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Research Article

Inelastic Structural Control Based on MBC and FAM

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A complex structure has the characters of many degrees of freedom and intricate shape, especially inelastic behavior under strong external loadings. It is hard to apply the structural control technology to it. In this paper, a new method that combines the Market-Based Control (MBC) strategy and Force Analogy Method (FAM) is presented to analyze the inelastic behavior of structure with magnetorheological dampers. The MBC is used to reduce the structural vibration response, and FAM is proposed to perform the inelastic analysis. A numerical example is used to compare the control effect of the new method and LQR algorithm, which show the accuracy and efficiency of the proposed computational method.

1. Introduction

The structural vibration control began in the mechanical engineering in the early twenteith century, subsequently developed in the aerospace engineering. The conception of structural control in civil engineering was proposed by Yao in 1972 [1]. In the past 30 years, the structural control technology has made considerable progress by the developing of theoretical and experimental researches. In recent years, the development of complex structures such as ultrahigh and long-span structure makes a change in structural control method. The conventional centralized control strategy gradually exposes limitation for the structures in civil engineering, because computing models of complex buildings generally have many thousands of degrees of freedom, and dynamic analysis of these structures usually takes considerable amount of computing time. For these structures, the traditional approach of using a central computer responsible for the control of the entire system will become less desirable. One effective approach to handling the complicated structural control problem is to use the decentralized control system.

As one of the decentralized methods, the Market-Based Control (MBC) is a multiobjective distributed control approach that provides effective control for a structure by means of simulating the activities of free market. The MBC was proposed firstly by Clearwater [2] in 1996. Voos [3] applied market-based algorithms to solve the optimal decentralized control problem of complex dynamic systems. Jackson et al. [4] described the implementation of a market-based scheme for allocating and coordinating the actions of many mechatronic systems using analog electronics. Such a system is versatile, of low cost, and robust against changes in the number and capabilities of the participating agents. Prouskas et al. [5] presented a Multiagent System (MAS), comprised of intelligent, autonomous, and self-interested agents, which makes use of a market-based approach to perform the real-time control of intelligent networks traffic. Tansu et al. [6] proposed a game theoretic of distributed power control in CDMA wireless systems, and made use of the conceptual framework of noncooperative game theory to obtain a distributed and market-based control mechanism. A market-based system was developed by Hilland et al. [7] to assist in mission planning for an Earth orbiting synthetic aperture radar mission. This approach was chosen over more traditional systems based on a functional model used to compare the market based system with human-expert, thematic, and geometric approaches. Bernardine and Stents [8] gave a comparative study between three multirobot coordination schemes that span the spectrum of coordination approaches. Results spanning different team sizes indicated that the market method was favorable compared to the optimal solutions generated by the centralized approach in terms of cost and computation time. Lynch and Law [9] firstly applied the MBC strategy to the structural vibration control in civil engineering. They [10] proposed a market-based energy control approach. However, the MBC is the effective decentralized control method for the complex structure. Huo and Li [11] presented a novel control law for semiactive tuned liquid column damper based on MBC. The result indicates that MBC semiactive TLCD on-off control method facilitates reducing structure vibration with a lower energy expenditure. Unfortunately, up to date this theory has only been applied to elastic structures in civil engineering. When a structure is excited by the strong earthquake motion, it is very likely to enter inelastic deformation phase. At the time, the structure is a complex system characterized by not only high dimensionality, but also nonlinear behavior. The conventional method used for calculating the structural nonlinear behavior is to modify the stiffness matrix using the step-by-step approach after yielding. Some problems arise when incorporating the inelastic structural analysis into the existing control theory. This type of computation is certainly time inefficient and induces significant time delay so as to produce negative effects on the application of the control system. One way to overcome this problem is to invest a large amount of money in highly efficient computers; another is to find new inelastic analysis methods that do not require changing stiffness.

Compared with the conventional analytical methods, the Force Analog Method (FAM) as a relatively new algorithm was proposed by Lin [12] in 1968. Using the FAM, the state transition matrix needs to be computed only once due to the consistent use of initial stiffness, and this greatly simplifies the overall computation and makes the inelastic analysis readily incorporated into the control theory. In 1999, Wong and Yang [13] applied the FAM to dynamic elastic-plastic analysis of structure using a time history method in civil engineering. Further, they [14] built the energy response model of structure based on the FAM. Especially, it showed the detailed solution and calculated procedure for the energy analysis of response and performance of structures subjected to severe ground excitations. Then, they [15] used the FAM for the predictive instantaneous optimal control (PIOC), in which their work greatly simplifies the computation procedure and makes the inelastic analysis readily applicable to the PIOC algorithm. All the researches showed that the FAM could reduce the stiffness storage spaces, simplify the computation course, and enhance the calculation speed.

The objective of this study is to develop the FAM with the MBC theory for considering the inelastic behavior of structure, in which the MBC is used to reduce the structural vibration response and FAM is proposed to perform the inelastic analysis.

2. Basic Theory on MBC and FAM

2.1. Basic Theory on MBC

In the field of economics, the free market can set up an effective distribution of resources by the means of price strategy. The complicated market economy can be idealized by the behavior of market institutions such as consumer (buyers), firms (sellers), trade unions, and governments. Mastering the basic concept as followed is very important to understand the MBC theory. The amount of commodity planned to sell by sellers in some time at the market price level is called "Supply," which is affected by the market price and produced power. The aim of the supply is to make the profit maximal. The amount of commodity planed to buy by buyers in the same period at market price is called "Demand." Making the utility maximal is the buyers' motivation and goal during trade in the marketplace. The price is paid for goods or the workers' salary. It makes the free market optimally "controlled." Because the price is also consistent to the controlled force from actuator, once the demand in market or environmental load increases, the price and wealth consumption become larger. Changes in regularity of the price and consumption are consistent to the ones of demand in market and environmental loads in structural control. Therefore, the precision and effectiveness of control strategy are judged by comparing the change of price and wealth consumption to demand or environmental load.

The competitive mechanisms of a free market can be extended for the application to the structural control field. In the control marketplace, the roles of market buyers and sellers are assumed by system actuators and power sources, respectively. The foundation of applying the MBC strategy to the civil engineering is that the decentralized complex system with the market model uses the merchandise's supply-demand law to distribute the control energy, where the energy system and controlled system are replaced by the seller and consumer. The behavior of a buyer is defined by the individual utility function, J_D, that measures the amount of utility derived by the buyer from purchasing the market commodity. The utility is a function of the price per unit commodity, p, the amount of purchased commodity, Q_D, and response measures of the dynamic system, $Y(t)$. Similarly, a seller is governed by the individual profit function, J_S, that measures the amount of profit derived by the seller from selling the commodity. The profit is modeled as a function of the price per unit commodity, p, and sold commodity Q_S. The goal of the seller is to maximize their profit that is constrained by the maximum amount of commodity they possess, $Q_{\max}$. Meanwhile, the maximization of the buyers' utility is constrained by the total purchase cost, $p \cdot Q_D$, to be less than their fictitious wealth, $W_{\max}$:

$$\begin{array}{llll} \max J_{S1}(Q_{S1}, p) & Q_{S1} \le Q_{\max 1} & \max J_{D1}(Q_{D1}, p, Y_1(t)) & p \cdot Q_{D1} \le W_{\max 1} \\ \max J_{S2}(Q_{S2}, p) & Q_{S2} \le Q_{\max 2} & \max J_{D2}(Q_{D2}, p, Y_2(t)) & p \cdot Q_{D2} \le W_{\max 2} \\ & \vdots & & \vdots \end{array} \tag{2.1}$$

