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HIGH-RISE BUILDINGS UNDER EARTHQUAKE EXCITATION: STABILIZATION BY SLIDING-MODE CONTROL

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Abstract. *Controlling the dynamics of high-rise buildings either to ameliorate the damage or prevent their destruction when subject to an earthquake excitation has been subject of extensive research. All known control designs have advantages and disadvantages as well as operating limits. The application of sliding-mode control to controlling earthquake induced vibrations of a multi-story structural system as an active seismic compensation plus base isolation has been investigated. The achieved performance has been compared to the one of traditional industrial controls, and relevant conclusions drawn. Results of simulation experiments, carried out using El Centro earthquake acceleration, have shown that the sliding mode control can decrease significantly displacements of the floors.*

Key words: *Earthquake; sliding mode control; structural systems; vibration control*

1. INTRODUCTION

The considerable research in controlling the dynamics of high-rise buildings and other structures alike in order either to ameliorate or prevent their destruction when subject to an earthquake excitation has been going on for quite some time. A number of models of high-rise building (HRB) dynamics as well as control techniques have been developed and also experimental and full-scale implementations curried out. All known control designs have advantages and disadvantages as well as operating limits (Lynch and Law, 2002; Schlacher et al., 2001; Spencer and Sain, 1997). The focus of the present study is put on using sliding

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mode control method to stabilize high-rise buildings in events of vibrations caused by a strong earthquake excitation, thus enabling them to resist such a natural disaster.

The structural plant used in this investigation on stabilization control design and the performance of the overall control system (Figure 1) is a four-degrees-of-freedom (4-DOF) benchmark model of a high-rise building structure (Figure 2-b). It is consisted of a basement, with mass m_0, and 3 storeys, with masses m_1, m_2, m_3. From systems and control point of view, apparently high-rise building structures represent interconnected large-scale mechanical systems such that for controlling their vibrating motion the decentralized control of large-scale mechanical systems (Vukobratovic and Stokic, 1984; Siljak, 1991) is a naturally appealing control strategy. Yet, it will be shown, an alternative departure on the grounds of plant's physical background and the concept of active mechanical systems (Vukoratovic, 2004) such a large-scale system is amenable to successful control (Dimirovski et al, 1994) beyond the decentralized feedback (Siljak and Zecevic, 2005)

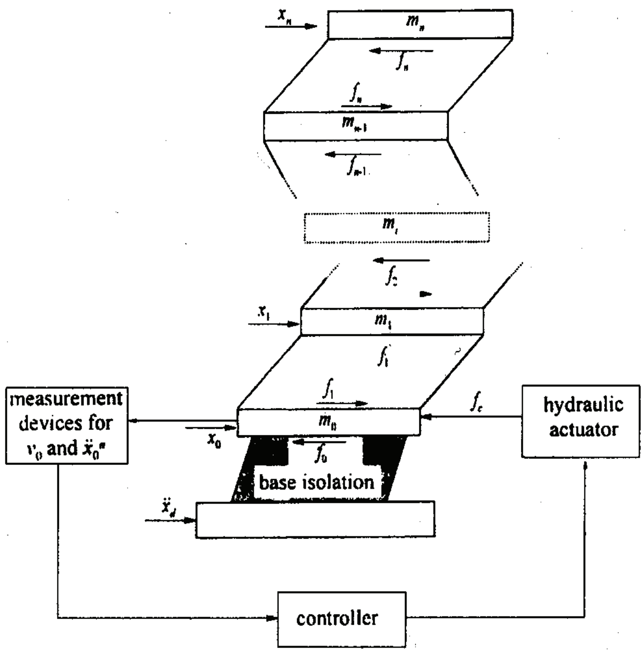


Fig. 1 A schematic diagram of the control system architecture for high-rise buildings.

