Sliding Mode Control For Gust Responses In Tall Building

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Abstract

The race toward new heights has led to the construction of tall flexible buildings with low inherent structural damping. As buildings get taller their sensitivity to wind excitations increases which threaten their integrity and serviceability. Therefore the control of gust responses of tall buildings has gained worldwide attention. In this work an adaptive Sliding Mode Control (SMC) driven Magneto Rheological (MR) fluid damper is proposed for the vibration control problem of a wind excited tall building. The equivalent control part proposed in this work is based on filtering the overall discontinuous control signal for a better satisfaction of the reachability condition on one hand, and to heal the chattering phenomenon on the other which is further reduced by replacing the hard switching sign function by the sigmoid-like function. The adaptive tactic is based on using 3 second time average variations of the gust speed to estimate the wind loading on the structure by utilizing the theory of quasi-steady aerodynamics.

Keywords: Sliding Mode Control (SMC), Wind Effects on Tall Buildings, Magneto Rheological (MR) fluid damper.

نظام السيطرة ذو النمط الأنزلاقي على أستجابة البنايات العالية لعصف الريح

الخلاصة

المنافسة الجارية لأحراز أرتفاعات جديدة أدت الى تشييد بنايات عالية ذات مرونة كبيرة و نسب منخفضة من عامل أخماد الأهتزاز الهيكلي.كلما أزداد أرتفاع البنايات أصبحت أسرع تأثراً بتهيج الريح مما يهدد أستقامتها و صلاحيتها الخدمية.بناءاً على ذلك أكتسبت السيطرة على أستجابة البنايات العالية لعصف الريح أهتماماً عالمياً. في هذا البحث تمت دراسة نظام السيطرة ذو النمط الأنزلاقي المتكيف لتنظيم عمل جهاز Magneto Rheological (MR) fluid damper لأخماد أهتزاز بناية عالية بسبب تأثير الريح. أن أسلوب تصميم المسيطر المكافئ (equivalent control part) المقترح يستند على ترشيح أشارة السيطرة المتقطعة العامة لتحقيق أستيفاء أفضل لشرط الوصول (the reachability condition) للسطح الأنزلاقي من جهة, ولعلاج ظاهرة الخروج المتكرر عن سطح الأنزلاق (chattering phenomenon)من جهة أخرى , والتي تم تقليلها أيضاً بأستبدال دالة الأشارة (sign function) بدالة sigmoid-like function. طريقة تكيف المسيطر تستند الى أستخدام معدل تغير سرعة عصف الريح لكل ثلاث ثواني من أجل تقدير قوة الريح على البناية بواسطة نظرية quasi-steady aerodynamics.

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Introduction

Tall buildings have continued soaring skyward translating certain man-made advances pertaining to civil structures and what comes ahead is quite promising. Since those flexible structures are standing tightly obstructing its flow, wind is one of the environmental hazards that threaten the building's integrity and pose serious serviceability issues. Under the influence of dynamic wind loads, typical high-rise buildings oscillate in the along-wind, across-wind, and torsional directions. Unfortunately, skyscrapers and other high-rise buildings are of low levels of damping and the suggested values for mechanical damping in the technical literatures, codes and standards for steel, concrete or composite structures are merely 1% to 2% of critical for buildings and less for simpler structures. Thus, structural control devices were introduced to augment damping.

The vibration control techniques have classically been categorized as passive, active, hybrid and semi-active control. The focus of recent research in structural control has shifted from active systems to semi-active devices for mitigating structural response. They are defined as those systems which are incapable of injecting energy into the system, made up of the structure and actuator, but can selectively dissipate, or channel the energy in the system to achieve favorable results [1]. Of these methods, most success has been obtained using Magneto Rheological (MR) dampers, which are capable of varying their viscosity upon the application of a magnetic field to the fluid to provide controllable dampers that have the ability to generate large forces, offer high reliability, demand small power requirements, and respond in milliseconds [2]. Hence, they are quite promising for civil engineering applications with the incorporation of a suitable controller. The controller plays the rule of regulation if there is not any desired reference input to track, instead it has to cancel, or at least, reduce the effect of the unknown external input, hence, improving the system's response to an acceptable level.