The system is constrained by the conservation of total energy, where the m systematic buyers purchase all the power produced by the system's n suppliers. According to the price rule and supply-demand law, the equation can be expressed as follows:

$$\sum_{j=1}^{n} Q_{Sj} = \sum_{i=1}^{m} Q_{Di}. \tag{2.2}$$

At each point in time, the solution of (2.1) and (2.2) is shown to be the Pareto Optimal Solution. That is to say, an equalization price is got according to the equations of supply and demand in each time step, and the distribution of scarce resources reaches to maximized benefits under the optimal price. In the fictitious market, there do not exist strict relations between the supply and demand. The commodity price, p, is a key factor with regard to supply function, Q_S, and demand function, Q_D. The supply function is usually chosen as a linear function as into the amount of supply is rising with the increasing price, and the demand function can be selected in several models for a high speed of calculation. Based on the forms of demand supply, the supply-demand mode can be classified four types, such as linear-supply and linear-demand model (LLM) [9], linear-supply and Power-demand model (LPM) [16], advanced linear-supply and power-demand model (ALPM), and Linear-supply, and exponential-demand model (LEM) [17].

2.2. *Basic Theory on FAM*

The force analogy method (FAM) [13] is an elastic-plastic dynamic response analytical method with strong dynamic stability and rapid computing speed, which focuses on a change in the structural displacement, not in the stiffness. It is assumed that structural inelastic deformation only occurs at some locations called Plastic Hinge Locations (PHLs) after entering nonlinear state, other parts of the elements are still elastic, and the plastic displacements are induced by the plastic rotation at the PHLs in the structure. The FAM fulfills the structural nonlinear solution procedure by means of building the relationship among the PHLs, structural horizontal displacement, and horizontal restoring force. Different from the conventional method for the nonlinear deformation analysis using the changed stiffness, the FAM is used to obtain the nonlinear relationship between force and displacement by changing the structural displacement, and reduce storage spaces, enhance the calculation speed. Moreover, it can capture the distribution of the PHLs, the plastic deformation of components at any time with and without devices.

The basic theory of the FAM is that the structural deformation can be divided into elastic displacement and plastic displacement:

$$x(t) = x'(t) + x''(t), \tag{2.3}$$

where $x(t), x'(t),$ and $x''(t)$ represent the total displacement, elastic displacement, and plastic displacement, respectively.

To be consistent with the displacement of the structural components, the total moment generated on the plastic hinge is divided into the moments of the elastic stage and plastic stage, respectively. The equation can be written as follows:

$$M(t) = M'(t) + M''(t), \tag{2.4}$$

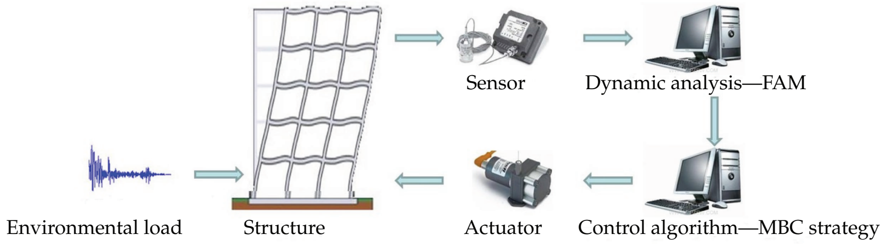


Figure 1: Schematic diagram of MBC nonlinear control strategy based on FAM.

where $M(t), M'(t)$, and $M''(t)$ are the total moment, elastic moment, and plastic moment at PHLs, respectively. After a series of derivation [13], the formulas can be drawn as follows:

$$\begin{aligned} M(t) &= M'(t) + M''(t) = K_P x(t) - K_R \theta''(t), \\ F(t) &= K x'(t) = K\left(x(t) - x''(t)\right) = K x(t) - K_P \theta''(t). \end{aligned} \tag{2.5}$$

It represents the governing equation of the force analogy method, where K_P denotes the stiffness matrix related to the plastic rotation $\theta''(t)$ with the resorting force, K is an elastic stiffness of structure, and K_R is a stiffness matrix related to the plastic rotation $\theta''(t)$ with the moment at the plastic hinge.

3. MBC Nonlinear Control Strategy Based on FAM

The whole process of the MBC of a structure using the FAM can be depicted as shown as in Figure 1.

The inelastic response of a structure installed with actuators is described by the following dynamic equation:

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}'(t) = -\mathbf{M}\ddot{\mathbf{x}}_g(t) + \mathbf{B}_s\mathbf{U}(t), \tag{3.1}$$

where $\mathbf{M}, \mathbf{C}$, and $\mathbf{K}$ are the structural mass, damping, and stiffness matrices, $\mathbf{X}'(t)$, $\dot{\mathbf{X}}(t)$, and $\ddot{\mathbf{X}}(t)$ mean the structural elastic displacement, velocity, and acceleration vectors, respectively, $\ddot{\mathbf{x}}_g(t)$ denotes the acceleration vector, $\mathbf{B}_s$ implies the location matrix of the actuators, and $\mathbf{U}(t)$ represents the control vector from actuators. Replacing the elastic displacement $\mathbf{X}'(t)$ by subtracting the inelastic displacement $\mathbf{X}''(t)$ from the total displacement $\mathbf{X}(t)$ as given in (2.3), (3.1) becomes

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = -\mathbf{M}\ddot{\mathbf{x}}_g(t) + \mathbf{B_s}\mathbf{U}(t) + \mathbf{K}\mathbf{X}''(t). \tag{3.2}$$

Using the state space method, (3.2) s changed to the first-order linear differential equation as

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{U}(t) + \mathbf{H}\ddot{\mathbf{x}}_g(t) + \mathbf{F}_p^c(t)\mathbf{X}''(t), \tag{3.3}$$

where $\mathbf{z}(t) = \left\{ \begin{smallmatrix} \mathbf{X}(t) \\ \dot{\mathbf{X}}(t) \end{smallmatrix} \right\}$, $A = \left[\begin{smallmatrix} 0 & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{smallmatrix} \right]$, $B = \left[\begin{smallmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{B_s} \end{smallmatrix} \right]$, $H = \left[\begin{smallmatrix} 0 \\ -\mathbf{1} \end{smallmatrix} \right]$, $F_p^c = \left[\begin{smallmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{K} \end{smallmatrix} \right]$.

