

# Review On the Performance of Different Control Systems for Non-Linear Benchmark Building

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**Abstract:** The aim of this paper is to review a state of the art of researches on effectiveness of several control systems, such as viscous fluid damper, magneto rheological (MR) dampers operated by a model-based fuzzy logic controller MBFLC formulated in terms of linear matrix inequalities LMIs and Piezo electric friction damper, active control systems damper used to control the seismic response of non-linear benchmark building. The benchmark problem on benchmark building developed some evaluation criteria to compare among the control devices. Comparing the performance of the control strategies it is found that, the passive control system which supplied the best results was viscous damper on the inter-story drift ratio. Among all the semi active control devices, MR damper with neuro-inverse model was found to be the best in controlling level acceleration, base shear and normal inter-story drift ratio.

**Keywords:** non linear benchmark building, Seismic response, Building; Control methods, Semi-active control.

## 1. Introduction

The protection of civil structures, including material content and human occupants, is, without doubt, a world-wide priority. The extent of protection may range from reliable operation and occupant comfort to human and structural survivability. Civil structures, including existing and future buildings, towers, and bridges, must be adequately protected from a variety of events, including earthquakes, winds, waves and traffic. The protection of structures is now moving from reliance entirely on the inelastic deformation of the structure to dissipate the energy of severe dynamic loadings, to the application of passive, active, and semi-active structural control devices to mitigate undesired responses to dynamic loads. However, even in controlled structures, it can be expected that large seismic events, such as the 1994 Northridge and the 1995 Kobe earthquakes, will cause structural members to exceed the elastic limit. The seismic response of nonlinear structures to severe earthquakes has also been studied and control algorithms for these nonlinear structures have been proposed by number of researchers.

## 2. Non-Linear Benchmark Building

The 3, 9, and 20-story structures used for this benchmark study were developed by Ohtori et. al [1]. The twenty-story benchmark structure is 30.48 m by 36.58 m in plan, and 80.77 m in elevation. The bays are 6.10 m on center, in both directions, with five bays in the N-S direction and six bays in the E-W direction as shown in Fig. 1. The details of the benchmark problems on non-linear building are given in paper [1].

## 3. Evaluation Criteria

In order to evaluate proposed control strategies, four historical earthquake records are selected:

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I. *El Centro*: The N–S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940.

II. *Hachinohe*: The N–S component recorded at Hachinohe City during the Tokachi-oki earthquake of May 16, 1968.

III. *Northridge*: The N–S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994.

IV. *Kobe*: The N–S component recorded at the Kobe Japanese Meteorological Agency station during the Hyogoken Nanbu earthquake of January 17, 1995.

The absolute peak acceleration of the earthquake records are 3.417, 2.250, 8.2676, and 8.1782 m/s<sup>2</sup>, respectively. Additionally, this benchmark study will consider various levels of each of the earthquake records including: 0.5, 1.0, and 1.5 times the magnitude of El Centro and Hachinohe; and 0.5 and 1.0 times the magnitude of Northridge and Kobe. This is a total of ten earthquake records to be considered in the evaluation of each control strategy. The evaluation criteria are divided into four categories: Building responses, building damage, control devices, and control strategy requirements. The first three categories have both peak-and Normed-based criteria. Small values of the evaluation criteria are generally more desirable [1].

Table. 1: Evaluation Criteria [1]