In recent years Sliding Mode Control (SMC) has been introduced to the structural control problem domain for its robustness against structural uncertainties, disturbances, actuator's nonlinearities and hysteresis [3]. Also, one would think of adaptive control scheme which takes on its account the variations in the wind excitation. Hence, an adaptive control scheme is proposed herein by modeling wind as piece-wise stationary process by applying the theory of quasi-steady aerodynamics. It is assumed that the mean wind velocity can be predicted by making a retrospective observation of the wind velocity [4]. However, the prediction of the wind velocity as well as the estimated wind forces cannot be free from uncertainties, but SMC can deal with it quite efficiently.

Five-DOF System under Random Wind Loading

The response of a high-rise wind-sensitive building of 183m in height, 31m × 31m in plane (as given by A. Kareem [5]) subjected to along-wind aerodynamic loading will be analyzed. The structural system is lumped as five levels described by:

$$\mathbf{M}\ddot{\mathbf{d}}(t) + \mathbf{C}\dot{\mathbf{d}}(t) + \mathbf{K}\mathbf{d}(t) = \mathbf{D}_1 w(t) \qquad (1)$$

where [5],

$$\mathbf{M} = (656.7255 \times 10^4) \times \mathbf{I}_{5\times 5} \quad \text{(Kg)}$$

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$$\mathbf{K} = \begin{bmatrix} 255977006 & -127988503 & 0 & 0 & 0 \\ -127988503 & 255977006 & -127988503 & 0 & 0 \\ 0 & -127988503 & 255977006 & -127988503 & 0 \\ 0 & 0 & -127988503 & 255977006 & -127988503 \\ 0 & 0 & 0 & -127988503 & 127988503 \end{bmatrix} \text{(N/m)}$$

The damping matrix is assumed to be:

$$\mathbf{C} = \begin{bmatrix} 5.1662 & -1.4448 & 0 & 0 & 0 \\ -1.4448 & 2.7582 & -1.3135 & 0 & 0 \\ 0 & -1.3135 & 1.4740 & -0.1605 & 0 \\ 0 & 0 & -0.1605 & 0.2919 & -0.1313 \\ 0 & 0 & 0 & -0.1313 & 0.1313 \end{bmatrix} \times 10^6 \text{ (N.s/m)}$$

The basis of the assumption is to achieve damping ratios ranging from 0.01 t0.03.

The state-space form of the structural system is:

$$\dot{\boldsymbol{x}}(\mathrm{t}) = \mathbf{A}\boldsymbol{x}(\mathrm{t}) + \mathbf{D}\boldsymbol{w}(\mathrm{t}) + \mathbf{B}u(\mathrm{t}) \qquad (2)$$

where $\boldsymbol{x}(\mathrm{t}) \in \mathrm{R}^{10\times1}$ is the state vector, $\mathbf{d}(\mathrm{t})$ and $\dot{\mathbf{d}}(\mathrm{t})$ are the displacement and velocity vectors respectively. $\mathbf{A} \in \mathrm{R}^{10\times10}$ is the system matrix, $\mathbf{B}, \mathbf{D} \in \mathrm{R}^{10\times1}$ are the controller distribution matrix and a disturbance vector, u(t) and $\boldsymbol{w}(\mathrm{t})$ are the control input and the wind load respectively . They are given by:

$$\boldsymbol{x}(\mathrm{t}) = \begin{bmatrix} d(\mathrm{t}) \\ \dot{d}(\mathrm{t}) \end{bmatrix}, \ \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{D_1} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ 0.001 * \mathbf{I} \end{bmatrix}$$

$$\mathbf{D_1} = -[\mathbf{32.3766} \quad \mathbf{32.3838} \quad \mathbf{32.8363} \quad \mathbf{39.4036} \quad \mathbf{40.0603}]^{\mathrm{T}}$$

The modal frequencies of this building are found using Bode plot to be 0.2, 0.583, 0.921, 1.182 and 1.348Hz. And the corresponding damping ratios are ranging from 0.01 to 0.03 for the uncontrolled structure.

As shown in figures (1) and (2) the response is unacceptable. Concerning the displacement, it approaches a half meter of vibration, so, the given wind exposure is extremely sever corresponding to the integrity of building cladding system, interior finishes, and operation of elevator system. On the other hand, the acceleration exceeds the given acceptable threshold for the occupant comfort presented in Table (1) [6].