The solution of (3.3) can be obtained as follows:

$$\mathbf{z}(t) = e^{A\Delta t}\mathbf{z}(t-\Delta t) + e^{At}\int_{t-\Delta t}^{t} e^{-As}\left[\mathbf{H}\ddot{\mathbf{x}}_g(s) + \mathbf{F}_p^c\mathbf{X}''(s)\right]ds, \tag{3.4}$$

where Δt is the integration time step. Let $t_{k-1} = t - \Delta t$ and $t_k = t$. The discrete state solution of (3.4) becomes

$$\mathbf{z}(k+1) = e^{A\Delta t}\mathbf{z}(k) + e^{A\Delta t}\mathbf{B}\Delta t\mathbf{U}(t) + e^{\mathbf{A}\Delta t}\mathbf{H}\Delta t\ddot{\mathbf{x}}_g(k) + e^{\mathbf{A}\Delta t}\mathbf{F}_p^c\Delta t\mathbf{X}''(t). \tag{3.5}$$

Assuming $\mathbf{A}_d = e^{\mathbf{A}\Delta t}$, $\mathbf{B}_d = e^{\mathbf{A}\Delta t}\mathbf{B}\Delta t$, $\mathbf{H}_d = e^{A\Delta t}\mathbf{H}\Delta t$, and $\mathbf{F}_{pd} = e^{\mathbf{A}\Delta t}\mathbf{F}_p^c\Delta t$, (3.5) can be simplified as

$$\mathbf{z}(k+1) = \mathbf{A}_d\mathbf{z}(k) + \mathbf{B_d}\mathbf{U}(k) + \mathbf{H}_d\ddot{\mathbf{x}}_g(k) + \mathbf{F}_{pd}\mathbf{X}''(k), \tag{3.6}$$

where $\mathbf{U}(k) = [U_1 \quad U_2 \quad \cdots \quad U_n]^T$ is the force vector form actuator.

The solution for this control force vector can be given in terms of the state vector $\mathbf{z}(\mathbf{k})$ using the supply-demand law. Such as for the ALPM law.

For a freedom system with n degrees, the linear supply function can be written as

$$Q_{S,j} = \eta_j \cdot p. \tag{3.7}$$

The demand function can be written as

$$Q_{D,i} = \frac{W_i\left|\alpha_i x_{d,i} + \beta_i\dot{x}_{d,i}\right|}{p}, \tag{3.8}$$

where η_j is the parameter that reflects the energy supply, $x_{d,i}$ and $\dot{x}_{d,i}$ are the storey displacement and storey velocity of the ith floor, and $\alpha_i \geq 0$ and $\beta_i > 0$ are the weighting coefficients, respectively.

Based on the optimal price solved from (2.2), the control force with the direction can be drawn as follows:

$$U_i = -K \cdot \frac{W_i \cdot \left(\alpha_i x_{d,i} + \beta_i\dot{x}_{d,i}\right)}{p}, \tag{3.9}$$

where $K > 0$ is a gain coefficient related to the actuator.

The equation at the time step of k becomes

$$\sum_{j=1}^{n}\eta_j p(k) = \sum_{i=1}^{n}\frac{W_i(k) \cdot \left|\alpha_i x_{d,i}(k) + \beta_i\dot{x}_{d,i}(k)\right|}{p(k)}. \tag{3.10}$$

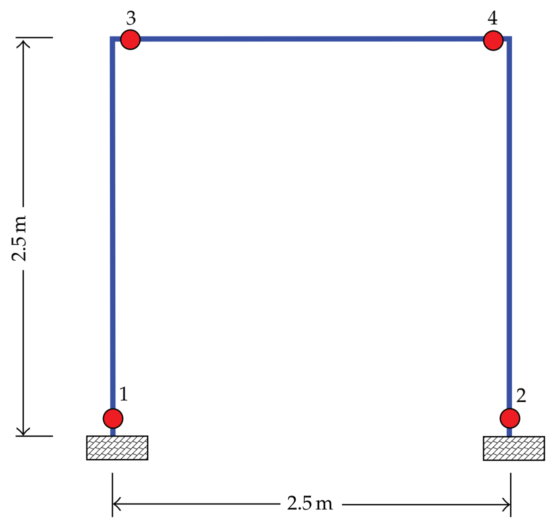


Figure 2: The sketch and PHLs of the structure.

The solving of equation is given by

$$p(k) = \sqrt{\sum_{i=1}^{n} \frac{W_i(k) \cdot \left|\alpha_i x_{d,i}(k) + \beta_i \dot{x}_{d,i}(k)\right|}{\sum_{j=1}^{n} \eta_j}}. \tag{3.11}$$

Substituting (3.11) into (3.9), then the solution of the control force is obtained as

$$\mathbf{U}(k) = -K \cdot \mathbf{Q_D}(k), \tag{3.12}$$

where $\mathbf{Q_D}(k) = [Q_{D,1}(k) \quad Q_{D,2}(k) \quad \cdots \quad Q_{D,N}(k)]^T$.

4. Numerical Example Analysis

4.1. Single Degree of Freedom (SDOF)

4.1.1. Given Information

A single-degree-of-freedom system is considered in validating the feasibility of inelastic control method presented in this paper. Assume four PHLs exist in this frame: two at the two ends of the beam and two at the bottom end of the two columns. The sketch and PHLs' number of structure were shown in Figure 2. The floor masses are assumed to be 16,000 kg, and other structural parameters were shown in Table 1. The structure is excited by ground motions, El Centro earthquake (NS, May 18, 1940, the acceleration peak of which is adjusted to 500 gal).

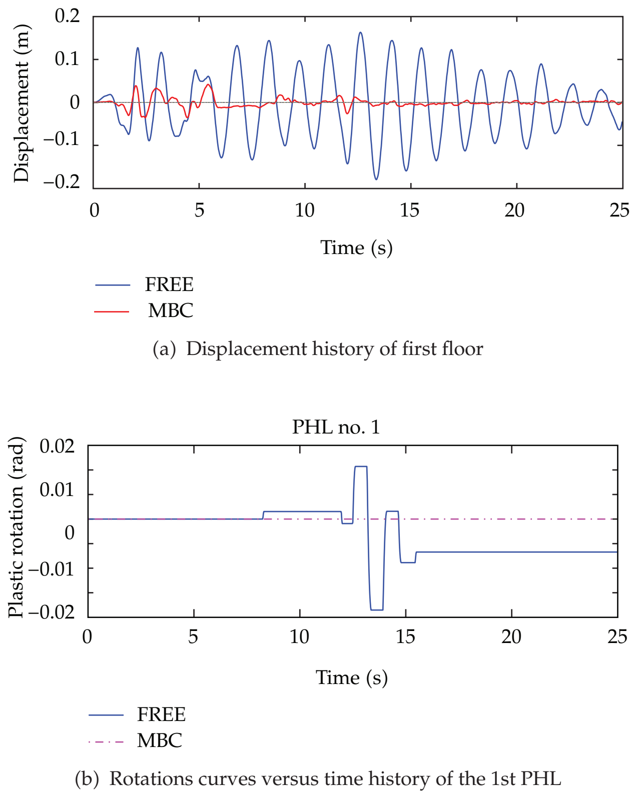


Figure 3: Structural response time histories under El Centro seismic excitation without control. (Note: FREE and MBC represent the structural response without and with the actuators controlled by MBC).

