MR fluids are stronger with maximum τ_y in the range of 50 to 100 kPa.

II. MAGNETO-RHELOGICAL (MR) FLUID AND DAMPER

1) *Magneto-rhelogical Fluid*

The MR fluids are suspensions of particles in inert carrier fluids. The particles, typically of the order of 1 to 10 μm in size, are added to fluids, such as mineral oils or silicone oils, in weight fraction as large as 50% with fractions of around 30 wt %. Most MR fluids also contain small amount of additives that affect the polarization of the particles or stabilize the structure of the suspension against settling. The effect of magnetic field on the MR fluids is to cause the particles to form chains or fibrils, in the direction of the applied field and the strength of this increases with increment of applied magnetic filed as shown in Fig. 1 [4].

The process of fibration occurs in a few milliseconds after application of the field. The formation of particle chains occurs when the magnetically polarized particles move into alignment with the applied field and are then drawn together like magnets whose opposite poles attract the adjacent particles in the chain. The process of fibration in the response to magnetic field within a field itself is known as ‘MR Effect’. These structures (fibrils) actually aggregations of solid particles, dominate the flow of the fluid, and can prevent flow entirely at lower stresses, and therefore requiring a minimum shear stress for the flow to be initiated. As the field-induced change increase the ability of MR fluid to support shear stress, most engineering application of MR fluids exploits their controllable yield stress to vary the coupling or load transfer between the moving parts, for examples in dampers and clutches [5].

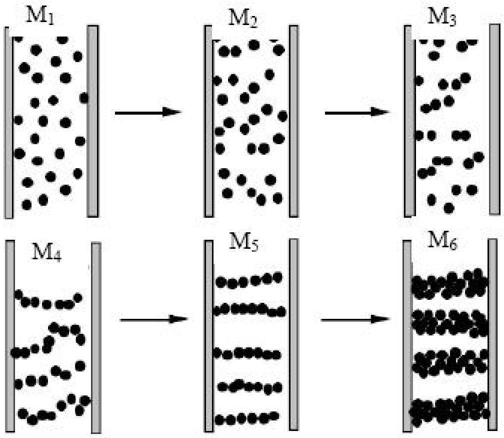

Fig. 1 Chain-like Structure Formation under the Applied External Magnetic Field [4]

For engineering application of MR fluid, understanding of mechanical behavior of MR fluid and subsequently physical/mathematical modeling of it, is most essential. Many researchers have undertaken experiments to understand the rheological effect. It was found that, in absence of magnetic field MR fluid may be characterized as Newtonian, i.e., as resisting shear strain γ with a shear stress τ proportional to the product of the strain rate $\dot{\gamma}$ and viscosity η. The mathematical relationship can be given as [5],

$$\tau = \eta \dot{\gamma} \tag{1}$$

where, η is the slope of the curve – viscosity, $\dot{\gamma}$ is shear strain rate and τ is shear stress of the fluid. However, it is important to note that this is an approximation, as most MR fluids are non-newtonian even when no field is applied because of their heavy loading of solid particles and, to some extent because of the additives they contain. The formation of fibrils within MR fluid under applied magnetic field is expected to increase the viscosity of fluid. But, it has been seen that, the slope of fibril formation is to produce a shear stress which is dependent on the applied magnetic field only. This shear stress is identified as yield stress τ_y, which is independent of the strain rate. The addition of this term τ_y which is a function of applied magnetic field with the Newtonian model results into Bingham Plastic Model. Therefore, the stress-strain relationship for Bingham Plastic Model is given as,

$$\tau = \tau_y(H) + \eta \dot{\gamma} \tag{2}$$

where, τ_y is the yield stress of the fluid & H is the applied magnetic field while rest parameters are as noted earlier. The relationship of stress-strain can be depicted in Fig. 2.