SMC Design

Sliding Mode Control (SMC) is a robust control technique designed for systems subjected to model uncertainties and external disturbances [7]. Within SMC framework a sliding surface is designed in the state space such that all the states of the system are guided toward it and thereafter to be constrained on it. The surface is expressed as a linear contribution of the states:

$$\sigma = \mathrm{S}\boldsymbol{x} \qquad (3)$$

where σ is the switching function, $\mathrm{S} \in \mathrm{R}^{1\times10}$ is the sliding surface.

The desired reduced order sliding dynamics are decided utilizing pole placement approach according to:

P = [-4 -6 -9 -10 -11 -12 -20 -22 -31]

in which P is a vector that contains the desired nine sliding mode poles.

The major SMC signal is given by:

$$u_t(t) = u_c(t) - k_d \operatorname{sign}(\sigma(\boldsymbol{x})) \qquad (4)$$

u_c is responsible for satisfying Liaponuv's reachability condition and is usually expressed as follows:

$$u_c = -SB^{-1}SAx(t) \qquad \ldots (5)$$

Benefitting from the notion of equivalent control u_{eq} in which it is the low frequency component of the overall SMC signal, it is proposed to use a low pass filter such that u_{eq} can be estimated to play the rule of u_c as shown in figure (3). u_d is usually expressed as follows:

$$u_d = -k_d sign(\sigma) \qquad \ldots\ldots(6)$$

In this work the general SMC signal is improved by smoothing the discontinuity function concerning the discontinues control part and filtering the overall SMC signal to yield the continues control part as follows:

$$u_t(t) = \tilde{u}_{eq}(t) - k_d v_\delta(\sigma(x)) \qquad \ldots(7)$$

$$v_\delta(\sigma) = \frac{\sigma}{|\sigma| + \delta} \qquad (8)$$

Let $\delta = 0.05$.

The low pass filter used herein is chosen to be:

$$\tilde{u}_{eq}(t) = \frac{0.01}{s + 0.01} u_t(t) \qquad (9)$$

where $\tilde{u}_{eq}(t)$ is the estimated equivalent control signal, $v_\delta(.)$ is the sigmoid-like function.

The uncertainty gain k_d usually compensates for disturbances and uncertainties and it is obtained by satisfying η- reachability condition of the sliding mode as follows:

$$k_d \geq |(SB)^{-1}SD\mathcal{W} + \eta| \qquad (10)$$

where η is a small positive design scalar, $\mathcal{W}$ is the wind loading expected upper bound as the Conventional SMC (CSMC) suggests. Otherwise k_d can be estimated by using the theory of quasi-steady aerodynamics as the Adaptive SMC (ASMC) suggests and as follows:

$$\widetilde{\mathcal{W}}(t) \approx \frac{1}{2}\ \rho C_D\, b^2\ (\bar{V}^2(t) + 2\,\bar{V}(t)\, v(t)) \quad (11)$$

where ρ is the density of air, C_D is the coefficient of wind drag, *b* is the width of the structure normal to the oncoming wind. $\bar{V}(t)$ and $v(t)$ are the mean wind velocity and the root mean square of its fluctuating component respectively.

Then the SMC signal is dispatched to three MR dampers in the first, third and fifth levels of the building which are located there to have a better distribution of the damping force.

SMC Driven MR damper

An MR damper consists of a hydraulic cylinder containing micron-sized, magnetically polarizable particles suspended in a liquid such as water, glycol, mineral or synthetic oil. The damping capabilities of this device can be quickly varied by changing the viscosity of the MR fluid from viscous to semi-solid through the introduction of a magnetic field. These devices have been used as controllable rotary resistance for programmable aerobic exercise equipment, suspension systems in vehicle seats, and more recently as seismic dampers [8]. The adopted model of the MR damper as presented by T. H. Nguyen et al [3] is:

$$\mathcal{F} = c\,\dot{x}_i + k\,x_i + \alpha\,\mathcal{Z} + \mathcal{F}_o \qquad .\,(12.a)$$

$$\mathcal{Z} = \tanh(\beta\,\dot{x}_i + \gamma\,\mathrm{sign}(x)) \qquad (12.b)$$

x_i is the damper diaphragm displacement corresponding to the ith building level.
$\mathcal{F}$ is the output force.
$\mathcal{Z}$ is the hysteresis function.
$\mathcal{F}_o$ is the damper force offset, $\beta = 0.09$ is a constant against the supplied current values, α is a scaling parameter and c, k are the viscous and stiffness coefficients. These parameters are described as function of the supplied current, *i*, as:

$$c = c_1 i + c_0 = 3.32\, i + 0.78 \qquad (12.c)$$
$$k = k_1 i + k_0 = -i + 3.97 \qquad (12.d)$$
$$\alpha = \alpha_2 i^2 + \alpha_1 i + \alpha_0 \qquad (12.e)$$
$$\alpha = -264\, i^2 + 939.73\, i + 45.86$$
$$\gamma = \gamma_1 i + \gamma_0 = 0.44\, i + 0.48 \qquad (12.f)$$
$$\mathcal{F}_o = h_1 + h_o = -18.21\, i - 256.50 \qquad (12.g)$$

Simulation Results

The response of the wind-excited building to the CSMC driven MR dampers is shown in figure (4) and figure (5).