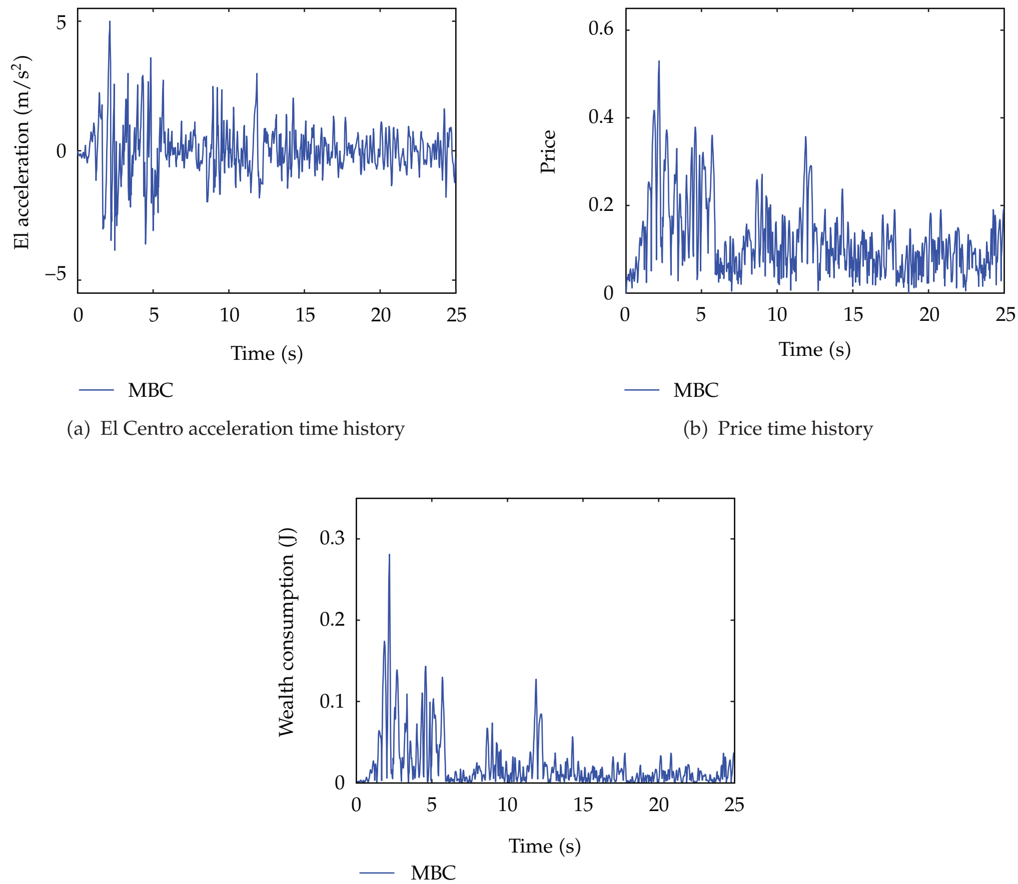
Table 1: The main parameters of the structure.

Structural component	Elastic modulus EI $(\mathrm{N\cdot m^2})$	Yielding moment M $(\mathrm{N\cdot m})$
1st rows columns	2.87×10^6	3.107×10^5
1st rows beams	2.87×10^6	3.107×10^5

Magnetorheological Damper (MRD), which damping force is from 23 kN to 1200 kN, is installed as actuators into the frame. As semiactive control model of MRD, Hrovat algorithm was adopted as follows [18]:

$$u_d = \begin{cases} c_d\dot{x} + f_{d,\min}\,\mathrm{sgn}(\dot{x}), & u\dot{x} \geq 0, \\ |u|\,\mathrm{sgn}(\dot{x}), & u\dot{x} < 0,\quad |u| < u_{d,\max}, \\ c_d\dot{x} + f_{d,\max}\,\mathrm{sgn}(\dot{x}), & u\dot{x} < 0,\ |u| > u_{d,\max}, \end{cases} \tag{4.1}$$

where $\dot{x}$ is the storey velocity; $u_{d,\max} = c_d|\dot{x}| + f_{d,\max}$, $u_{d,\min} = c_d|\dot{x}| + f_{d,\min}$ are the maximum and the minimum damping force from MRD at any time.

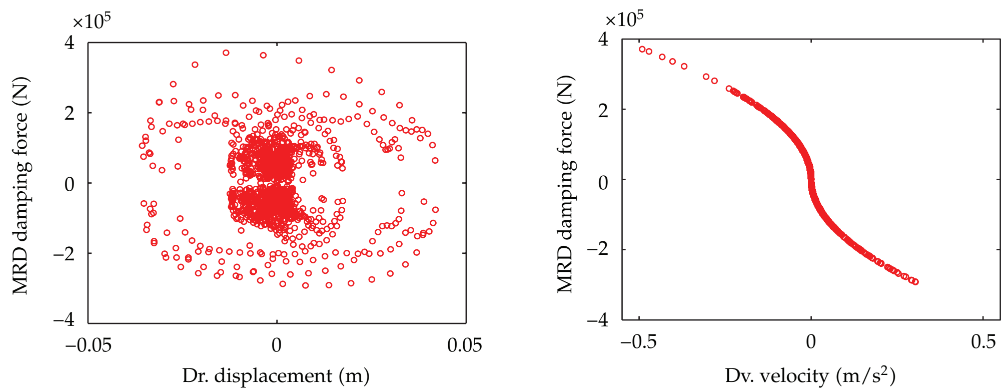


(a) El Centro acceleration time history

(b) Price time history

(c) Wealth consumption time history

Figure 4: Comparison of results among time histories.



(a) Damping force versus storey displacement

(b) Damping force versus story velocity

Figure 5: MRD damping force versus storey displacement and storey velocity under El Centro seismic excitation.

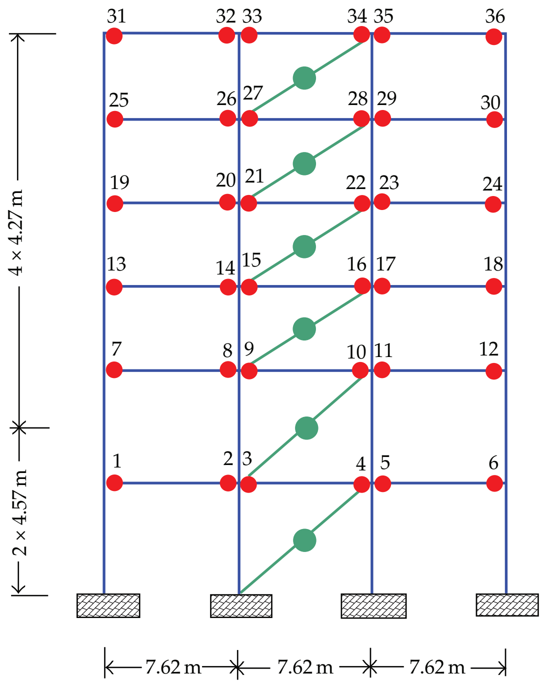


Figure 6: Distribution of the plastic hinges.

