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SEMI-ACTIVE CONTROL OF SEISMIC BEHAVIOR OF STATIONARY EQUIPMENT SUPPORTING STRUCTURES

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Abstract

In this study, a simple adaptive controller is developed to mitigate the responses of stationary equipment supporting structures subjected to seismic excitation. With a wide application in oil and gas industries, these structures are designed to safely support the operational and occasional loads of acceleration-sensitive industrial equipment, such as vessels and heat exchangers. Hence, mitigating the acceleration response of such structures can extensively improve the equipment's serviceability during strong ground motion events and prevents considerable financial loss. This study aims at providing a practical and efficient semi-active control scheme applicable to industrial plants by using accelerometers as measurement sensors, Magneto-Rheological (MR) dampers as semi-active actuators, and adaptive controllers which are robust against environmental and structural uncertainties. This enhancement leads to a more optimized and economically efficient structural design and also prevents the disasters like explosion and serious equipment damage caused by high values of acceleration and displacement responses during the earthquake. In order to investigate performance of the proposed control system, numerical studies are conducted on a large-scale model of 2-story structure (supporting two horizontal vessels) which is subjected to the various earthquake records. Results show a substantial reduction of the seismic responses under the effect of different ground motions.

Keywords: seismic control; adaptive control; industrial structures; equipment supporting structures; MR damper

1. Introduction

Over the past decades, the approach to construct seismically-safe structures has been developed from traditional strength-stiffness design methods to novel smart control systems which are proved to be practically effective during strong ground motions [1]. Control systems are classified into three major categories [2]:

a) Passive control systems: Comprise devices that do not require external power source and encompass a range of materials and parts for enhancing the energy dissipation capacity of the structure. They include: friction dampers, viscoelastic dampers, viscous dampers, tuned mass dampers, etc.
b) Active control systems: Usually utilize feedback and feed-forward loops and different sensors to control the structural responses using mechanical actuators that include: active mass dampers, hybrid mass dampers, tendon controls, etc. which require a large power source during excitation. Power failure and system stability are serious concerns regarding these systems. Hybrid control systems which are a combination of active and passive controllers also have been introduced to compensate for the limitations of power failure and adaptability of such schemes.
c) Semi-active control systems: While comprising the basic merits of both passive and active systems (stability and adaptability), they require small power sources (usually a battery) to produce control forces. The mechanical properties of these devices are adjusted based on feedback and feed-forward measurements. They include: stiffness control devices, Electro-Rheological (ER) dampers, Magneto-Rheological (MR) dampers, friction control devices, etc.

For each aforementioned control systems, numerous amount of research has been conducted by researchers to demonstrate their efficiency [3-6]. Among the semi-active control devices, MR dampers have been thoroughly studied theoretically and experimentally and are implemented in full-scale civil structures since 2001 [7-9]. Several semi-active controllers have been developed and suited well for MR-damper-equipped seismically-excited structures. Jansen and Dyke [10] proposed few control schemes based on acceleration feedback and clipping algorithms. Du and Zhang [11] presented a model-based fuzzy controller for seismic enhancement of buildings installed with MR dampers. Amini and Doroudi [12] developed a fuzzy semi-active controller for complex building systems consisted of a main building and a podium structure connected through MR dampers. Optimal location of MR dampers in a structure subjected to seismic loads using Ant Colony Algorithm was studied through the work of Amini and Ghaderi [13]. Most recently, practical issues regarding the application of adaptive controllers in buildings equipped with MR dampers have been demonstrated in the work of Amini and Javanbakht [14].

Adaptive controllers have been developed since late 50's and successfully implemented in complicated dynamic processes like autopilots [15]. An adaptive controller would try to perform an online estimation of the process uncertainty and then produce a control input to anticipate, overcome, or minimize the undesirable deviations from the prescribed closed-loop plant behavior [16]. The Simple Adaptive Control (SAC) method, as a type of Direct Model Reference Adaptive Control (DMRAC), was first introduced by Sobel, et al. [17] and further developed by the works of Bar-Kana and Kaufman [18, 19] and Iwai and Mizumoto [20, 21]. The appealing advantages of SAC in contrast with other adaptive control methods include: (a) simplicity and speed, (b) applicability to large and complicated systems, (c) the ability to cope with internal uncertainties and unknown environmental disturbances and (d) successful experimental validation [22].

In oil and gas industries, stationary equipment supporting structures are designed to safely support the operational and occasional loads of acceleration-sensitive industrial equipment, such as vessels and heat exchangers. In seismically active zones, mitigating the acceleration response of such structures can extensively improve the equipment's serviceability during strong ground motion events and prevents considerable financial loss. Applying control systems to equipment supporting structures is considered as a new practical way to improve their efficiency and safety during useful lifetime. This enhancement leads to a more optimized and economically efficient structural design and also prevents the disasters like explosion and serious equipment damage caused by high values of acceleration and displacement responses during the earthquake.