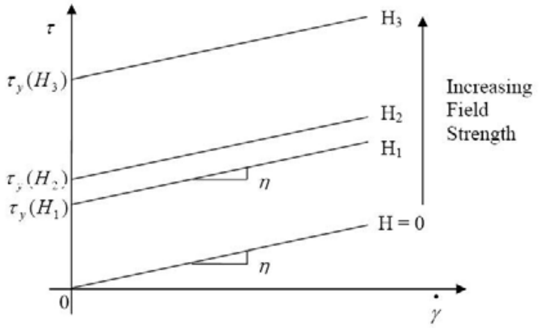

Fig. 2 Shear Stress vs. Shear Strain Rate for the Bingham Plastic Model [5]

2) Magneto-rhelogical (MR) Damper

To take full advantage of the unique features of MR fluids in structural control applications, the device must be developed that can be house the MR fluids and magnetic field coil. A prototype MR damper as shown in Fig. 3 has been developed by the Lord Corporation, USA which comprised of a fixed orifice damper filled with MR fluid [6]. The damper is 21.5 cm long in its extended position, and the main cylinder is 3.8 cm in diameter. The main cylinder housed the piston, the magnetic circuit, an accumulator and 50 ml of MR fluid, and the damper has a ± 2.5 cm stroke. The magnetic field is generated in the MR damper by a small electromagnet in the piston head, as shown in Fig. 3. The current for the electromagnet is supplied by a linear current driver running off of 120 V AC, which generates a 0 – 1 amp current that is proportional to an applied DC input voltage in the range 0 – 3 V. The peak power required is less than 10 W, which could allow the damper to be operated continuously for more than an hour on a small camera battery. Forces of up to 3000 N can be generated with this MR damper device. The force is stable over a broad temperature range, varying less than 10% in the range of -40 to 150 Celsius.

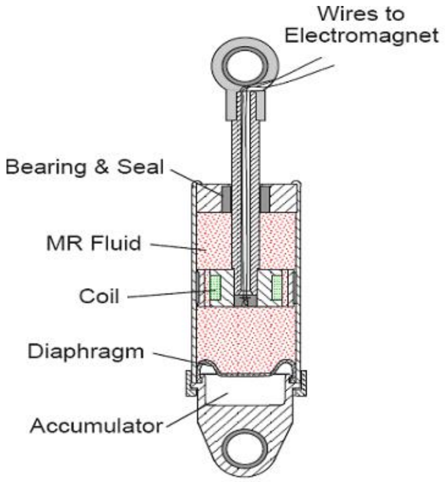

Fig. 3 Schematic Diagram of Prototype MR Damper Device [6]

Most devices which use controllable fluids like MR fluid operates in any one of the operating modes namely, Valve

Mode (Pressure Driven Flow Mode or Parallel Plate Mode), Direct Shear Mode (Relatively Movable Plate Mode) and Squeeze Mode as shown Fig. 4 [7].

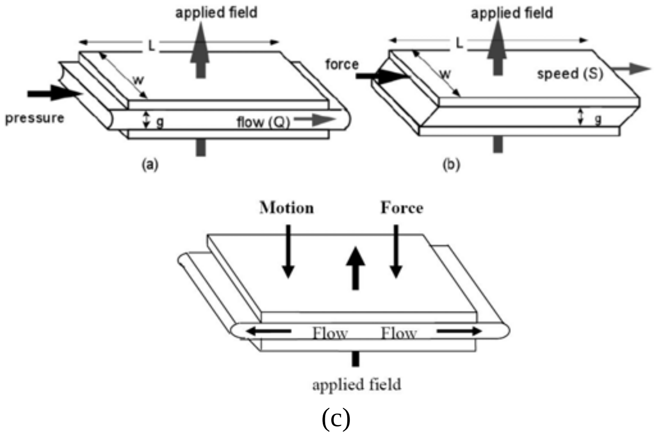

Fig. 4 Operating Modes of Controllable Fluids (a) Valve Mode (b) Direct Shear Mode (c) Squeeze Mode [7]

With reference to Fig. 4, it is evident that prototype MR damper device mentioned above and shown in Fig. 3 is working in Valve mode (Parallel plate mode), as MR fluid is passing through the annular orifice of the damper. It has been observed through the literatures that most common operating mode of majority of the MR dampers developed so far is parallel plate mode followed by direct shear mode and squeeze mode is seldom in use.