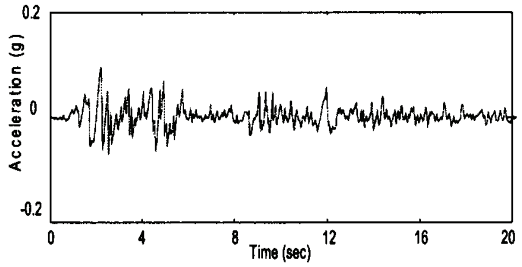
Under earthquake excitation, the benchmark structure for high-rise buildings in Fig. 1 has its four degrees of freedom in the lateral horizontal direction. The investigation of the structural control problem was carried out by using both stochastic El Centro (see Figure 2-a) and step disturbance inputs at the building's base. A couple of variable-structure system (VSS) sliding mode controls (SMC) have been separately designed using a linearized model of the observed 4-DOF; for comparison a conventional PID control (omitted in here) was designed too.

Further this article is written as follows. In Section 2, there are rather briefly recalled certain important facts on the physics of the vibrating motion of high-rise buildings.

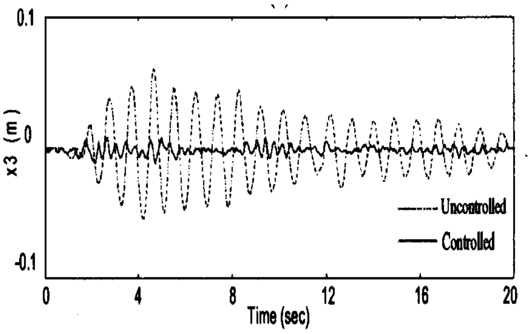
Thereafter Section 3 presents the main theoretical and modeling points of the sliding-mode control methodology and the respective design approach applied in the research tasks of this study. In Section 4, there is presented a characterizing selection of the obtained results in the simulation experiments carried out by using the benchmark El Centro earthquake acceleration, which demonstrated the achieved high performance in suppressing the earthquake induced vibrations in high-rise buildings.

2. Control System And Physics Of High-Rise Building Vibrating Motion

The control system architecture (Fig. 1), essentially being a feedback one, must remain asymptotically stable in the closed loop in the event of structure vibrations caused when an earthquake such as the famous El Centro excitation may strike the building (Fujino et al., 1996). The task of structural control is a typical stabilization control problem aimed at active compensation of the externally induced vibrating motion of the building (Dimirovski and Zhao, 2006). These control systems are supposed to be employed as active seismic compensation and isolation devices for structures with multiple degrees of freedom of motion and inbuilt passive base isolation (see Figures 1 and 2-b). In their essence, in fact, these are active systems (Vukobratovic, 2004).



(a)



(b)

Fig. 2 Recorded El Centro earthquake acceleration with a PGA of 0.1g (a) used in simulations; the uncontrolled and SCM stabilization controlled displacement responses at the 3-rd storey (b) under El Centro earthquake excitation stroke.

The tuning of the control designs, however, was carried out primarily with a disturbance input, representing El Centro earthquake with PGA 0.1 g (Fig. 2-a) and applied to the base as happens during natural earthquake events. The performance assessment was also carried out using step disturbance at the building's base of magnitudes 1, 5, and 10 kN. The simulation results showed high attenuation of the consequence displacement effects as seen in Fig. 2-b.

On the other hand, the linear PID control is indeed an appealing conventional method of structural control too because of its great pragmatic importance (Dimirovski et al., 1994; Fujino et al., 1996; Lynch and Law, 2002; Soong et al., 1987; Spenser and Sain, 1997). However, it is also well known that PID controls cannot cope with parameter changes and model uncertainties. Yet high-rise building (HRB) models may well have uncertainties and/or parameter changes, and even more so is the case with external forces induced by earthquakes (Housner at al., 1994; Spencer and Sain, 1997; Schlacher et al., 1997). Sliding mode control strategy (Drakunov and Utkin, 1992; Fillipov, 1960, 1961; Utkin, 1974, 1977), which was proven to possess an inherent robustness, should perform superior in HRB control as in many applications (Dimirovski and Zhao, 2006). Besides, this control method can be equally well applied to both linear and non-linear structural systems as an alternative to other proposed methods of structural control (e.g., see Aldemir et al., 2001; Guenfaf et al., 2001; Schlacher et al., 2001; Yang et al., 1992 a, b).