Obviously the displacement response is 50% reduced using CSMC scheme as compared to figure (1); its ability to guide the states at the first instant toward the sliding surface during a short reaching phase is undeniable and the wind excitations are resisted until t =73s when the wind loading succeeds in exciting the building and take the states out of the surface for a certain amount of time. Actually, the CSMC paid a valuable effort to get the states back as fast as possible to slide again on the surface. The controller associated with the MR dampers made a hard work to provide the necessary damping force to absorb the building vibration during that period.

Each time the building oscillates, the MR damping forces suddenly increase to face the unexpected change in the circumstances, and moreover the controller reaction has to be fast enough to handle the problem, this is intolerably translated in an excessive change in the acceleration which is the measure of human sense to the building vibration. Clearly, the serviceability threshold is rapidly exceeded each time the wind force is stronger; and hence this mode of sliding cannot be accepted.

On the other hand the estimated wind drag force in Eq. (11) is substituted into Eq. (10) such that the discontinuity gain k_d is updated according to the 3 seconds gust speed employed in Eq. (11) such that:

$$u_t(t) = \tilde{u}_{eq}(t) - k_d(t)\, v_\delta(\sigma(\boldsymbol{x})) \quad \ldots(13)$$

And the above ASMC control signal is applied to each MR damper to achieve the optimal damping force and the response of the wind-excited building to the ASMC scheme is demonstrated in figure (6) and figure (7).

Without a doubt it is a satisfactory response, the building stopped shaking, sliding motion is securely continued and the wind loading is finally prevented. The proposed ASMC scheme is very efficient to successfully regulate the system resisting a harsh wind event; the reaching phase is even shorter than that using CSMC and the sliding motion is kept unbreakable. Table (2) summarizes the results of the uncontrolled building, the CSMC driven MR dampers controlled building and the ASMC driven MR dampers controlled building.

Conclusions

In this work the structural vibration control problem of a tall wind-excited building modeled as five levels is investigated. The given 183m tall five levels vertical civil structure is represented mathematically by a tenth order differential equation.

An MR fluid damper is utilized to augment damping to the structural system. This smart failsafe semi-active damper is electrically controlled to provide controllable yield strength without injecting external energy.

At first a conventional sliding mode controller is designed which is based on a fixed predicted wind load to design the uncertainty gain. The adaptive scheme has shown a perfect ability to mitigate the wind excitations quite efficiently while the conventional scheme stumbles whenever the wind loading is stronger, thus it failed to constrain the system states on the surface.

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Table (1): Human perception levels [6].

Level	Acceleration (m/s^2)	Effect
1	< 0.05	Humans cannot perceive motion.
2	0.05 - 0.1	a)Sensitive people can perceive motion; b) Hanging objects may move slightly.
3	0.1 - 0.25	a) Majority of people will perceive motion; b) level of motion may affect desk work; c) Long-term exposure may produce motion sickness.
4	0.25 - 0.4	a) Desk work becomes difficult or almost impossible; b) Ambulation still possible.
5	0.4 - 0.5	a) People strongly perceive motion; b) difficult to walk naturally; c) Standing people may lose balance.
6	0.5 - 0.6	Most people cannot tolerate motion and are unable to walk naturally.
7	0.6 - 0.7	People cannot walk or tolerate motion.
8	> 0.85	Objects begin to fall and people may be injured.

Table (2): The major results of the responses of the wind-excited building.