<p><b>Interstory Drift Ratio</b></p> $J_1 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,i} \frac{ d_i(t) }{h_i}}{\delta^{\max}} \right\}$	<p><b>Level Acceleration</b></p> $J_2 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,i}  \ddot{x}_{ai}(t) }{\ddot{x}_a^{\max}} \right\}$	<p><b>Base Shear</b></p> $J_3 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_t \left  \sum_i m_i \ddot{x}_{ai}(t) \right }{F_b^{\max}} \right\}$
<p><b>Normed Interstory Drift Ratio</b></p> $J_4 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_i \frac{\ d_i(t)\ }{h_i}}{\ \delta^{\max}\ } \right\}$	<p><b>Normed Level Acceleration</b></p> $J_5 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_i \ \ddot{x}_{ai}(t)\ }{\ \ddot{x}_a^{\max}\ } \right\}$	<p><b>Normed Base Shear</b></p> $J_6 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\left\  \sum_i m_i \ddot{x}_{ai}(t) \right\ }{\ F_b^{\max}\ } \right\}$
<p><b>Ductility</b></p> $J_7 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,j} \frac{ \phi_j(t) }{\phi_{yj}}}{\phi^{\max}} \right\}$	<p><b>Dissipated Energy</b></p> $J_8 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,j} \frac{\int dE_j}{F_{yj} \cdot \phi_{yj}}}{E^{\max}} \right\}$	<p><b>Plastic Connections</b></p> $J_9 = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{N_d^C}{N_d} \right\}$
<p><b>Normed Ductility</b></p> $J_{10} = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_j \frac{\ \phi_j(t)\ }{\phi_{yj}}}{\ \phi^{\max}\ } \right\}$	<p><b>Control Force</b></p> $J_{11} = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,l}  f_l(t) }{W} \right\}$	<p><b>Control Device Stroke</b></p> $J_{12} = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_{t,i}  y_i^a(t) }{x^{\max}} \right\}$
<p><b>Control Power</b></p> $J_{13} = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\max_t \left[ \sum_l \mathcal{P}_l(t) \right]}{x^{\max} W} \right\}$	<p><b>Normed Control Power</b></p> $J_{14} = \max_{\substack{\text{El Centro} \\ \text{Hachinohe} \\ \text{Northridge} \\ \text{Kobe}}} \left\{ \frac{\sum_t \frac{1}{t_f} \int_0^{t_f} \mathcal{P}_l(t)}{x^{\max} W} \right\}$	<p><b>Control Devices</b></p> $J_{15} = \text{Number of control devices}$
		<p><b>Sensors</b></p> $J_{16} = \text{Number of required sensors}$
		<p><b>Computational Resources</b></p> $J_{17} = \dim(\mathbf{x}_k^c)$

## 4. Passive Damping Devices

### 4.1. Viscous fluid damper

Fluid viscous dampers operate on the principle of fluid flow through orifices. A stainless steel piston travels through chambers that are filled with silicone oil. The silicone oil is inert, non flammable, non toxic and stable for extremely long periods of time. The pressure difference between the two chambers cause silicone oil to flow through an orifice in the piston head and seismic energy is transformed into heat, which dissipates into the atmosphere. The force/velocity relationship for this damper can be characterized as  $F = C.V^\alpha$ , where  $F$  is the output force,  $V$  the relative velocity across the damper,  $C$  is the damping coefficient and  $\alpha$  is a constant exponent which is usually a value between 0,3 and 1,0. Fluid viscous dampers have the unique ability to simultaneously reduce both stress and deflection within a structure subjected to a transient.

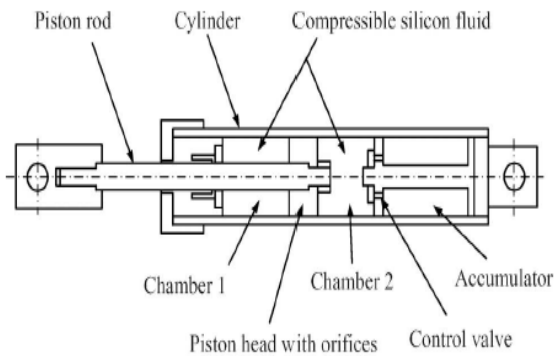


Fig. 1: Viscous Fluid Damper

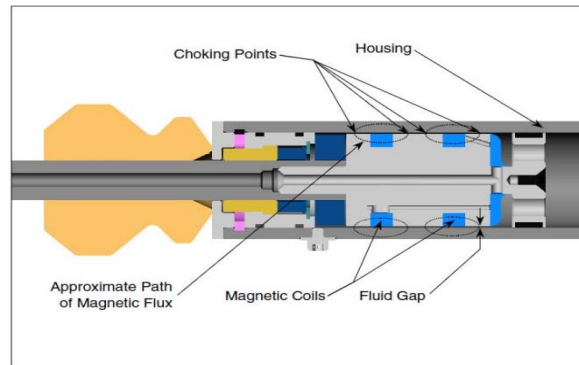


Fig. 2: MR Damper

## 5. Semi Active Devices

### 5.1. Magnetorheological damper

A magnetorheological damper is a damper filled with magnetorheological fluid, which is controlled by a magnetic field, usually using an electromagnet. This allows the damping characteristics of the shock absorber to be continuously controlled by varying the power of the electromagnet.