In time, there have been developed many technical ways to controlled seismic energy dissipation and damping the earthquake induced vibrations in HRBs. The active structural control (Fujino et al., 1996; Vukobratovic, 2004) has emerged as a potential technology for enhancing structural functionality and structural safety of civil engineering structures against natural loads of an earthquake. From the control point of view, it has been shown that vibrating motion processes in an exogenously induced vibrating motion of real-world HRBs are characterized in terms of the complexity of constraints on displacements, velocities and accelerations (Dimirovski et al, 1994; Housner et al, 1994; Spencer and Sain, 1997; Schlacher et al, 2001). From the point of view of energy, during the vibrating motion induced by an earthquake, the lateral inertial forces are induced in the structures causing vibrations with amplitudes depending on the input energy. If a large part of this energy can be dissipated during the motion of the structure, the seismic response can be reduced considerably hence the possible damage to an economically acceptable level.

The benchmark HRB (planar model diagram for lateral vibrating motion depicted in Fig. 1) is assumed to have masses concentrated on the respective floors; variables x_0, x_1, x_2 and x_3 represent their lateral displacements. Following the sensor-actuator collocation principle, springs and dampers are assumed to be acting in horizontal direction of lateral vibrating motion, and two dynamic actuators are installed between the ground and first floor. The information coded in the energy equation indicates the technical ways of controlled dissipation of energy due an earthquake excitation, hence the importance of adequate implementation of control designs, a point largely overlooked until the late 1990s (Spenser and Sain, 1997; Schlacher et al., 2001).

A building structure in vibrating motion has the following energy balance equation:

$$E_i = E_k + E_s + E_v + E_h \,. \tag{1}$$

Here, E_i is the input energy due to the displacement of the ground under HRB foundation caused by earthquake acceleration (e.g., El Centro, Fig. 2-b), E_k denotes the kinetic energy, E_s represents the elastic strain energy, E_v is the viscously dissipated and E_h the hysteretically dissipated energy. The essential difference between E_v and E_h lies in the fact that the hysteretic dissipation is attained by deformation, while viscous dissipation is attained by velocity. Active structural control enhance the dissipation of the input energy by counteracting with controlled actuators, however, it has been found crucial that the passive means of base isolation (Fig. 1) be implemented beforehand (Spenser and Sain, 1997; Schlacher et al., 2001), and it is assumed to be built in. Thus the problem reduces to the design and implementation of efficient stabilization control that can be practically employed to suppress the lateral vibrating motion of the HRB induced by earthquake. For this to be feasible, the closed-loop asymptotic stability has to be guaranteed with employed either continuous (e.g., Dimirovski et al., 1994; Schlacher et al., 2001; Yang et al., 1992) or switching operating modes (Liberzon and Morse, 1999; Zhao and Dimirovski, 2004).

The traditional conceptual model of high-rise building vibrations, representing lateral planar displacements of its stories caused by exogenous forces from the environment such as an earthquake, is considered in here (see Fig. 1); it is most often used in studies on structural control (Fujino et al., 1996; Housner et al., 1994; Soong et al., 1987). As shown in the literature cited, it can be idealized by an n degree-of-freedom linear dynamic system model that is subjected to a vector of environmental load forces, $v(t)$ and a vector of some control $u(t)$ forces, possibly. The mathematical representation model of the dynamics of such a structure, i.e. equation of motion in the state space in matrix-vector form, is given as follows:

$$M\ddot{x}(t) + D\dot{x}(t) + Kx(t) = Cu(t) + Ew(t)\,. \tag{2}$$

Symbols in here denote the following variables and coefficients of building's physical parameters: $x(t)$ is the n-vector of displacements relative to the ground; M, D, K are $n \times n$ matrices of mass, damping and stiffness, respectively; C is a $n \times m$ location matrix of control forces; $u(t)$ is a m-vector of controls; E is a $n \times r$ location matrix of external load forces from the proximity environment; and $w(t)$ is a r-vector of environmental forces. Upon adoption of the state vector as the $2n$-vector of displacements and velocities

$$z(t) \mathrel{\hat{=}} [x(t) \quad \dot{x}(t)]^T \tag{3}$$

the equation of motion is readily converted into the standard state equation model

$$\dot{z}(t) = Az(t) + Bu(t) + W_E w(t) \tag{4}$$

in the augmented state space defined by (3). In here: $z(t)$ is the $2n$-state vector of displacements and velocities; $A = [a_{ij}]$ is a $2n \times 2n$ system state matrix; $B = [b_{il}]$ is a $2n \times m$ system control matrix; and W_E is a $2n \times r$ system disturbance matrix. These system matrices are found to be given as follows:

$$A = \begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}D \end{bmatrix}, \tag{5-a}$$

$$B = \begin{bmatrix} O \\ M^{-1}C \end{bmatrix},\ W_E = \begin{bmatrix} O \\ M^{-1}E \end{bmatrix}. \tag{5-b}$$

The above class of linear dynamic models is employed to represent the local dynamics of HRB vibrating motion for the area of structural control problems in either civil or mechanical engineering.