3) The Modified Bouc-wen Model

The model, which is numerically tractable and has been used extensively for modeling hysteresis systems, is the modified bouc-wen model. The schematic diagram of modified bouc-wen model is as shown in Fig. 5.

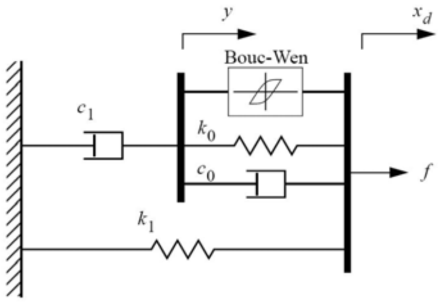

Fig. 5 Schematic Diagram of The Modified Bouc-wen Model [8]

To obtain the governing equations for the model, consider only the upper section of the model. The forces on either of the rigid bar are equivalent, therefore,

$$c_1\dot{y} = \alpha z + k_0(x_d - y) + c_0(\dot{x}_d - \dot{y}) \qquad (3)$$

Where the evolutionary variable z is governed by [8]

$$\dot{z} = -\gamma\,|\dot{x}_d - \dot{y}|\,z\,|z|^{n-1} - \beta(\dot{x}_d - \dot{y})\,|z|^{n} + A(\dot{x}_d - \dot{y}) \qquad (4)$$

Solving equation (3) for $\dot{y}$ results in,

$$\dot{y} = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{x}_d + k_0(x_d - y)\} \qquad (5)$$

The total force generated by the system is then found by summing the forces in the upper and lower sections of the system in Fig. 5, yielding,

$$f = \alpha z + c_0(\dot{x}_d - \dot{y}) + k_0(x_d - y) + k_1(x_d - y) \qquad (6)$$

From equation (3), the total force can be also be written as,

$$f = c_1\dot{y} + k_1(x_d - x_0) \qquad (7)$$

In this model, the accumulator stiffness represented by k_1 and the viscous damping observed at larger velocities is represented by c_0. A dashpot, represent by c_1, is included in the model to produce the roll-off that was observed in the experimental results (excluded explicitly due to space limitation) at low velocities, k_0 is present to control the stiffness at large velocities, and x_0 is the initial displacement of spring k_1 associated with the nominal damper force due to the accumulator.

To determine a model that is valid for fluctuating magnetic fields, the functional dependence of the parameters on the applied voltage (or current) must be determined. Therefore, the following relations were proposed by Dyke [9].

$$\begin{aligned} \alpha &= \alpha(u) = \alpha_a + \alpha_b u \\ c_1 &= c_1(u) = c_{1a} + c_{1b}u \\ c_0 &= c_0(u) = c_{0a} + c_{0b}u \end{aligned} \qquad (8)$$

where the dynamics involved in the MR fluid reaching rheological equilibrium are accounted for through the first order filter

$$\dot{u} = -\eta(u - v) \qquad (9)$$

and v is the voltage applied to the current driver. Optimal values of a total of fourteen parameters ($c_{0a}, c_{0b}, c_{1a}, c_{1b}, k_0, k_1, x_0, \alpha_a, \alpha_b, \gamma, \beta, A, \eta, n$) must be determined for the prototype MR damper. The Table 1 indicates the optimized parameters for the generalized model determined by Dyke [9].

To predict the behavior of the MR damper, the model given by equations (4, 5 & 6) was subjected to the 2.5 Hz frequency & 1.5 cm amplitude – sinusoidal forcing function and command voltage to the current driver was kept at 1.5 V.

The simulation of the modified bouc-wen model through MATLAB is shown in Fig. 6. For simulation of modified bouc-wen model, determination of initial conditions of MR damper at $t = 0$ was crucial. To determine the initial conditions, the experimental response (excluded explicitly due to space limitation) of MR damper was used. The value of evolutionary variable z at $t = 0$ was calculated as 0.05.