The building status	X_{1max} (m)	X_{2max} (m)	X_{3max} (m)	X_{4max} (m)	X_{5max} (m)	$\ddot{X}_{4\,RMS}$ (m/s^2)	t_s (Sec.)
Uncontrolled	0.0930	0.1793	0.2523	0.3069	0.3357	0.1741	---
With CSMC-3MR dampers	0.0819	0.1506	0.2119	0.2524	0.2816	0.191	23, 136
With ASMC-3MR dampers	0.040	0.00813	0.0115	0.015	0.018	0.0762	20

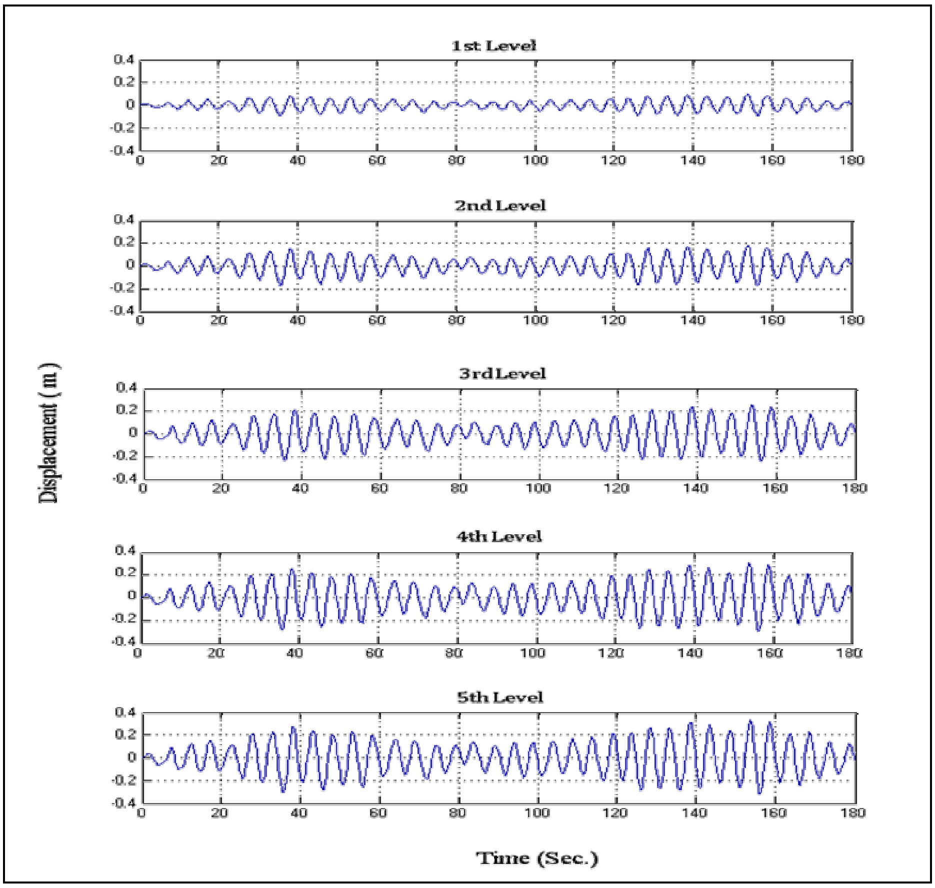

Figure (1): Displacements of the five levels of the building.

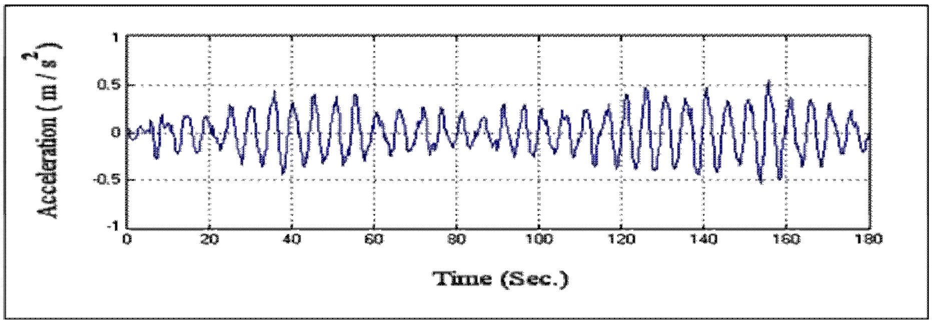

Figure (2): The acceleration of the fourth level of the building.