3. Sliding-Mode Control Methodology And Control Design

3.1. Some Essential Remarks on Sliding-Mode Control Method

It is well know that sliding-mode control (SMC) systems belong to the class of variable structure (VSS) systems with control embedded. In essence, a VSC implements several different continuous control functions that map plant state to a control surface while the switching among different functions is determined by the plant state. In fact, SMC systems employ a particular type of VSS controllers that are designed to implement controlled drive towards and then confinement of the dynamics within a neighborhood of the switching function (Drakunov and Utkin, 1992) thereby guiding the closed-loop dynamics to the desired equilibrium of the plant. That switching function is employed in the control law. Hence, the overall system dynamics becomes governed by a class of differential equations with discontinuous right-hand sides the basic theory of which was first developed and applied to nonlinear control problems by Filippov (1961). The actual design consists of two complementary parts, in principle (Drakunov and Utkin, 1992; Slotine and Li, 1991; Utkin, 1974). The first one involves designing a switching function so that the sliding motion satisfies design specifications. The second part deals with the selection of a control law that will make the switching function attract the system state on a hyper-surface leading to the desired equilibrium state.

3.2. Considerations of the Sliding-Mode Control Design

The design of a sliding mode controller is considered on the grounds of the following system model

$$\dot{z}(t) = A[z(t) - z_d] + Bu(t) + f(z,u,t) \,, \tag{6}$$

which also includes model (4) and is suitable for local vibration dynamics of high-rise buildings (2). In (6), z_d is the desired reference trajectory and $u(t)$ is the control input to the plant. Theory of sliding-mode control suggests a possible choice of the sliding-mode controller structured as follows:

$$u(t) = -k_c \operatorname{sgn}(s(t)) + u_{eq} \,. \tag{7}$$

Quantities in (7) denote: u_{eq} is the so called equivalent control when the system state is in sliding mode based on Filipov's equivalent dynamics (Filippov, 1961); coefficient k_c represents the maximum controller gain; variable $s = s(t)$ is called switching function because the control action switches its sign on the two sides of the switching surface $s(t) = 0$. The term sgn(·) is the function

$$\operatorname{sgn}(s) = \begin{cases} +1, \; \mathit{if}\; s < 0, \\ -1, \; \mathit{if}\; s > 0. \end{cases} \tag{8}$$

In this application, the switching surface is generated by means of the equation

$$s(t) = \dot{e}(t) + \lambda e(t), \; e(t) = [z(t) - z_d] \tag{9}$$

although, to begin the design investigations, one can choose (Utkin, 1974) the hyperplane

$$s(t) = c^T z(t) \tag{10}$$

with vector c subject to design selection. In Eq. (9), z_d is representing the desired trajectory, and λ is a constant that impacts the asymptotic stability of desired equilibrium. The desired state trajectory z_d the considered stabilization control problem is represented by a constant of the desired asymptotically stable equilibrium, e.g. almost zero vibrations. In here, the definition of $e(t)$ requires that k_c in (7) be positive.

In essence, the sliding-mode control strategy defined by Eqs. (7)-(8) is actually performing like the ideal relay or bang-bang control law. (*Remark*: Recall that such control law can globally stabilize the second-order dynamics of a simple servomechanism or vibrating beam.) For k_c large enough, the adopted SMC strategy is known to guarantee that, from any initial state condition, a system trajectory shall move toward and stay on the sliding surface s=0 provided the sliding condition is satisfied :

$$s(t)\,\dot{s}(t) \le -\eta\left|s(t)\right|, \tag{11}$$

In here, η is a strictly positive constant. Further, this sliding condition guarantees system trajectories will hit the sliding surface in a finite time. In fact, given the system dynamics while in sliding mode, $\dot{s} = 0$, and sliding surface (9) (8) together with the re-written sliding condition (11) in the form $(1/2)d(s^2(t))\,/\,dt \le -\eta\,|\,s(t)\,|$ show that the choice of control law $u(t)$ as defined by (7) ensures that $s^2(t)$ remains a Lyapunov-like function of the closed-loop system, despite the plant model imprecision and the acting disturbances.