TABLE 1
Parameters for the Generalized Modified Bouc-wen Model [9]

Parameter	**Value**
c_{0a}	21.0 N.sec/cm
c_{0b}	3.50 N.sec/cm V
c_{1a}	283 N.sec/cm
c_{1b}	2.95 N.sec/cm V
k_0	46.9 N/cm
k_1	5.00 N/cm
x_0	14.3 cm
α_a	140 N/cm
α_b	695 N/cm V
γ	363 cm^{-2}
β	363 cm^{-2}
A	301
η	190 sec^{-1}
n	2

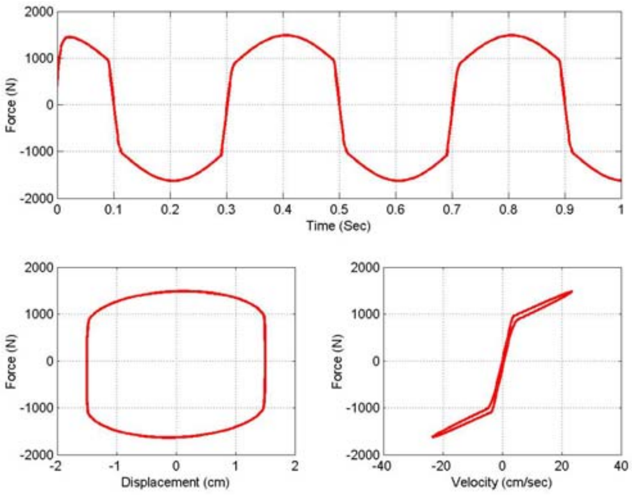

Fig. 6 Simulation Result of the Modified Bouc-wen Model

III. NUMERICAL PROBLEM FORMULATION

A model three storey building with a single MR damper attached at ground floor was considered for the seismic response control study. It has been assumed that, masses are lumped at floor levels. The schematic diagram of three storey building with MR damper installed at ground floor is shown in Fig. 7.

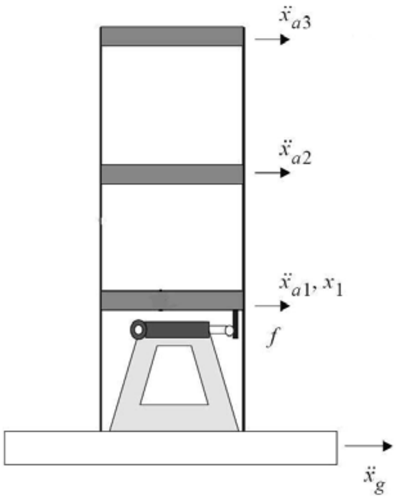

Fig. 7 Configuration of Three Storey Building Model

The structural properties of three storey building – mass, stiffness and damping are symmetric matrices and are as follows.

$$M_s = \begin{bmatrix} 112.5 & 0 & 0 \\ 0 & 112.5 & 0 \\ 0 & 0 & 112.5 \end{bmatrix} kg,$$

$$C_s = \begin{bmatrix} 210 & -60 & 0 \\ -60 & 120 & -60 \\ 0 & -60 & 60 \end{bmatrix} N.\sec/m,$$

$$K_s = 10^5 \begin{bmatrix} 14 & -7.98 & 0 \\ -7.98 & 15.96 & -7.98 \\ 0 & -7.98 & 7.98 \end{bmatrix} N/m,$$

$$G = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}, \; J = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

The equation of motion of the structure is given by,

$$M_s \ddot{x} + C_s \dot{x} + K_s x = Gf - M_s J \ddot{x}_g \qquad (10)$$

where, M_s, C_s & K_s are mass, damping and stiffness matrices, G is the location matrix for MR damper, J is the location matrix for ground excitation due to earthquake, $\ddot{x}_g$ is the earthquake excitation, f is the measured control force as defined by equations (4, 5, & 6), and $x = \{x_1 \quad x_2 \quad x_3\}^T$ is a state vector of the displacement of the three floors of the building relative to ground.