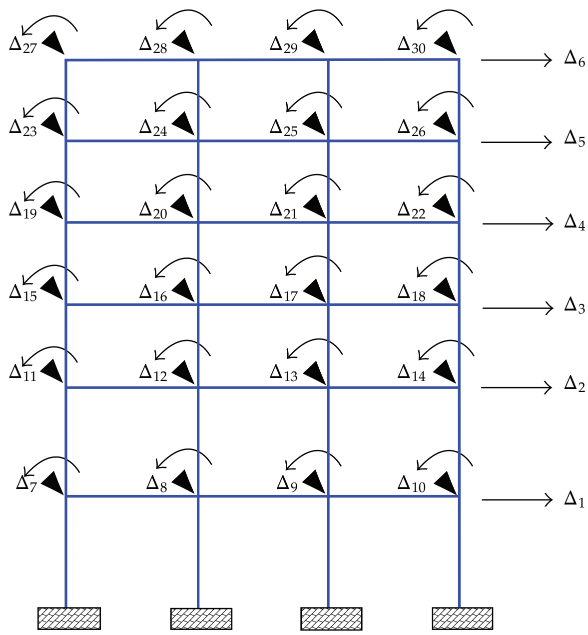
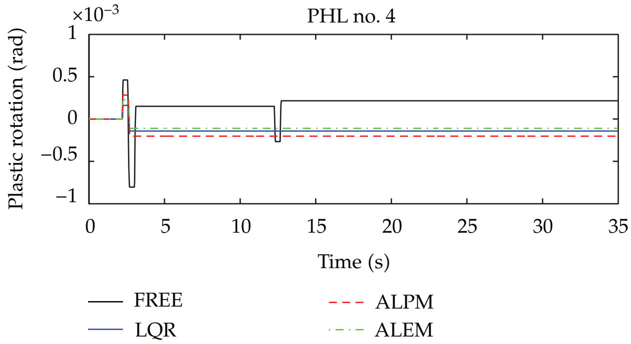


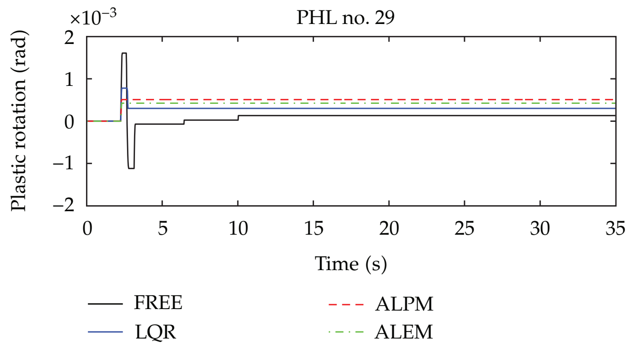
Figure 7: Numeration of structural degree of freedom.

4.1.2. Results Analysis

To understand the performance of the inelastic control method combing the FAM and MBC, Figure 3 compares the displacement and the plastic rotations response at the 1st PHL of



(a) 4th PHL



(b) 29th PHL

Figure 8: Rotations curves versus time history of the 4th and 29th PHL under El Centro seismic excitation.

Table 2: The main parameters of the structure.

Structural component	Elastic modulus EI $(\mathrm{N} \cdot \mathrm{m}^2)$	Yielding moment M $(\mathrm{N} \cdot \mathrm{m})$
1st to 2nd rows columns	7.680×10^8	0.953×10^6
3rd to 4th rows columns	6.800×10^8	0.844×10^6
5th to 6th rows columns	4.800×10^8	0.596×10^6
1st to 3rd rows beams	2.604×10^9	3.388×10^6
4th rows beams	1.808×10^9	2.363×10^6
5th rows beams	1.560×10^9	2.070×10^6
6th rows beams	0.654×10^9	1.313×10^6

structure with and without the MRD. As shown in these figures, the 1st PHL has entered inelastic deformation phase, and FAM completed the process of inelastic dynamics analysis, rapidly; MBC executed the effective inelastic control.

In considering the MBC, it is interesting to consider the price and wealth consume with respect to time. The curves of these variations were shown in Figure 4. A clear relationship exists among the price, wealth consumption, and the input ground motion to the structure. As the structural dynamical responses increase with respect to the input ground acceleration, the price and wealth consumption increase.