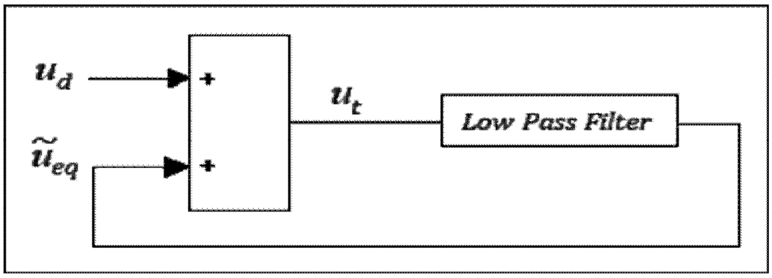

Figure (3): An estimation of the equivalent control.

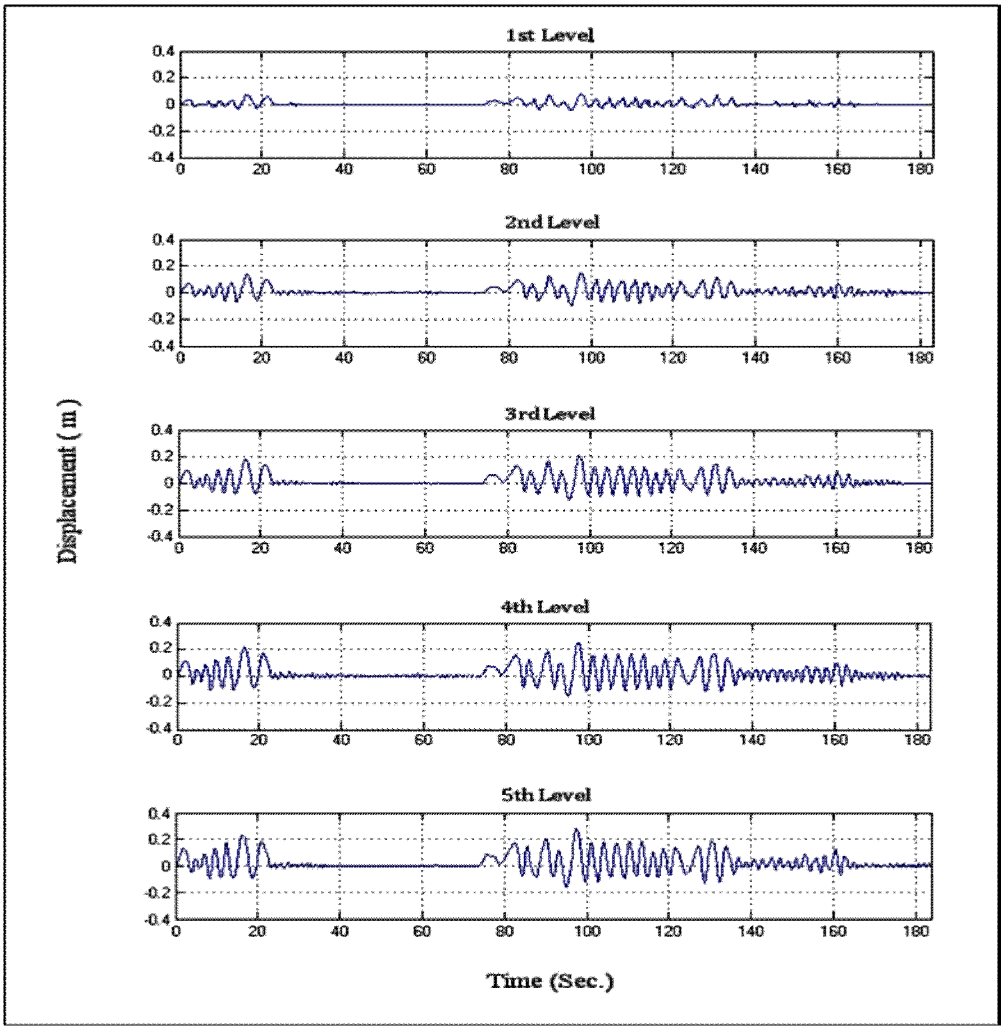

Figure (4): The levels' displacements using CSMC-3 MR dampers.