This study aims at providing a practical semi-active control scheme by simultaneous application of accelerometers as measurement sensors (which are reliable and cost-efficient), Magneto-Rheological (MR) dampers as semi-active actuators, and SAC as an adaptive controller. In order to investigate performance of the proposed control system, numerical studies are conducted on a large-scale model of 2-story structure (supporting two horizontal vessels) which is subjected to the various earthquake records. A nonlinear time-history analysis tool implemented in the MATLAB/Simulink environment has been utilized to perform the simulations whereas the time delay effects have been considered in the analytical model. However, using acceleration feedback as control measurements causes some stability issues in the SAC algorithm. This problem has been tackled by applying some modifications in the original form of the SAC system. For comparison purposes, MR dampers are also used as passive actuators (by holding the damper's command voltage at its maximum value) to verify the superior performance of the semi-active system. Results show a substantial reduction of the seismic responses under the effect of different ground motions.

2. Problem Definition

2.1. Simple Adaptive Control (SAC)

As a direct model reference adaptive control method, SAC produces control forces by mitigating the error between plant and Reference Model (RM) output. Thus, controller design is independent of plant dynamics and only requires sensor measurements for computing control forces. The state-space form of a nonlinear plant is represented by:

$$\dot{x}_p(t)=\mathbf{A_p}(x_p)x_p(t)+\mathbf{B_p}(x_p)u_p(t)+d_p(x_p,t) \tag{1a}$$

$$y_p(t)=\mathbf{C_p}(x_p)x_p(t)+\mathbf{D_p}(x_p)u_p(t)+d_o(x_p,t) \tag{1b}$$

where $x_p(t)$, $y_p(t)$, $u_p(t)$, $d_p(t)$ and $d_o(t)$ are plant's state vector, output vector, control input, plant and output disturbances, respectively, and $\mathbf{A_p}$, $\mathbf{B_p}$, $\mathbf{C_p}$ and $\mathbf{D_p}$ are uniformly bounded state-space matrices.

RM is an ideal system which will be tracked by the plant's output. The state-space equation of RM is defined as:

$$\dot{x}_m(t)=\mathbf{A_m}x_m(t)+\mathbf{B_m}u_m(t) \tag{2a}$$

$$y_m(t)=\mathbf{C_m}x_m(t)+\mathbf{D_m}u_m(t) \tag{2b}$$

where $x_m(t)$, $y_m(t)$ and $u_m(t)$ are RM's state vector, output vector and command input, respectively.

The error function:

$$e_y(t)=y_m(t)-y_p(t) \tag{3}$$

has to be minimized by an adaptive gain to produce appropriate control command using the following rule:

$$u_p(t)=\mathbf{K}(t)r(t) \tag{4}$$

where:

$$\mathbf{K}(t)=\mathbf{K_P}(t)+\mathbf{K_I}(t) \tag{5}$$

$$r(t)=[e_y{}^T(t) \quad x_m{}^T(t) \quad u_m{}^T(t)]^T \tag{6}$$

The adaptive gain $\mathbf{K}(t)$ consists of two proportional and integral parts which are defined as:

$$\mathbf{K_p}(t)=e_y(t)r^T(t)\overline{\mathbf{T}} \tag{7}$$

$$\dot{\mathbf{K}}_\mathbf{I}(t)=e_y(t)r^T(t)\mathbf{T}-\sigma\mathbf{K_I}(t) \tag{8}$$

where the positive-definite matrices $\overline{\mathbf{T}}$ and $\mathbf{T}$, and the positive value σ are the only selective parameters of SAC algorithm that should be tuned appropriately by the designer, in addition to the RM design. Fig.1 shows a block diagram of the SAC method.

Despite the simplicity of SAC algorithm, its asymptotic stability and perfect tracking requires the plant to satisfy Almost Strictly Positive (ASP) condition [23]. However, for a proper non minimum-phase system with $\mathbf{D_p} < 0$ the ASP condition is not satisfied. As in the case of acceleration feedback where a negative $\mathbf{D_p}$ appears in the structural state-space model, the plant does not satisfy ASP condition. This issue has been tackled by considering three strategies: a) utilizing inherently stable MR dampers as the semi-active actuator, b) defining an appropriate reference model that is best suited to the nonlinear structure, and c) adding a compensator to control feedback loop to decrease the observed relative degree of the plant's transfer function. These ideas will be discussed with more detail through the subsequent sections.

As mentioned earlier, defining an appropriate RM is essential for designing an efficient SAC controller. Since the order of RM can be smaller than the plant, the designer has discretion over the RM choice. RM has three parameters that affect the control performance, namely $x_m(t)$, $y_m(t)$ and $u_m(t)$. These parameters should be designed based on control targets, actuator type, plant's behavior and designer's experience to obtain the best possible performance.