Nonetheless, the fact that control law must be discontinuous across sliding surface $s(t)$ inevitably causes the *chattering* phenomenon pertinent to SMC systems because the implementation of the associated control *switching* is imperfect always. This is unacceptable in many practical applications and it must be attenuated to the bare minimum. The same is required in the case of high-rise buildings where high-power actuators have to be employed (such as the electro-hydraulic ones) albeit these all perform as low-pass filters. In order to remedy this situation, one possible approach is to introduce a boundary layer around the switching surface. One way of doing this is equation (7) be modified to a suitable saturation function approximation. Then it becomes apparent such a ‘sliding-mode’ controller employing saturation is actually performing a continuous approximation of the ideal relay control.

It is within this framework of approximation re-thinking that a better feasible sliding-mode structural control synthesis is found by making use of

$$u(t) = -k_c \tanh(s(t)/b) + u_{eq} \tag{12}$$

(Fig. 3) in terms of an approximating control law. Given the previously discussed sliding-mode controllers above, it may be inferred this is only another variant of the same. However, the current research showed the approximating SMC control law (11) along with (12), despite the approximation, enables much better implementation of SM controllers than the previous saturation based one, which can be tuned to be rather close to the original one Eqs. (7)-(8)-(11).

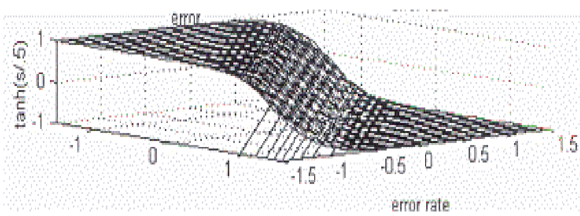


Fig. 3 Corresponding control surface of SMC-VSS controller approximations (12).

Further, it is known from the simple case of closed-loop performance with the second-order dynamics that all discussed SMC-VSS controllers can guarantee the asymptotic stability provided gain design for k_c is properly chosen and large enough, and if the sliding-mode condition is satisfied. The latter, however, due to the approximation character of laws (12) and (11) relative to the original SMC low (7) and (11), has to be additionally investigated and shown not violated. In each given practical case, this can be done via simulation investigations. In this conceptual design scheme, the system robustness becomes a function of the width of the boundary layer, which may be observed as an additional design parameter. However, the lost of the invariance property (Draxenovic, 1969; Utkin, 1974, 1977) of the sliding-mode variable-structure control system may well appear to be and unacceptable consequence of this control scheme. Alternatively, the theory of quadratic stability of switching systems (Zhao and Dimirovski, 2004) has to be used to ensure practical asymptotic stability in the closed loop. In either case, an appropriate careful simulation investigation of the design has to be carried out and verified at a laboratory-scale model (Dimirovski et al, 1994).

4. Simulation Results With A 4-DOF Building Structure

The recommended test earthquake excitation used was the celebrated acceleration record of El Centro earthquake with PGA of 0.1, and the desired equilibrium state is $z_d = 0$ the origin of the space of lateral displacements. The mathematical representation model of this HRB structural system has been simulated for two cases of a striking excitation force: the case of 10 kN as a step input to the base and the case of El Centro excitation with a PGA of 0.1g (being applied at the fifth second following the initial equilibrium state). One of the simulation results was shown in Figure 2-b.

Figure 4 and Figure 5 present the characterizing set of the obtained simulation results. Time-histories of displacement responses at the first and third stories for the uncontrolled (i) and for SMC stabilization controlled (ii) 4-DOF building plant are depicted in Fig. 4. Simulation confirmed the experiments showing the evolution of the 3rd-storey displacement, $x_3(t)$, for uncontrolled and SMC controlled HRB model, Figure 5 (a3)-(b3). These are jointly superimposed for apparent comparison presentation; for the uncontrolled building, the pick responses amounted 6.34, 4.85, and 2.19 cm at the 3rd, 2nd, and 1st floors, respectively, and for the SMC controlled building corresponding values are 0.96, 0.56, and 0.79 cm, respectively.