Because the MR damper is attached between the first floor and the ground, its displacement is equal to the displacement of the first floor of the building relative to the ground, i.e. $x = x_1$ in equations (3 – 7). The control force can be calculated using the measurements of the absolute accelerations of the three floors of the building and the displacement of the MR damper. Therefore, the output vector can be defined as,

$$y = \left\{ \ddot{x}_{a1} \quad \ddot{x}_{a2} \quad \ddot{x}_{a3} \quad x_1 \right\}^T \tag{11}$$

Defining the state vector consists of state variables, which are primarily mechanical degree-of-freedom of the building as,

$$z = \left\{ x \quad \dot{x} \right\}^T \tag{12}$$

The equation of motion of the building given by equation (10) can be represented in State Space form as,

$$\dot{z}(t) = Az(t) + Bf(t) + E\ddot{x}_g \tag{13}$$

The above equation (13) is a state equation of the building and output equation of building is given as,

$$y(t) = Cz + Df(t) + v \tag{14}$$

Where, state co-efficient matrices are defined as,

$$A = \begin{bmatrix} 0 & I \\ -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, \; B = \begin{bmatrix} 0 \\ M_s^{-1}G \end{bmatrix}$$

$$E = -\begin{bmatrix} 0 \\ J \end{bmatrix}, \; C = \begin{bmatrix} -M_s^{-1}K_s & -M_s^{-1}C_s \\ 1,0,0 & 0,0,0 \end{bmatrix}$$

$$\& \; D = \begin{bmatrix} M_s^{-1} \\ 0 \end{bmatrix}$$

The MR damper parameters given in Table 1 were used for numerical simulation studies, except x_0 was set to zero to cancel the initial offset due to the accumulator of the MR damper.

The aim of the numerical problem simulation was to control the structural responses of the three storey building subjected to N-S component of the 1940 El Centro ground motion as shown in Fig. 8.

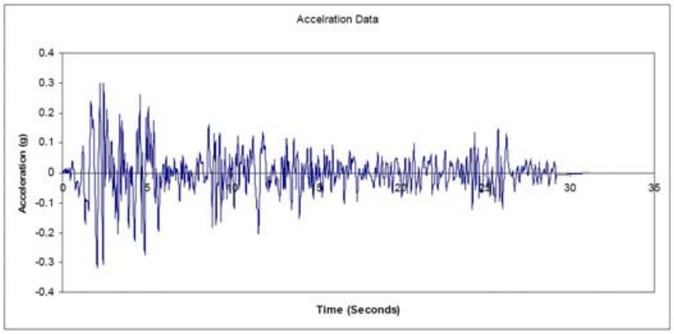

Fig. 8 N-S Component of 1940 El Centro Ground Motion

IV. NUMERICAL PROBLEM RESULT

The state equations (13) of the building with MR damper consists of non-stiff first order matrix differential equation related to mechanical degrees-of-freedom and stiff first order algebraic non-linear differential equation related to MR damper. The state equations were solved using MATLAB through numerical integrator 'ODE45' which is a fourth order Runge-Kutta method. To solve differential equation, initial conditions were needed. Deciding initial condition for mechanical degrees-of-freedom of the building was straight forward, as at $t = 0$, the building was at rest and therefore, all the state variables were zero. However, deciding initial conditions pertaining to MR damper required physical interpretations. Because no physical motion of any part of MR damper was expected at $t = 0$, evolutionary variable of MR damper z was set at zero. Therefore, the initial condition vector is defined as,

$$IC = \{0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\}^T \tag{15}$$

The numerical simulation was done through MATLAB programming to obtain the structural response quantities like displacement, velocity and acceleration at all the floors levels of the building. The applied voltage of 2.25 V (related to saturation of MR damper) was kept constant throughout the earthquake ground motion time history.

Table 2 shows the maximum structural responses due to El Centro ground motion for the three storey building with MR damper. The x_i is the displacement of the i^{th} floor relative to ground, d_i is the inter-storey drift (i.e. $x_i - x_{i-1}$ of the i^{th} floor) and x_{ai} is the absolute acceleration of the i^{th} floor of the building.