#### 5.1.1 Fuzzy Logic Controller (FLC)

Fuzzy logic enables the use of linguistic Directions as a basis for control, generally very robust and capable of handling nonlinear systems. A FLC is incorporated into a closed-loop control system similar to conventional controllers. The most widely used fuzzy control inference M is the “if-then” Rule, which can be written as follows when two input data are used in their antecedent parts  $M_i$ : if  $X_{15}A_i$  and  $X_{25}B_i$  then  $Y_{5}C_i$  (1) where  $i$  number of control rules;  $X_1$  and  $X_{25}$  variables of the antecedent parts;  $Y_5$  variable of the sequent part; and  $A_i$ ,  $B_i$ , and  $C_i$  fuzzy variables. Various components of this controller are defined as follows.

*Fuzzification*: This unit maps the measured inputs, which may be in the form of crisp values, into fuzzy linguistic values using fuzzy reasoning mechanism. Rule base: This is a collection of the expert control rules knowledge needed to achieve the control goal.

*Decision making*: This unit is the fuzzy reasoning mechanism, which performs various fuzzy logic operations to infer the control action for a given fuzzy input.

*De fuzzification*: The inferred fuzzy control action is converted into the required crisp control value in this unit. In this paper, the preliminary design of the controller will incorporate the Larsen’s minimum product rule to combine the membership values for each rule, with the center of gravity de-fuzzification scheme, to obtain the output crisp value.

#### 5.1.2 Magneto-Rheological Fluid

MR fluid is composed of oil and varying percentages of iron particles that have been coated with an anti-coagulant material. When not activated, MR fluid behaves as ordinary oil. When exposed to a magnetic field, micron-size iron particles that are dispersed throughout the fluid align themselves along magnetic flux lines. This reordering of iron particles can be visualized as a large number of microscopic spherical beads that are

threaded onto a very thin string. One can picture this thin string stretching from one magnetic pole to the other and perpendicular to each paramagnetic pole surface. In this analogy, the spherical beads represent iron particles and the string represents a single flux line. One can picture many of these strings of beads placed closely together much like the bristles of a toothbrush. Once aligned in this fashion, the iron particles resist being moved out of their respective flux lines and act as a barrier to fluid.

When MR fluid is used in the valve mode, the areas where the MR fluid is exposed to magnetic flux lines are usually referred to as “choking points”. MR fluid restricts the flow of fluid from one side of the piston to the other when the fluid is in the vicinity of the “choking points”. Varying the magnetic field strength has the effect of changing the apparent viscosity of the MR fluid. The phrase “apparent viscosity” is used since the carrier fluid exhibits no change in viscosity as the magnetic field strength is varied. Upon exposure to a magnetic field, the MR fluid as (a whole) will appear to have undergone a change in viscosity. As the magnetic field strength increases, the resistance to fluid flow at the choking points increases until the saturation point has been reached. The saturation point is the point where any increase in magnetic field strength fails to yield an increase in damper resistance. This resistance to movement that the iron particles exhibit is what allows us to use MR fluid in electrically controlled viscous dampers.