The respective physics behind this control performance can be better understood should frequency responses are also examined. Figures 5 show the respective frequency responses of both the 1st and the 3rd storeys for uncontrolled and SCM stabilization controlled building, in a superimposed manner, for apparent comparison. The actual ranges of frequency spectra remain very much the same; however frequency response amplitudes are considerably different between the uncontrolled and controlled HRB. Not unexpectedly, the differences in the frequency domain between the cases of PID and SMC controlled building have become rather apparent.

In order to study further the potential of the design and implementation of SMC stabilization of HRB structures, an insight into switching function and control chattering is presented next. The present findings with respect to approximation of the switching function and the respective effects on the SMC generated control signal, respectively, can be inferred from the result in Fig. 6. All these are rather characteristic sample results that were found in an iterative way, via fine tuning of the available design parameters in Eq. (12) and through a comparison analysis. It should be noted, since SMC controlled structure becomes governed by an essentially nonlinear dynamics in closed loop, the SMC control system rightly possesses superior performance. Hence the SMC stabilization system, along with the base isolation, fulfils rather well the main control objective in earthquake resisting building structures.

It should be noted though some improvement of the lateral displacements has been also achieved by appropriate tuning the PID control law, in particular weakening the resonant picks. Nonetheless, this research has once more demonstrated that the non-linear control laws have by far greater potential than the linear ones. Nonetheless, it should be

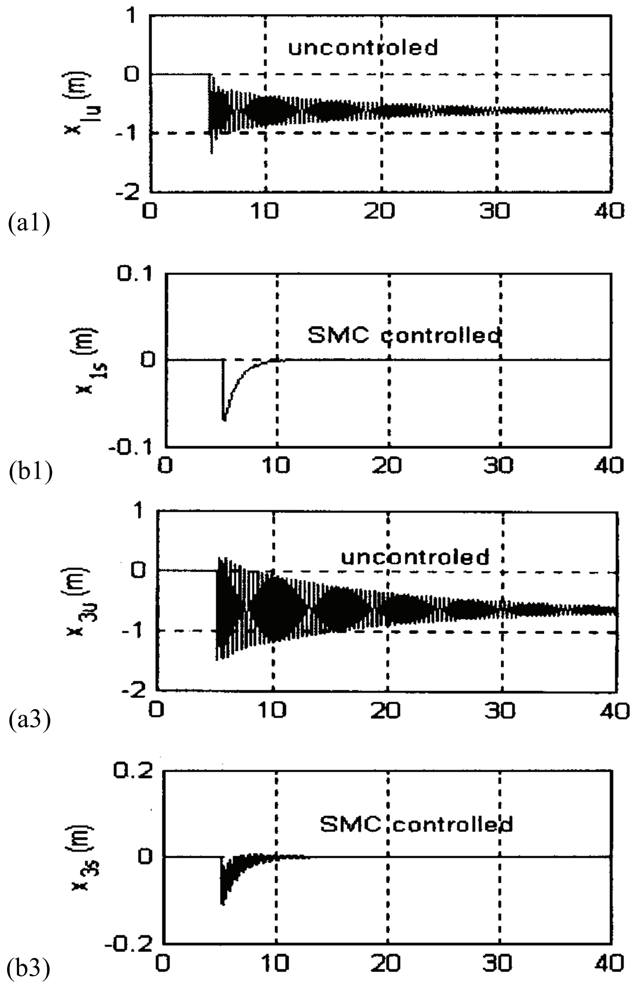
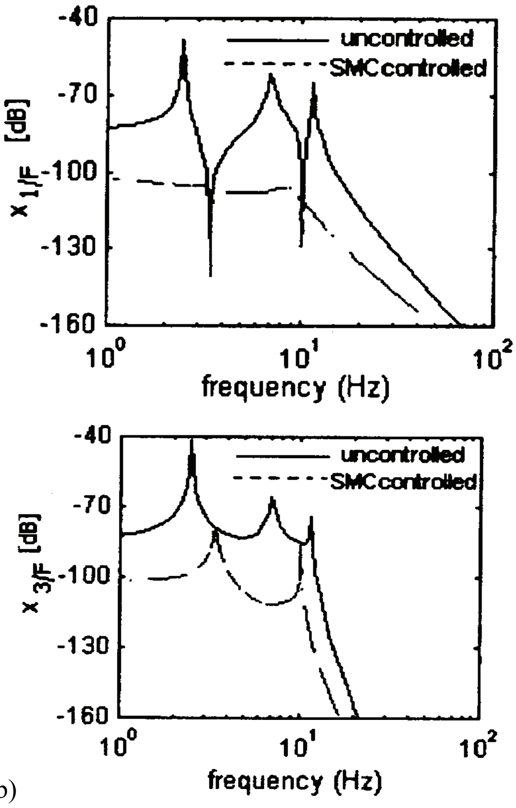