TABLE 2
Maximum Response of Structural Quantity due to El Centro Ground Motion

Response Quantity	**Floor No.**	**Uncontrolled**	**Passive On**

		Response	
x_i Displacement (cm)	1	0.7224	0.3996
	2	1.153	0.6191
	3	1.3926	0.7232
d_i Inter-storey Drift (cm)	1	0.7224	0.3996
	2	0.4306	0.2195
	3	0.2396	0.1041
x_{ai} Acceleration (cm/sec^2)	1	827.49	760.80
	2	1355.8	818.53
	3	1701.4	808.32
Damper Force (N)	---	---	1332.8

The numerical simulation result of displacement response of top floor of the three storey building is shown in Fig. 9.

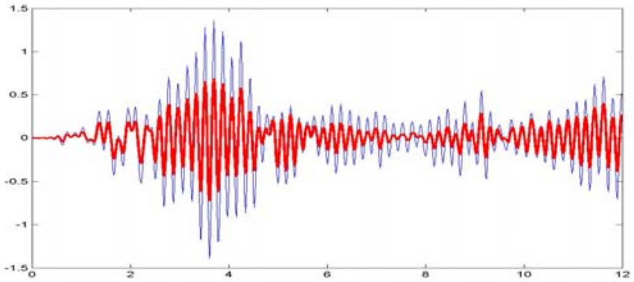

Fig. 9 Simulation Result of Displacement Response

It is clear from the Fig. 9 that, the displacement response reduces substantially. The decrement in top floor displacement is observed around 48% compared to uncontrolled displacement response of the three storey building.

The numerical simulation result of acceleration response of top floor of the three storey building is shown in Fig. 10.

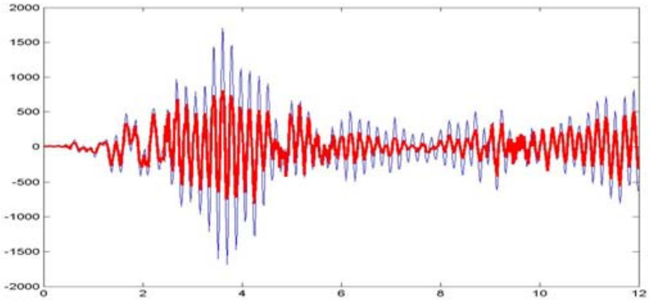

Fig. 10 Simulation Result of Acceleration Response

It is clear from Fig. 10 that, the acceleration response also reduces substantially. The decrement in top floor acceleration is observed around 52% compared to uncontrolled acceleration response of the three storey building.

It was observed that, the MR damper produce a maximum force of 1332.8 N as shown in Fig. 11, which helps in reducing the uncontrolled responses of the three storey building.

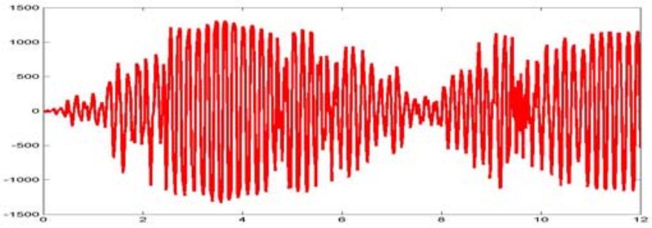

Fig. 11 Simulation Result of MR Damper Force

V. CONCLUSIONS

It was observed that, the implementation of MR damper in three-storey building reduces structural response like displacement & acceleration, substantially.

It was observed that displacement response shows the reduction of about 48%, while acceleration response reduces about 52%. The MR damper produces a force of 1332.8 N due to applied voltage of 2.25 V. Obviously, the other voltage levels less than 2.25 V must produce less MR damper force and hence not included in the present study.

The numerical problem undertaken indicates the straight forward use of MR damper, however, optimal No. of MR dampers and their position is a next class of problem to be aimed for.

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