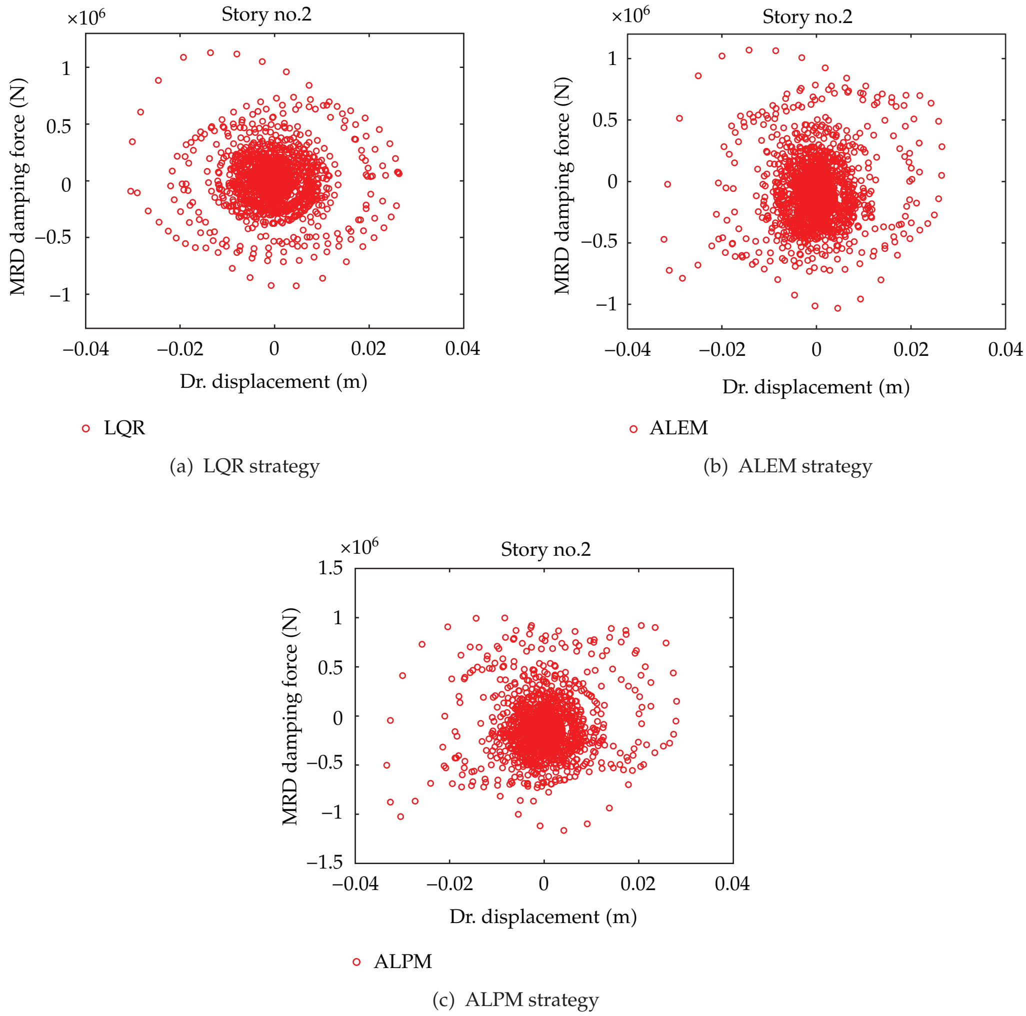


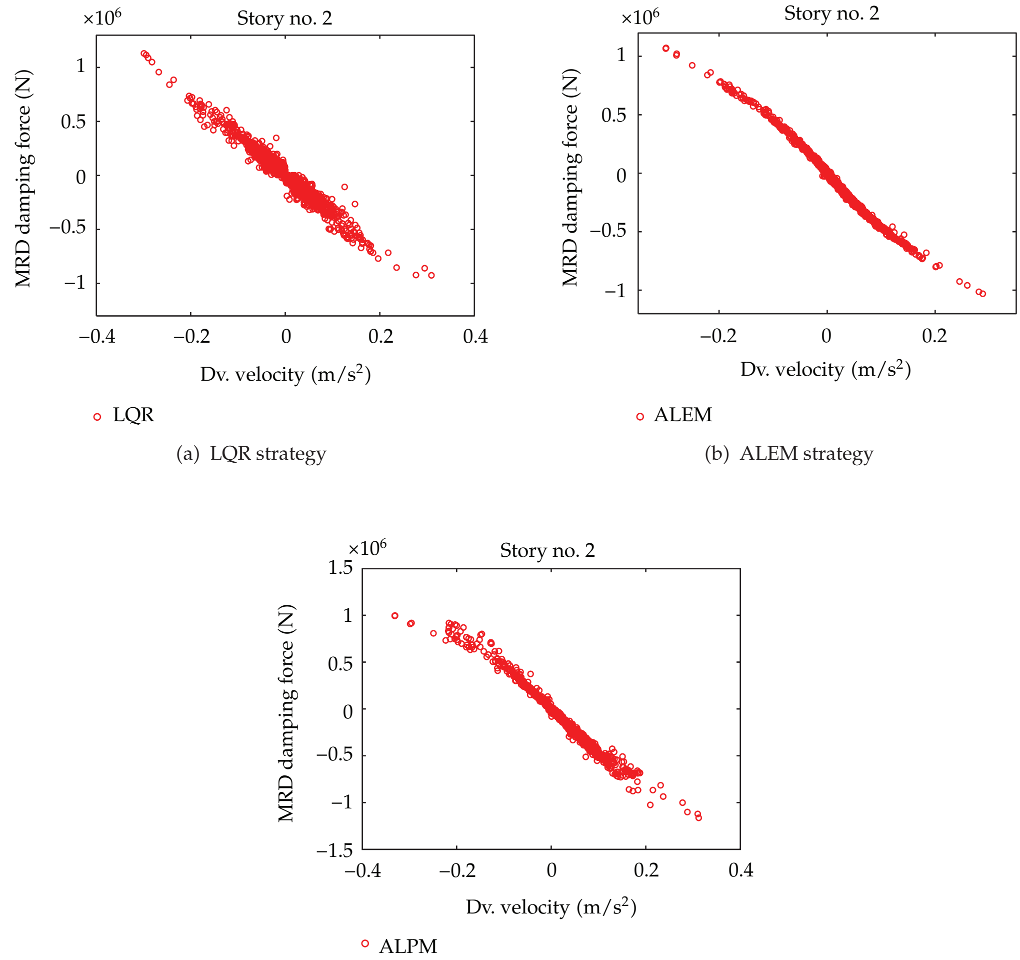
Figure 9: MRD damping force versus storey displacement under El Centro seismic excitation.

The curves of the damping force versus story displacement and storey velocity of MRD under El Centro earthquake excitation were shown in Figure 5.

4.2. Multidegree of Freedom (MDOF)

4.2.1. Giving Information

A six-story structure shown in Figure 6 is used for numerical simulation. The floor masses are assumed to be 10,800 kg on every floor, and other structural parameters are shown in Table 2. The locations of PHLs are illustrated in Figure 6. The joint numbers of structural elements are depicted in Figure 7. The structure is excited by two ground motions, El Centro (NS, May 18, 1940) and Hachinohe (NS, May 16, 1968), the acceleration peak of which is adjusted to 500 gal. The actuators the same as to the ones used in above SDOF system mounted into structure.



(a) LQR strategy

(b) ALEM strategy

(c) ALPM strategy

Figure 10: MRD damping force versus storey velocity under El Centro seismic excitation.

4.3. Results Analysis

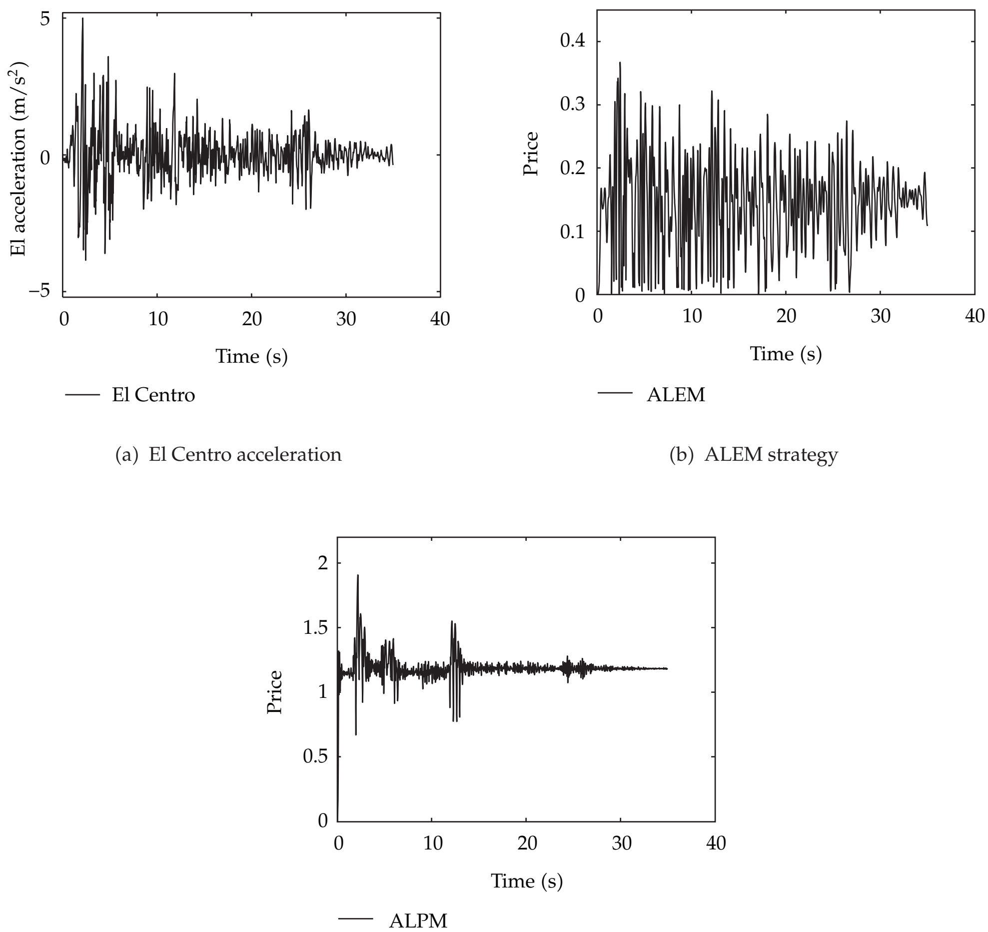
4.3.1. Comparison of Structure Response

Define the reduction rate

$$\gamma = \frac{x_0 - x}{x_0} \times 100\%, \tag{4.2}$$

where x_0 and x are the response of the structure without and with actuators, respectively.

Table 3 shows the comparing results of the response of third floor. It can be seen from this table that the control effects of MBC are similar to those of LQR under the seismic excitation. For the comparison of absolute acceleration peak, the responses of structure using MBC are smaller than those using LQR, obviously.