Fig. 4 Stabilization performance of the 4-DoF benchmark HRB: The 10kN step-disturbance (into building base) responses of the uncontrolled versus the SMC stabilization controlled displacements at the first and the third storeys in the time domain.



(a)

(b)

Fig. 5 Stabilization performance of the 4-DoF benchmark HRB: uncontrolled versus SMC controlled displacement responses at the first and the third storeys for 10kN step disturbance to the base in the frequency domain.

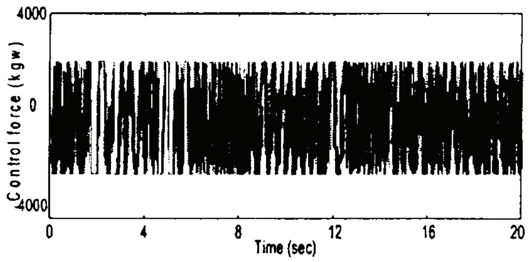


Fig. 6 SMC stabilization of 4-DoF benchmark HRB: Time responses of the switching control force applied.

noted the issues of their maintenance and tuning are more complex and involved to understand by the standard maintenance personnel; they would prefer the traditional industrial control laws. Yet, this issue aspect is outside the scope of the present research.

5. Conclusion

The sliding-mode control design for a benchmark 4-DOF building problem was investigated using the approximation (12) of the SMC strategy, thus enabling a kind of smoothing confinement of state trajectories within a boundary layer around the switching surface during the transients. The smooth approximation of SMC law implies replacing function sgn(·) with function tanh(·), which theoretically may well affect the well known invariance condition in sliding-mode control. Hence additional investigation was carried out to confirm the asymptotic stability was preserved.

The SMC strategy has been explored for the conceptual control system architecture with actuators between the zero-th and the first floor in the presence of passive base isolation in the basement. Results of the simulation experiments were obtained by using El Centro earthquake acceleration. These have demonstrated that the SMC strategy can reduce 6-7 times the displacement of the top third floor compared to that of uncontrolled HRB, which is by far superior to the 2-3 times when the conventional PID law is employed. The chattering phenomenon was also investigated and found to be reduced to an acceptable level for the tentative actuators to be employed in structural engineering.

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VISOKE ZGRADE POD POBUDOM ZEMLJOTRESA: STABILIZACIJA UPRAVLJANJEM SA KLIZNIM MODUSOM

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Upravljanje dinamike visokih zgrada bilo za ublažavanje oštećenja ili za sprečavanje njihovog razaranja kada su podlžne na zemljotresnu pobudu bilo je predemet obimnih istraživanja. Sva poznata projektovanja takvih upravljanja poseduju kako prednosti tako i nedostatke. Ovde se istražuje primena upravljanja sa kliznim modusom za upravljanje zemljotresno pobudjenih vibracija u višespratnoj zgradi kao sistem sa aktivnom kompenzacijom plus izolacija gradjevinske baze. Postignute performance su uporedjene sa onima iz tradicionalnog industijskog upravljanja. Rezultati simulacionih eksperimenata, sprovedenih sa upotrebom registrovane akceleracije cuvenog zemljotresa El Centro, su pokazale da upravljanje sa kliznim modusom moze značajno smanjiti pomeranja spratovima zgrade.

Ključne reči: *zemljotres; upravljanje sa kliznim modusom; strukturni sistemi; upravljanje vibracija*