2.2. Structural and MR damper dynamics

Since the development and progression of plastic hinges throughout the structural members is inevitable during the strong seismic ground motions, this issue has been included in the current study by introducing a bilinear hysteresis model which presents the plastic behavior of bending hinges (Fig.2). The plastic hinges are assumed to occur at the moment resisting beam-column and column-column connections [24]. A MATLAB tool has been developed and utilized here to perform the nonlinear time history analysis via Newmark-β integration method [25].

The nonlinear structural system is governed by the following incremental equation:

$$\mathbf{M}\delta\ddot{U} + \mathbf{C}\delta\dot{U} + \mathbf{K}\delta U = -\mathbf{M}\Lambda\delta\ddot{x}_g + \mathbf{\Gamma}\delta f + \delta F_{err} \tag{9}$$

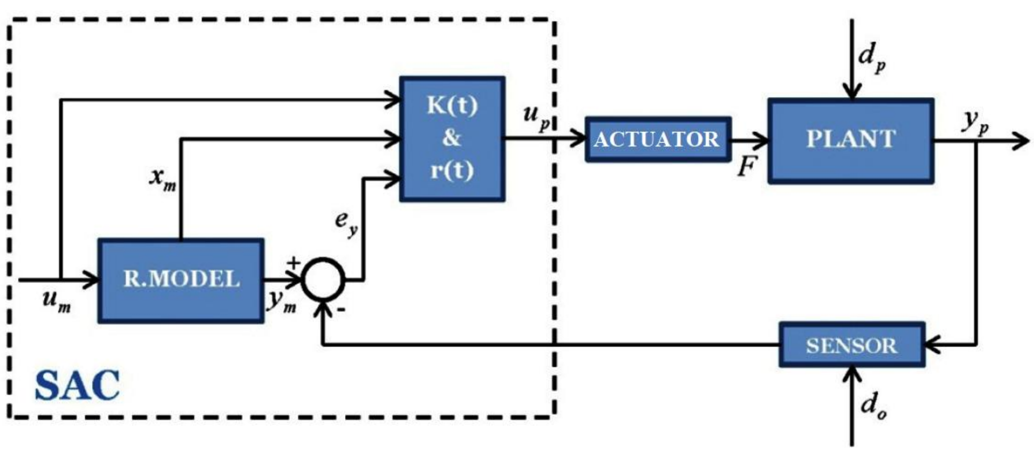

Fig. 1 – Block diagram of SAC algorithm

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are mass, damping and stiffness matrices, respectively; Λ is a column vector of ones and $\delta\ddot{x}_g$ is the ground acceleration increment; $\mathbf{\Gamma}$ is the location matrix of control forces; δf is incremental control force and δF_{err} is the unbalanced force vector resulting from the difference between restoring force evaluated using the hysteresis model and the restoring force assuming constant linear stiffness; and δU is the incremental response vector.

Substituting Eq. (9) into the Newmark expressions to solve the incremental equation of motion yields:

$$\mathbf{T_R}^{\mathrm{T}}\mathbf{K_D}\mathbf{T_R}\delta U_{act} = \mathbf{T_R}^{\mathrm{T}}\delta f_D \tag{10}$$

where δU_{act} is the active node displacement that include all vertical, all rotational and one horizontal DOF per level (assuming the floor slab to be horizontally rigid), $\mathbf{T_R}$ is a transformation matrix for expressing the full response vector in terms of the active degrees of freedom (i.e., $\delta U = \mathbf{T_R}\delta U_{act}$). $\mathbf{K_D}$ and δf_D are given by:

$$\mathbf{K_D} = \frac{1}{\beta(\Delta t)^2}\mathbf{M} + \frac{\gamma}{\beta\Delta t}\mathbf{C} + \mathbf{K_t} \tag{11}$$

$$\delta f_D = -\mathbf{M}\Lambda\delta\ddot{x}_g + \left(\frac{1}{2\beta}\mathbf{M} + \left(\frac{\gamma}{2\beta}-1\right)\Delta t\mathbf{C}\right)\ddot{U}_t + \left(\frac{1}{\beta\Delta t}\mathbf{M} + \frac{\gamma}{\beta}\mathbf{C}\right)\dot{U}_t + \mathbf{\Gamma}\delta f + \delta F_{err} \tag{12}$$

where Δt is the calculation time interval, $\{\ \}_t$ is the response at t, β and γ are the Newmark parameters, $\mathbf{K_t}$ is the tangent stiffness matrix of the structure at time t (calculated based on a concentrated plasticity model) and $\mathbf{C}$ is the damping matrix based on an assumption of Rayleigh damping and is expressed as:

$$\mathbf{C} = a_0\mathbf{M} + a_1\mathbf{K} \tag{13}$$

with the coefficients a_0 and a_1 determined from specified damping ratios and natural circular frequencies of i^{th} and j^{th} modes:

$$\frac{1}{2}\begin{bmatrix} 1/\omega_i & \omega_i \\ 1/\omega_j & \omega_j \end{bmatrix}\begin{Bmatrix} a_0 \\ a_1 \end{Bmatrix} = \begin{Bmatrix} \zeta_i \\ \zeta_j \end{Bmatrix} \tag{14}$$