(a) El Centro acceleration

(b) ALEM strategy

(c) ALPM strategy

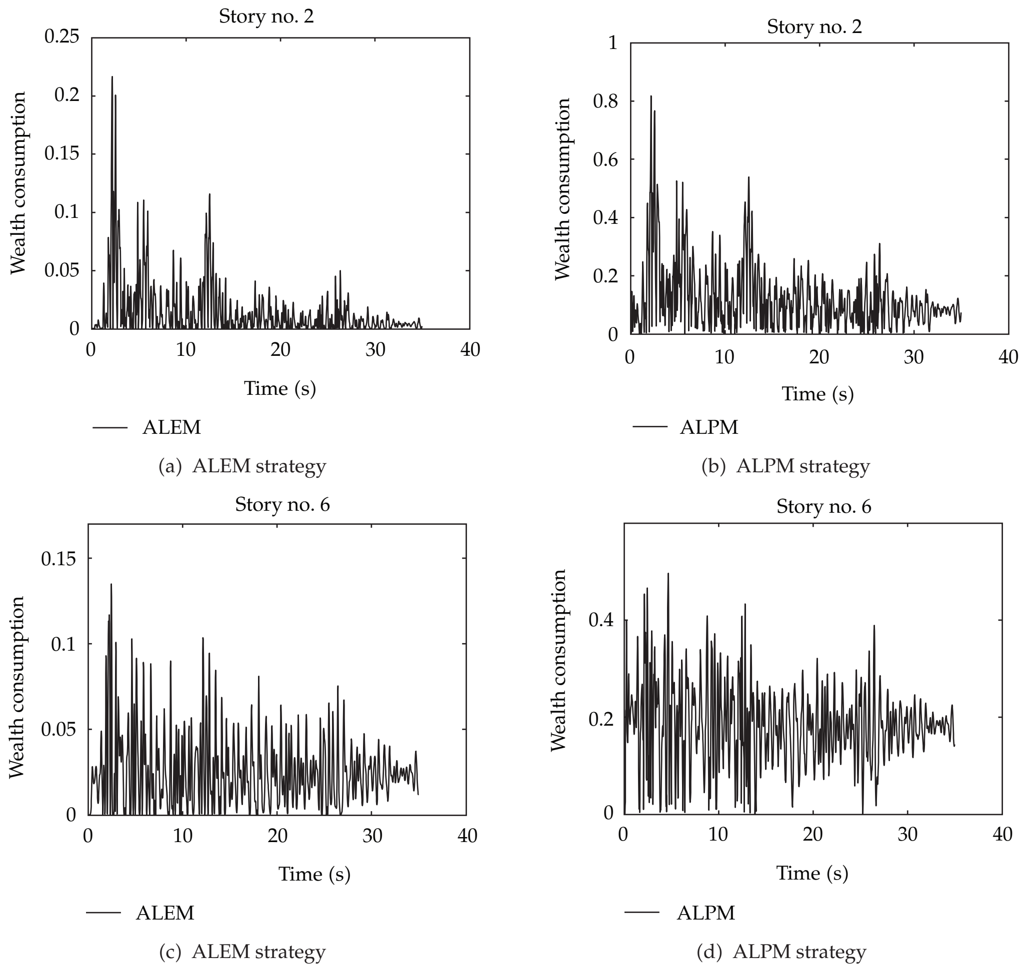
Figure 11: Comparison of results between price curves time history with MBC and El Centro acceleration time history.

4.3.2. Inelastic Analysis of Structure

Figure 8 shows the rotations versus time history of the 4th and 29th PHLs under the El Centro earthquake at 500 gal. It can be known that parts of structural elements have entered nonlinear state and the maximum plastic rotation of beam is 0.00318 rad from Table 4. The new model presented in this paper can carry out nonlinear structural control and has capability to perform an inelastic control.

4.3.3. Performance Analysis of MRD

Figures 9 and 10 show the relationship diagrams of MRD damping force versus storey-displacement and storey-velocity with LQR and MBC strategy. The conclusion can be obtained, that the direction of MRD damping force is opposite to storey velocity, and MBC is more adapting to semiactive control algorithm than LQR method.



(a) ALEM strategy

(b) ALPM strategy

(c) ALEM strategy

(d) ALPM strategy

Figure 12: Wealth consumption curves versus time history of second floor and top floor under El Centro seismic excitation.

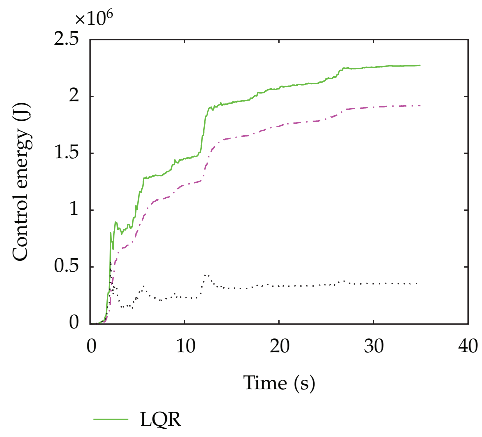
4.3.4. Analysis of MBC

The consumption of the fictitious wealth using MBC method at the third floor and top floor is shown in Figures 11 and 12. It was demonstrated that the consumption at lower floor is bigger than at the higher floor, which is in accordance with the condition that the shear at lower floor is bigger than that higher floor.

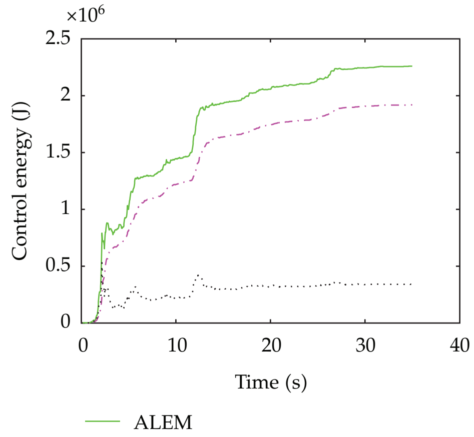
The energy response curves of structure controlled by LQR and MBC methods are displayed in Figure 13. From these figures, a considerable portion of input seismic energy (IE) is dissipated by MRD (CE), which were controlled by inelastic control method proposed in this paper. It makes the kinetic energy (KE), potential energy (DE), and damping energy (SE) smaller and minimizes possible structural damage.