### 5.2. Piezoelectric Friction Damper (PFD)

Variable friction dampers have the advantages of low operating power requirement and guaranteed dissipation of energy by friction, and therefore do not cause instability of the structure being controlled. Recently, the authors introduced the PFD concept to mitigate the seismic response of building structures. The clamping force in a PFD is regulated by piezoelectric stack actuators, which can quickly and accurately respond to a driven command such as a voltage signal. The PFD was designed and fabricated in the Structures Laboratory. The  $0.254 \text{ m} \times 0.152 \text{ m} \times 0.102 \text{ m}$  damper included four piezoelectric stack actuators to modulate its clamping force, with PZT-100 material doped with Tungsten or PZWT-100. The piezoelectric constant,  $d$ , and the modulus of elasticity,  $E$ , of the material along the axial direction are equal to  $3.71 \times 10^{-10} \text{ m/V}$  and  $4.62 \times 10^7 \text{ kN/m}^2$ , respectively. Each stack is 2.54 cm in diameter and approximately 1.27 cm tall. It is composed of 24 individual piezoelectric layers stacked in series and wired in parallel, each 0.051 cm thick.

### 5.3. Oil Damper:

Oil damper as the semi-active control, the maximum damping force generated by one oil damper is limited to 2000 KN, and it can be realized by an actual damper. A total of 25 oil dampers are placed on each floor, the same number as viscous damping walls, to control the building. Twenty acceleration sensors are placed on all floors which are used to perform feedback control of the system. We also tried to use only five acceleration sensors on the 4th, 8th, 12th, 16th, and 20th levels and compared the results with the control performance when using 20 sensors.

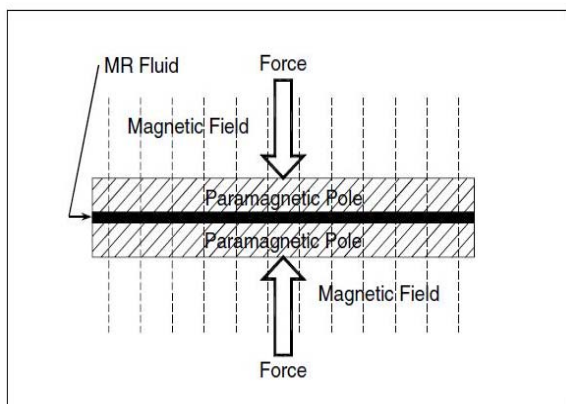


Fig. 3: MR fluid used in squeeze mode

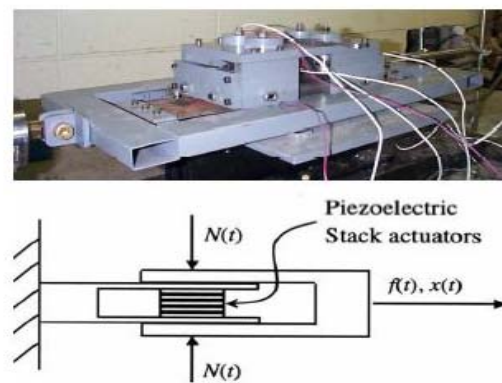


Fig. 4: Prototype PFD and its schematic diagram

## 6. Discussion

The numerical results of all the dampers used in non-linear benchmark building are tabulated in Table 2. It is observed from the Table 2, that the control strategy proposed by akira et al [2], using viscous damper is able to control inter-story drift ratio ( $J_1$ ) significantly. Its performance is outstanding in controlling the level acceleration ( $J_2$ ). The MR damper with active neuro inverse model proposed by Karamodin et al [3] reduces the peak responses of base shear ( $J_3$ ) very effectively. But in case of ductility ( $J_7$ ), MR damper in terms of LQG by Yeessock et al [4]. is more effective.

## 7. Conclusion

The study was done to provide the non-linear benchmark building with all the control devices and to find out the most effective and the best devices which can control all the four major aspects i.e. inter-story drift ratio, level acceleration, base shear and ductility. Benchmark buildings are vulnerable to seismic motions due to their low stiffness and damping.

The passive control system which supplied the best results was viscous damper on the inter-story drift ratio. By using the viscous damper, there is about a 20–52% reduction in the peak level acceleration and about a 22–58% reduction in the peak drift ratio judging from the results of the evaluation criteria.

The semi-active strategy consist of PFD can maintain the seismic effectiveness of active dampers while it requires significantly less external power to operate. As the passive friction force increases, the damper performance generally degrades but the demand for external power is significantly reduced. The semiactive strategy is considerably more effective than passive friction dampers in peak acceleration reduction of buildings under earthquakes of various magnitudes.