The phenomenological model of MR damper is introduced by Spencer, et al. [7] based on the response of a prototype MR damper through experimental studies. Fig.3 illustrates the mechanical idealization of MR damper based on a Bouc-Wen hysteresis model which is governed by the following simultaneous nonlinear equations:

$$f = \alpha z + c_0\dot{x} \tag{15}$$

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta(\dot{x})|z|^n + A\dot{x} \tag{16}$$

where f and $\dot{x}$ are the damper force and velocity, respectively; c_0 is the observed viscous damping at large velocities; z is an evolutionary variable that describes the hysteretic characteristic of MR damper; γ and β affect the shape and A affects the slope of hysteresis loop, while n governs the smoothness of linear to non-linear transition.

The voltage-dependent model parameters are given by the following equations:

$$\alpha = \alpha_a + \alpha_b u \tag{17}$$

$$c_0 = c_{0a} + c_{0b}u \tag{18}$$

$$\dot{u} = -\eta(u - v) \tag{19}$$

where Eq. (19) is a first order filter to account for the dynamics of rheological equilibrium of MR fluid and v is the command voltage sent to current driver. A total number of 9 parameters for a prototype MR damper are given in Table 1. The saturation voltage for this damper is equal to 5 V.

One of the challenges associated with MR damper implementation is determining the appropriate command voltage in order to translate the required control force into generated damper force. Due to damper's highly nonlinear behavior, several numerical and experimental methods have been proposed for this purpose. In this study, the clipping algorithm developed by Yoshida and Dyke [26] is utilized to convert control force into damper's voltage. This algorithm requires only the measurement of generated damper force at previous time step. With an assumption of linear relationship between input voltage and output force, clipping algorithm is governed by:

$$v_i = V_{ci} H\left[(f_c - f_{MR}) f_{MR}\right] \tag{20}$$

$$V_{ci} = \begin{cases} V_{\max}(f_c / f_{MR}^{\max}) & f_c \le f_{MR}^{\max} \\ V_{\max} & f_c > f_{MR}^{\max} \end{cases} \tag{21}$$

where $V_{\max}$ is damper's saturation voltage, f_{MR} is damper's force at previous time step, f_c is the control force and H(.) is the Heaviside step function.

3. Numerical Study

To evaluate the efficiency and performance of the proposed semi-active adaptive control system, the numerical model of a 2-story nonlinear structure (supporting two horizontal vessels with operational weight of 5 Ton for each of them) is studied through this section. This 2-story steel moment-resisting frame is equipped with one MR damper device rigidly connected between the ground level and first story. It is subjected to two different earthquake records with different PGA intensity factors (0.5 and 1) while the acceleration response of the structure and ground acceleration are measured via ideal accelerometers (sensor noise has been ignored). Fig.4 illustrates the studied 2-story steel moment-resisting frame (frame span is 6 m). Nonlinear behavior is considered in the structure by defining flexural plastic hinges at connections. More information about the engineering properties of the profiles used in this structure is reported in Table 2 (refer to Fig.2 for mentioned parameters).

Seismic mass of each story is assumed to be 5 Ton, equal to the vessel's operational weight. Time delay effect has been considered in the simulations, i.e., forces generated at the previous time step are applied to the structure at the current step. A simple adaptive controller is designed to mitigate the seismic response and subsequent damage in the building based on acceleration feedback. The performance of SAC controller is compared to the case of passive MR dampers (i.e., holding the damper's voltage at maximum value during the ground motions) by assessing different evaluation criteria based on the benchmark control study [24]. The following sections describe some details about controller design and numerical analysis procedure.

3.1. Controller design

Requiring no prior access to plant parameters and having a simple and fast structure, simple adaptive controllers have been successfully implemented in complex and large systems. In the case of nonlinear systems, the adaptive stability of controller requires the plant to satisfy ASP conditions. For a proper non minimum-phase system with $\mathbf{D_p} < 0$, however, this condition is not met. Since a negative $\mathbf{D_p}$ appears in the structural state-space model in the case of acceleration feedback, the plant does not satisfy ASP condition. In order to overcome this issue, an appropriate Reference Model (RM) is defined. RM is an important part of SAC algorithm and defines a desired behavior to be continuously tracked by the plant. In this study, the reference model is defined based on parameter studies, as:

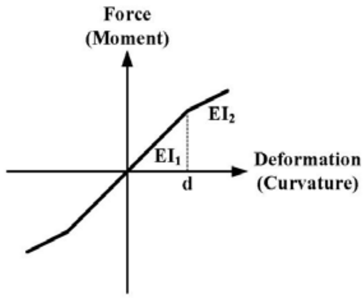

Fig. 2 – Bilinear hinge model for beam-column connection in bending

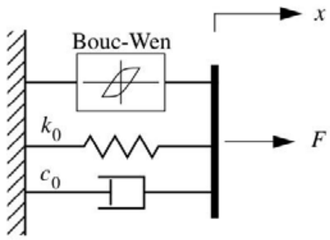

Fig. 3 – Bouc-Wen physical model for MR dampers

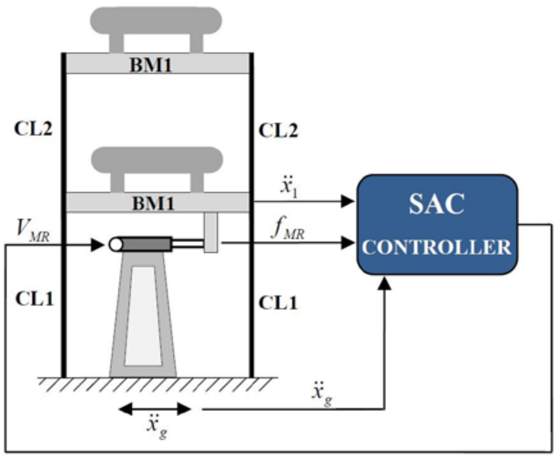

Fig. 4 – Model of controlled 2-story moment-resisting steel frame supporting two vessels

Table 1 – Bouc-Wen Parameters for a 5 Ton MR damper

Parameter	Value	Parameter	Value
c_{0a}	0.044 kN.sec/m	A	1.2
c_{0b}	0.44 kN.sec/m.V	n	1
α_a	1087.2 kN/m	γ	300 m^{-n}
α_b	4961.6 kN/m.V	β	300 m^{-n}
η	50 sec^{-1}	V_{max}	5 V

Table 2 – Engineering properties of used steel profiles (units: N, m)

Profile	EI_1	EI_2	EI_3	EA	GA	d_1	d_2
CL1	4.94E+08	4.45E+08	1.47E+07	5.25E+09	8.90E+15	0.01	0.015
CL2	1.88E+08	1.69E+08	5.59E+06	4.94E+09	8.90E+15	0.003	0.01
BM1	2.45E+08	2.21E+08	7.28E+06	4.63E+09	8.90E+15	0.005	0.012

$$y_m(t) = 0.1 y_p(t),\ \ x_m(t) = \begin{Bmatrix} \iint y_m(t)dt \\ \int y_m(t)dt \end{Bmatrix},\ \ u_m(t) = \begin{Bmatrix} \ddot{x}_g \\ \int \ddot{x}_g dt \\ \iint \ddot{x}_g dt \end{Bmatrix} \tag{22}$$

where $y_p(t)$ is the acceleration response of first story and $\ddot{x}_g$ is the ground acceleration. Sensor noise has been neglected in this study. The controller starts at $t = 0$ whenever an earthquake occurrence is detected.

In order to improve the algorithm efficiency and performance for a non-ASP plant, a compensator is added to the control feedback loop to decrease the observed relative degree of the plant's transfer function. Since the acceleration feedback causes stability issues in the adaptive controller by contravening the ASP condition (since a negative $\mathbf{D_p}$ appears in the structural state-space model), the controller output is passed through a compensator of the following form:

$$G(s) = \frac{a}{b+s} \tag{23}$$

where the transfer function's parameters are tuned as $a = 10$ and $b = 10$ to obtain best results. This compensator tends to reduce the plant's relative degree and hence the controller performance is substantially improved. The SAC algorithm parameters are selected after several iterations to obtain the best results, as $\overline{\mathbf{T}} = 10^3 diag([0.1\ 1\ 1\ 1\ 1\ 1])$, $\mathbf{T} = 10^2 diag([80\ 1\ 1\ 1\ 1\ 1])$ and $\sigma = 1$. The generated SAC control command is then converted to MR damper voltage using the clipping algorithm described in Sec. 2.2.

3.2. Simulation and results

The MR-damper-equipped 2-story nonlinear building is subjected to two earthquake records as given in Table 3. Two PGA levels of each earthquake (0.5 and 1) are considered in order to assess the controller's adaptability to applied loading. Since the damper is rigidly connected between ground and first story, its relative displacement is equal to that of the first level. The simulation is performed at a constant time step of 0.001 sec. and the Newmark-β parameters are set as $\beta = 1/4$ and $\gamma = 1/2$ to stabilize the calculations. Also the modal damping coefficients of Rayleigh damping are set as $\zeta_1 = \zeta_5 = 0.02$. The absolute acceleration of each story is measured using accelerometers and used in control feedback loop while the acceleration sensor is ideally modeled.