5. Conclusions

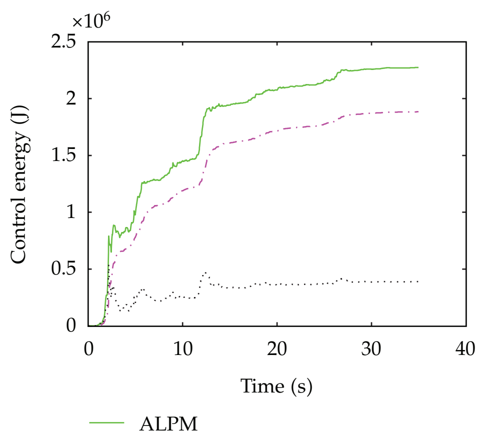
Inelastic control of complex structure during strong earthquake motion often arises computing time inefficient. The effective method of overcoming this problem is finding



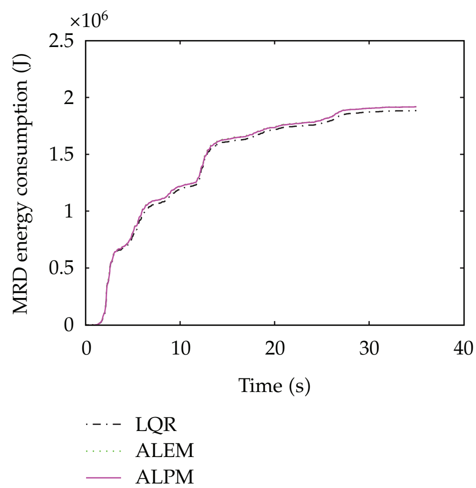
(a) ALEM strategy



(b) ALEM strategy



(c) ALPM strategy



(d) Comparison

Figure 13: Structural energy response with LQR and MBC strategy under El Centro seismic excitation. Solid green line: IE, dashed pink line: CE, dotted black line: KE+DE+SE.

a control strategy for complex system and applying a rapid computing method into inelastic dynamical analysis. In this paper, a new method which combines Market-Based Control (MBC) strategy and Force Analogy Method (FAM) is presented, and the following conclusions were drawn throughout numerical simulation analysis.

(1) The force analogy method (FAM) simplifies the computation of the inelastic structural response greatly and makes inelastic analysis easily combined into the MBC strategy.

Table 3: The structural response and the control effect of third floor.

Earthquake	Cases	Relative displacement peak to ground		Storey displacement peak		Absolute acceleration peak	
		Peak (cm)	Reduction rate (%)	Peak (cm)	Reduction rate (%)	Peak (cm)	Reduction rate (%)
El Centro	FREE	9.90	—	3.30	—	11.34	—
	LQR	7.70	22.22	2.60	21.16	8.94	21.15
	ALEM	7.77	21.47	2.51	23.87	7.26	35.97
	ALPM	8.03	18.86	2.59	21.40	7.18	36.69
Hachinohe	FREE	10.97	—	2.81	—	10.32	—
	LQR	8.72	20.49	2.23	20.71	8.46	18.00
	ALEM	8.46	22.84	2.15	23.43	7.39	28.38
	ALPM	8.75	20.24	2.26	19.70	8.69	15.76

Note. FREE represents the structural response without actuators; LQR, ALEM, and ALPM represent the structural response with actuators controlled by LQR, ALEM, ALPM strategies, respectively.

Table 4: Maximum plastic rotations at all 36 PHLs under El Centro seismic excitation.

PHL	θ''/rad	PHL	θ''/rad	PHL	θ''/rad	PHL	θ''/rad
1	0.003018	10	0.00069	19	0.002546	28	0.000241
2	0.001481	11	0.001301	20	0.001336	29	0.001608
3	0.000804	12	0.002538	21	0.000809	30	0.000801
4	0.000804	13	0.002152	22	0.000809	31	0.000459
5	0.001481	14	0.001141	23	0.001336	32	0.000229
6	0.003018	15	0.00048	24	0.002546	33	0
7	0.002538	16	0.00048	25	0.001608	34	0
8	0.001301	17	0.001141	26	0.000801	35	0.000229
9	0.00069	18	0.002152	27	0.000241	36	0.000459

(2) Market-Based Control theory has good control performance for complex structure. Advanced linear-supply and exponential-demand model (ALEM) and advanced linear-supply and power-demand model (ALPM) both are effective and easy supply-demand law.

(3) The new attempt combing FAM and MBC is feasible to carry out inelastic complex structural control. It not only accelerates the FAM development, but also enlarges the MBC application scope.

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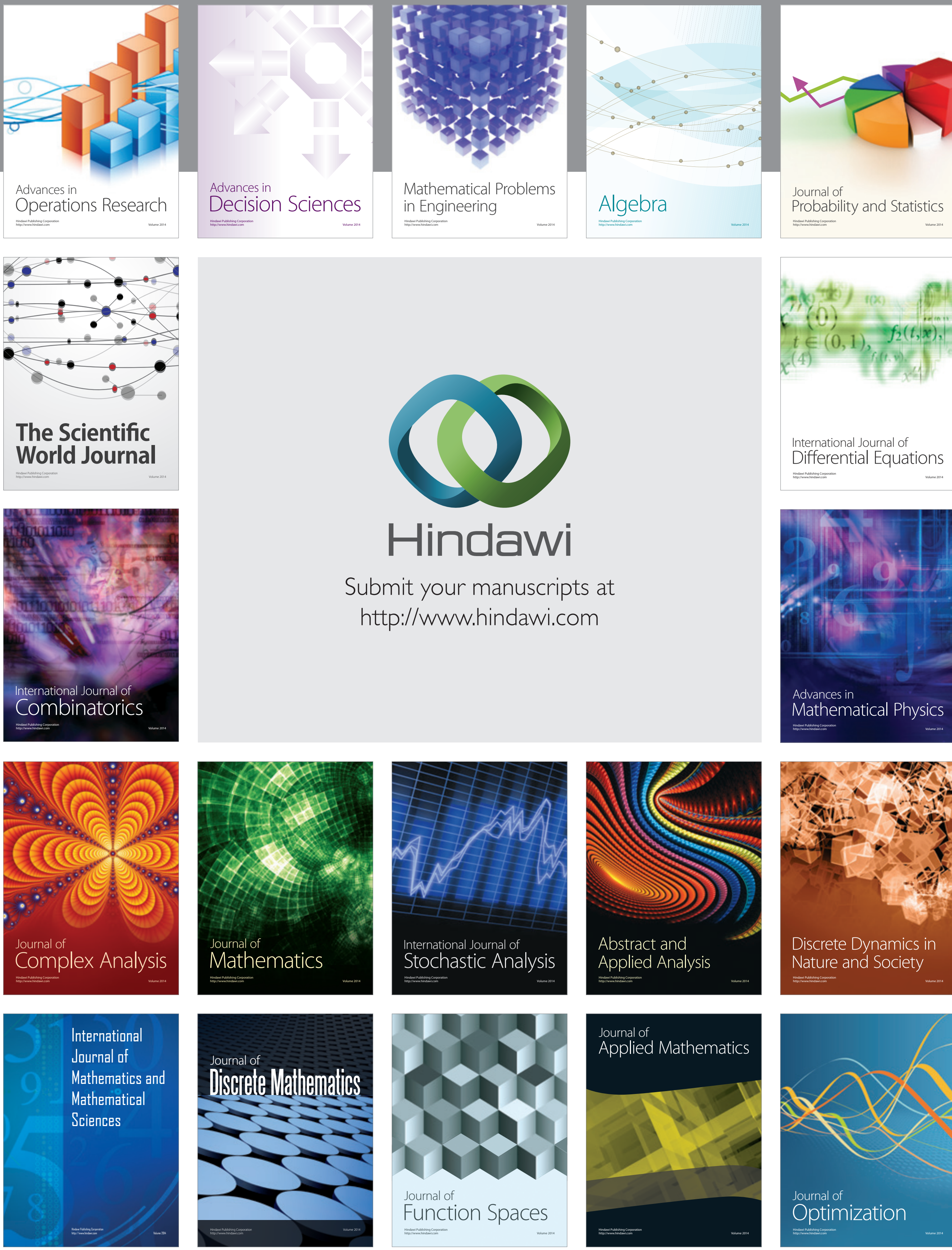

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