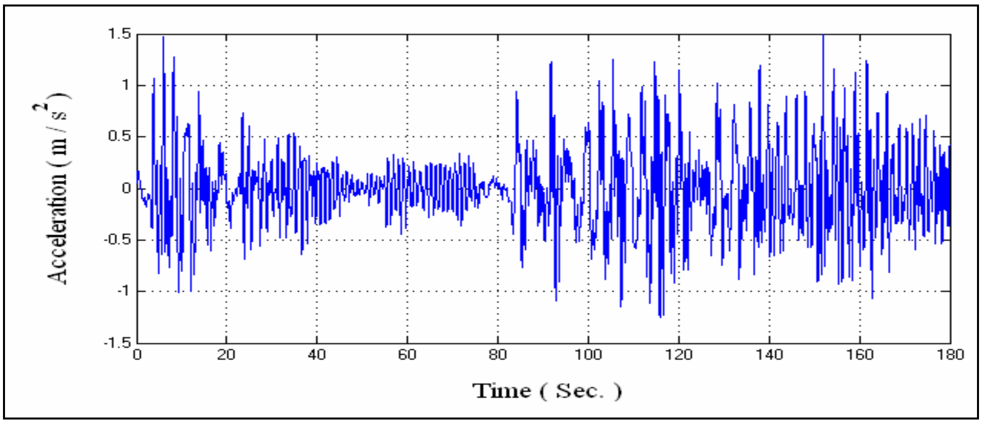

Figure (5): The fourth level acceleration using CSMC-3MR dampers.

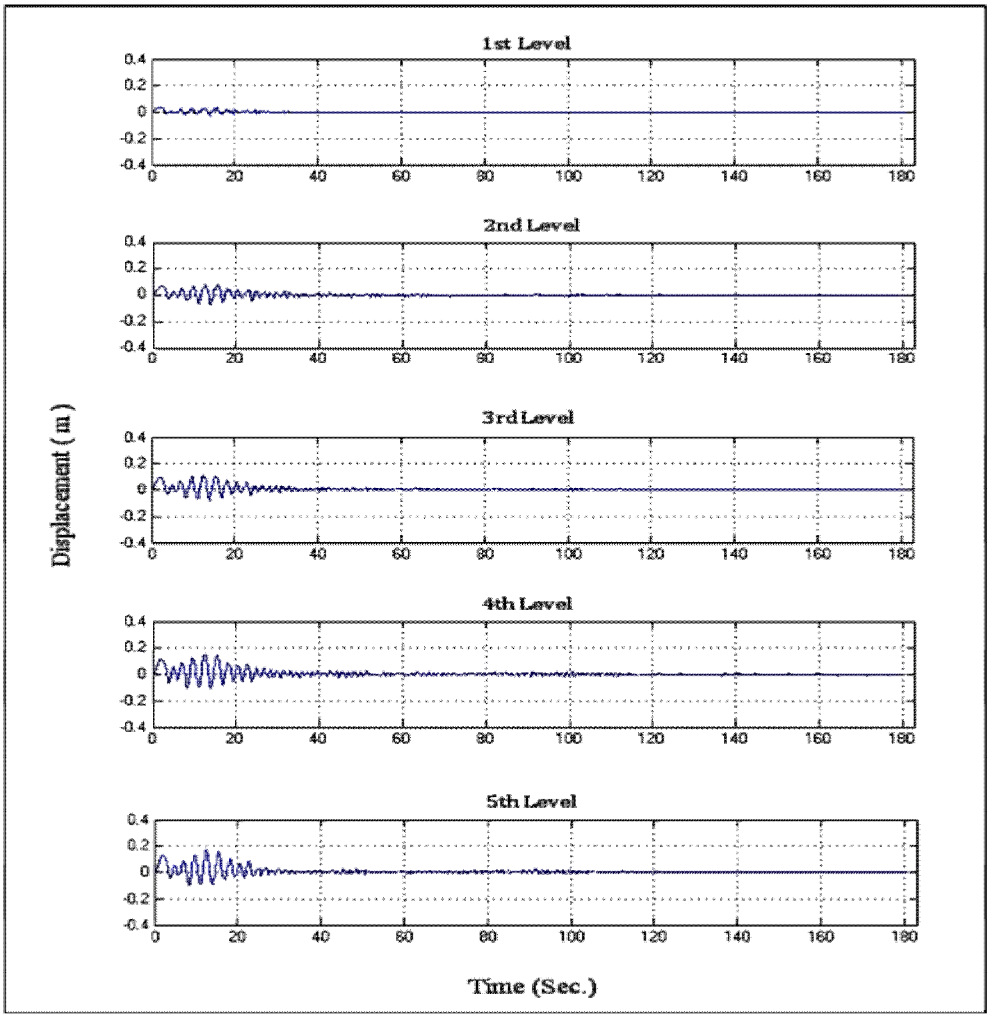

Figure (6): The Stories displacements using ASMC-3 MR dampers.