For comparison purposes, MR dampers are also used as passive actuators (by holding the damper's command voltage at its maximum value equal to 5 V) to verify the superior performance of the semi-active system. This simulation case is abbreviated as P-on (Passive-on) in the results. Passive dampers are expected to insert high levels of energy to the structure and hence cause some disturbance in acceleration response. Stationary equipment like horizontal vessels are normally sensitive and vulnerable to intense acceleration excitation. Thus, providing a control system to reduce this effect is highly desired for both financial and safety reasons. Acceleration feedback controllers are potential choices for this purpose.

Table 3 – Summary of earthquake records [24]

Earthquake name and date	**Station and component**	**PGA (m/sec^2)**
Imperial Valley (1940)	El Centro (N-S)	3.417
Kobe (1995)	KJMA (N-S)	8.178

Fig.5 illustrates the peak responses of each story of the uncontrolled and controlled (SAC and P-on) structure under the effect of all excitation cases. From this figure, it can be seen that the SAC algorithm has reduced both story acceleration and drift responses effectively in all earthquake cases. As mentioned earlier, mitigating the story accelerations is essential for protecting vibration-sensitive equipment supported by the structure. Hence the control objective here is to mitigate acceleration levels and control parameters have been set primarily to fulfill that goal. It is observed that passively-used dampers (P-on case) can reduce drifts more efficiently in contrast with semi-active dampers (SAC), however, they fail to keep this superior performance in acceleration reduction. In the case of Elcentro earthquake, passive damper magnifies the acceleration response up to 200% the uncontrolled structure. SAC controller can reduce the acceleration responses up to 76%, 72%, 60% and 68% of the uncontrolled structure for the EL 1.0, EL 0.5, KO 1 and KO 0.5 excitation cases, respectively. It also reduces the inter-story drifts up to 54%, 59%, 41% and 43% of the uncontrolled structure for the EL 1.0, EL 0.5, KO 1 and KO 0.5 excitation cases, respectively.

Fig.6 illustrates the acceleration time history of 2nd story of the uncontrolled and controlled (SAC and P-on) structure under the effect of all excitation cases. This figure clearly shows the previously mentioned acceleration distortion caused by passive damper. Main advantage of the semi-active controller is to adaptively change damper's command voltage to cope with different internal and external uncertainties. For example, in EL 0.5 case, constant saturation voltage injected to the damper has caused a severe noise in damper's generated force and consequently, 2nd story measured acceleration. This figure shows an acceptable adaptive action by SAC in reducing responses compatible to uncontrolled state.