Neural networks are used to model the inverse dynamics of MR damper. The performance of the controller has been checked, based on the evaluation criteria specified ( $J_1$ - $J_6$ ) for the benchmark building. The results show that the mean of the average indices,  $J_1$  to  $J_6$ , for different earthquake records are 0.768, 0.825, 0.825, 1.010 and 0.691, respectively, for NIMR, COC, LQG, PON and OPC methods.

Among all the semi active control devices, MR damper with neuro inverse model was found to be the best in controlling level acceleration, base shear and normal inter-story drift ratio.

Table. 2: Evaluation criteria tables for max values of all the selected earthquakes

NAME & TYPE OF THE DEVICE USED	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$	$J_6$	$J_7$	$J_8$	$J_{11}$	$J_{12}$	$J_{15}$	$J_{16}$
Passive Control using viscous damper	0.777	0.7 98	1.2 13	0.9 13	0.4 81	0.7 34	0.8 00	0	0.012	0.10 4	0	0
Semiactive Control using variable oil damper with 20 Sensors	0.862	0.8 19	1.1 85	0.8 73	0.5 71	0.7 85	0.8 71	0	0.018	0.10 6	0	0
Semiactive Control using variable oil damper with Five Sensors	0.913	0.8 33	1.1 62	1.0 69	0.5 63	0.7 66	0.9 46	0	0.018	0.10 3	0	0
Mr damper by MBFLC	0.804	0.9 32	1.0 31	1.0 87	0.3 98	0.5 60	0.6 23	0.7 27	0.039	0.09 2	6.0 00	0
mr damper in terms of LQG	0.842	0.8 91	0.9 09	0.9 30	0.6 98	0.7 32	0.6 21	0.7 01	0.020	0.07 0	62. 000	0
smart dampers(mr damper) --- active control	0.922	0.8 09	1.1 03	1.2 59	0.5 69	0.7 77	0.9 61	0.3 31	0.009 203	0.09 8 54	65. 000	0
smart damper(mr damper) ---ideal semiactive control	0.909	0.8 17	1.0 94	1.2 41	0.5 16	0.7 72	0.9 41	0.2 65	0.009 202	0.09 8 97	65. 000	0
smart damper(mr damper)-original clipped optimal	0.904	1.0 47	1.1 71	1.2 07	0.6 42	0.8 15	0.9 29	0.2 40	0.009 427	0.09 7 57	65. 000	0
smart damper(mr damper) -modified clipped optimal	0.906	0.8 20	1.0 79	1.1 88	0.6 65	0.8 23	0.9 57	0.2 57	0.009 429	0.09 8 33	65. 000	0
fuzzy logic controller 20-Story Benchmark Building First Set	1.061	0.9 77	1.0 59	1.0 23	1.0 27	1.0 07	1.0 62	1.2 53	0.007	0.15 1	12. 000	5.0 00
fuzzy logic controller 20-Story Benchmark Building Second Set	0.975	0.8 88	0.9 68	0.9 25	1.0 59	0.9 29	1.0 62	0.8 09	0.007	0.10 9	12. 000	5.0 00

mr damper - replica neuro inverse model-nimr	0.674	0.8 65	0.8 45	0.7 01	0.7 52	0.3 86	0	0	0	0	0	0
mr damper --- replica neuro inverse model coc	0.728	0.8 89	0.8 83	0.8 54	0.7 95	0.4 00	0	0	0	0	0	0
mr damper --- replica neuro inverse model active	0.790	0.8 00	0.8 03	0.9 16	0.8 22	0.4 09	0	0	0	0	0	0
mr damper -replica neuro inverse model pon	0.478	0.8 29	0.8 45	0.3 61	2.5 02	1.0 48	0	0	0	0	0	0
mr damper ---replica neuro inverse model opc	0.612	0.8 16	0.8 56	0.5 25	0.7 27	0.6 13	0	0	0	0	0	0
20-Story Benchmark Building with Piezoelectric Friction Dampers	0.962	0.9 80	1.0 47	0.9 05	0.8 73	0.9 43	0.9 46	0.8 07	0.001	0.14 6	80. 000	14. 000

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