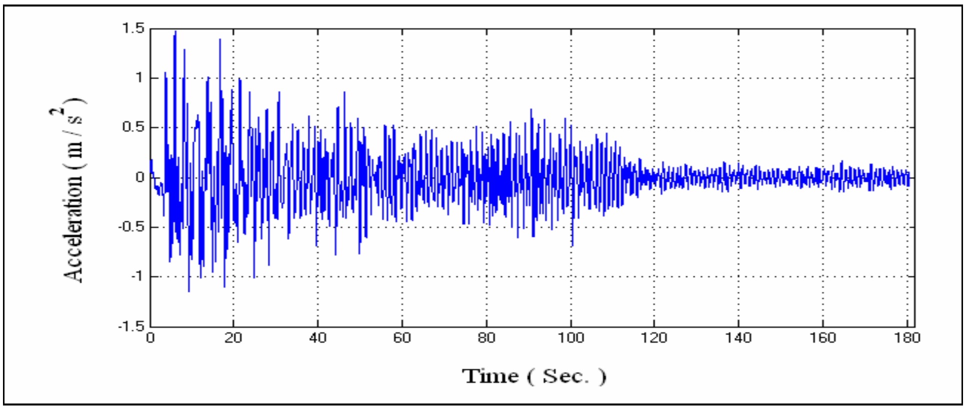

Figure (7): The fourth level acceleration using ASMC-3MR dampers.

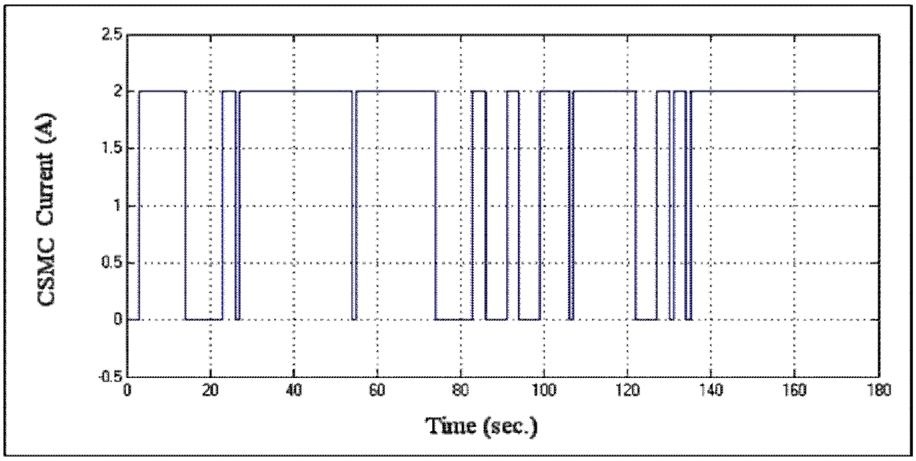

Figure (8): The input CSMC signal to each damper.

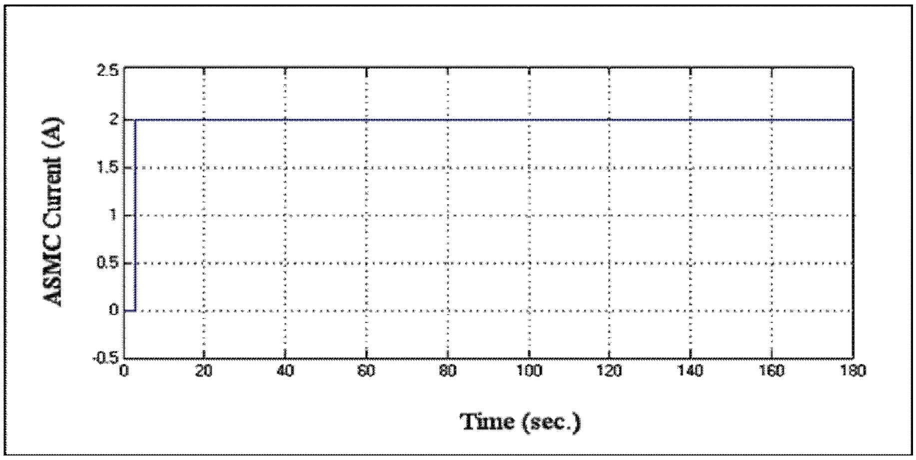

Figure (9): The input ASMC signal to each MR damper