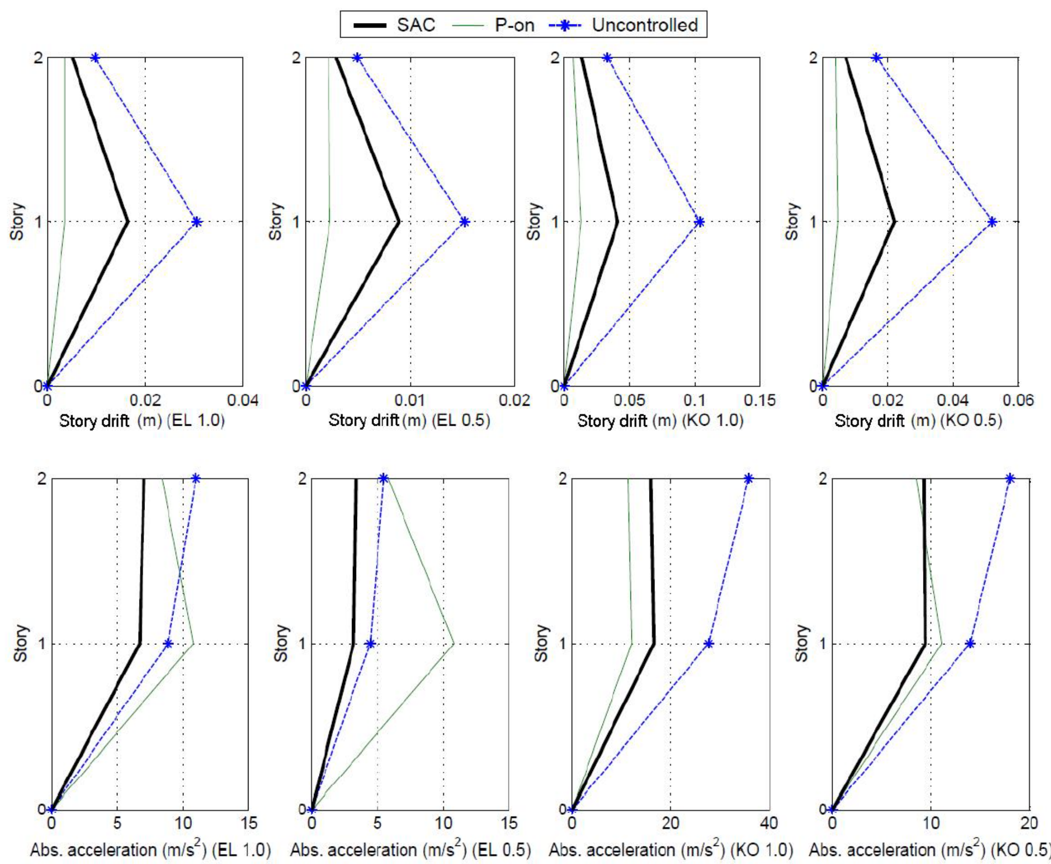

Fig. 5 – Peak response of the structure stories subjected to different excitations
(EL=ELCENTRO , KO=KOBE)

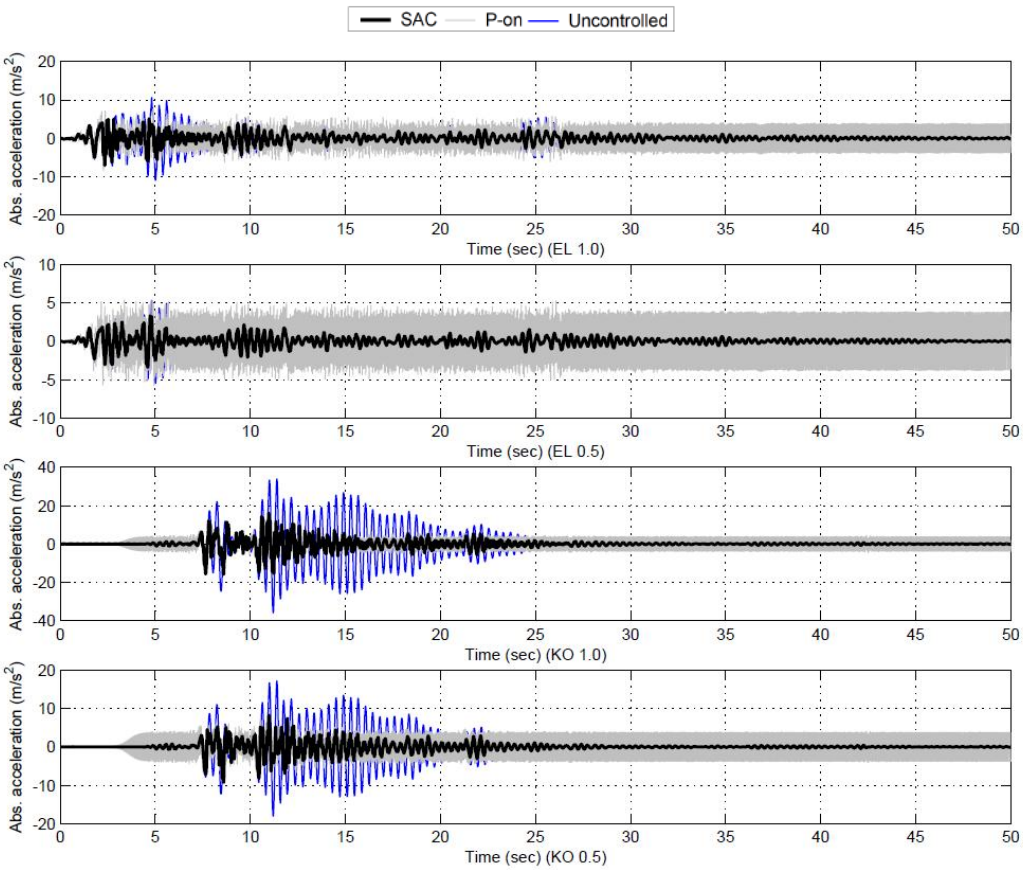

Fig. 6 – Time history of the 2nd story absolute acceleration response under different excitations
(EL=ELCENTRO , KO=KOBE)

In order to evaluate the controller's performance, SAC-generated damper voltage and force is shown in Fig.7 in addition to Passive-on damper force. First, an intense noise is observed in P-on force which can be harmful to the structure and supported equipments. To avoid force distortions, it is necessary to reduce damper voltage when there is a lower demand on the structure. As is illustrated in the figure, SAC algorithm has been able to efficiently control command voltage and therefore, resistant force peaks are generated exactly when they are required to suppress the response peaks.

Nonlinear structures can absorb applied energy content through the development of plastic hinges. In order to evaluate the SAC performance in mitigating the induced seismic damage, number of plastic hinges throughout the structural connections can be investigated. During more severe ground motions, generation of the plastic hinges is inevitable. In this study, Kobe 1.0 earthquake is considered for damage investigation. In the uncontrolled state, two plastic hinges are created in the 1st story beam where the ratio of connection's actual curvature to yield curvature is 1.164 for both sides. It is observed that for the SAC controlled structure, hinge generation is completely prevented for the same excitation. In this case, ratio of connection's actual curvature to yield curvature is reduced to 0.462 for both sides which is a safe margin (60% reduction in ratio). This improvement can lead to a more economic and efficient structural design which is crucial in oil and gas mega-projects. Using semi-active controllers can reduce the seismic demand on the critical structures and provide both safety and cost-efficiency. SAC controller requires only output measurements and once appropriately designed, will be independent of structural dynamic properties and external uncertainties. These merits can introduce SAC as a potential controller for application in sensitive, large and nonlinear structural systems.

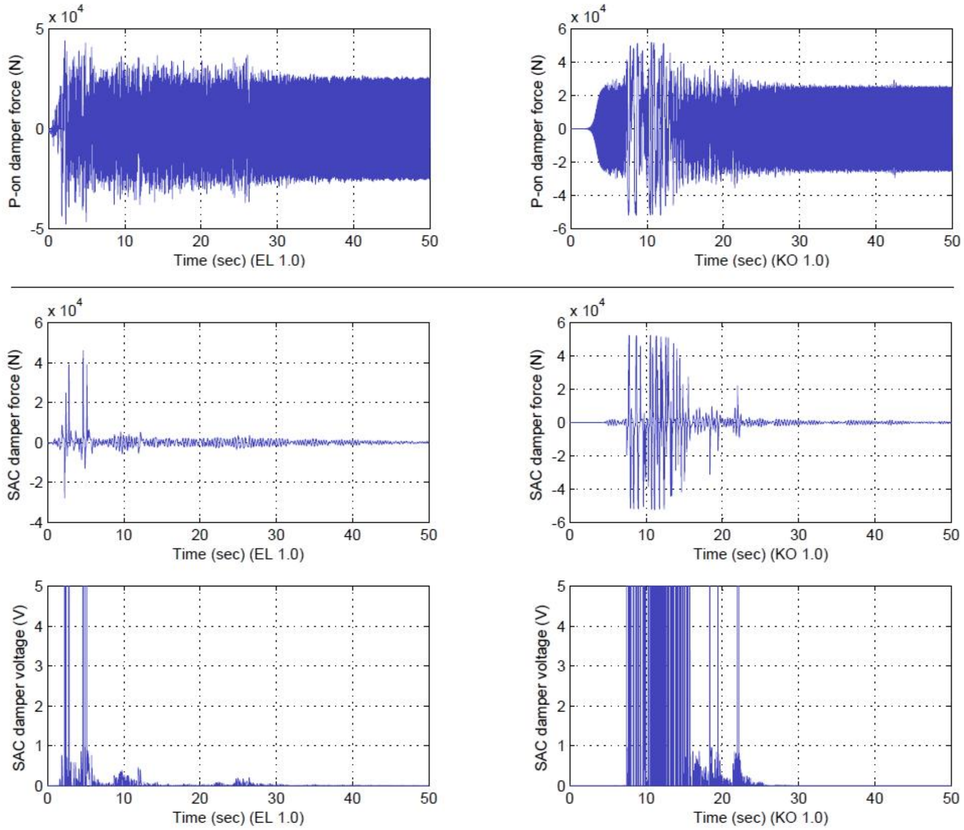

Fig. 7 – Time history of the generated damper force and control command voltage
(EL=ELCENTRO , KO=KOBE)

4. Conclusions

In this study, a simple adaptive controller is developed to mitigate the responses of stationary equipment supporting structures subjected to different seismic excitation. These structures are considered to safely support the operational and occasional loads of acceleration-sensitive industrial equipment, such as horizontal vessels. Hence, reducing the acceleration response of such structures can extensively improve the equipment's function during strong earthquakes and prevents probable damage and financial loss. This study aims at providing a practical and efficient semi-active control scheme applicable to industrial plants by using accelerometers as measurement sensors, Magneto-Rheological (MR) dampers as semi-active actuators, and output-based SAC controller which is robust against environmental uncertainties. In order to investigate performance of the proposed control system, numerical studies are conducted on a large-scale model of 2-story structure (supporting two horizontal vessels at each level) which is subjected to the various earthquake records. For comparison purposes, MR dampers are also used as passive actuators (by holding the damper's command voltage at its maximum value) to verify the superior performance of the semi-active system. Results show a maximum reduction of the inter-story drift and acceleration responses by 41% and 60% of the uncontrolled structure under the effect of different ground motions, respectively. SAC algorithm is able to efficiently reduce acceleration responses (as the primary control objective) and prevents plastic hinge development without any access to structural dynamic parameters, while passive MR dampers inject large force distortions into the system.

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