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Semi-active control of seismically excited structures with variable orifice damper using block pulse functions

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Abstract. The present study aims at proposing an analytical method for semi-active structural control by using block pulse functions. The performance of the resulting controlled system and the requirements of the control devices are highly dependent on the control algorithm employed. In control problems, it is important to devise an accurate analytical method with less computational expenses. Block pulse functions (BPFs) set proved to be the most fundamental and it enjoyed immense popularity in different applications in the area of numerical analysis in systems science and control. This work focused on the application of BPFs in the control algorithm concerning decrease the computational expenses. Variable orifice dampers (VODs) are one of the common semi-active devices that can be used to control the response of civil Structures during seismic loads. To prove the efficiency of the proposed method, numerical simulations for a 10-story shear building frame equipped with VODs are presented. The controlled response of the frame was compared with results obtained by controlling the frame by the classical clipped-optimal control method based on linear quadratic regulator theory. The simulation results of this investigation indicated the proposed method had an acceptable accuracy with minor computational expenses and it can be advantageous in reducing seismic responses.

Keywords: semi-active control; variable orifice damper (VOD); block pulse function (BPF); clipped-optimal control; linear quadratic regulator; seismic response

1. Introduction

Safety of structural systems against critical loads, including seismic excitations and wind force is one of the most important matters in the life cycle of a building. Current limitations on structural design, such as low materials, damping and vulnerability against dynamic excitations because of the fixed properties, made researchers to find new strategies for designing structures. Among the various strategies, passive, active and semi-active control seem to be better methods of preventing damage in structures subjected to dynamic loads (Casciati, Rodellar *et al*. 2012). Therefore, over the last four decades, extensive research has been targeted by control researchers from both theoretical and experimental points of view. Structural control strategies are materialized by special devices which are added to the structure to reduce the structural response and fulfill multiple objectives. The concept of employing structural control to minimize structural vibration

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instead of the conventional techniques of strengthening the structural members was first suggested in the 1960’s and 1970’s (Kobori and Minai 1960, Yao 1972). Passive control system devices usually dissipate energy by means of friction, viscosity and may also stiffen the building, hence reducing the inter-story drifts (Cimellaro, Lavan *et al*. 2009). Passive control devices are inadequately compatible to ever-changing external excitation since they do not sense excitation and response, so that in many cases active and semi-active control have been considered for structural applications. Numerous active and semi-active devices have been proposed and studied by researchers (Cha, Zhang *et al*. 2013). Active control systems promise to effectively minimize structural responses. This control system relies on external power sources to operate actuators generating control forces and require routine maintenance (Ghaffarzadeh 2013). Semi-active control systems are fully-fledged passive control systems that are intelligent and adaptable to variations of dynamic loads. Besides, in semi-actively controlled systems, external energy is not applied into the system as active systems. Therefore, they do not require a large power source, and semi-active devices always assure control stability when inserted into structures. As a conclusion semi-active control devices provide some of the best features of both the passive and active control systems. Many of this control system devices can be operated by a battery when the main power system fails during the seismic events (Bitaraf, Barroso *et al*. 2010). Among many semi-active control devices, the variable orifice damper is the common hydraulic device which may be utilized within the lateral bracing of a building. It provides an adaptable damping force by changing the size of the orifice through which a viscous fluid flows when a piston moves in a hydraulic cylinder (Ghaffarzadeh, Dehroud *et al*. 2013). A full-scale VOD in a semi-active variable stiffness system was implemented to investigate semi-active control at the Kobori research complex (Kamagata and Kobori 1994). Spencer and Nagarajaiah (2003) report that near 800 semi-active variable orifice fluid dampers have been installed in building structures in Japan. Block Pulse Functions (BPFs) have been widely studied and used as a basic set of functions for signal characterizations in controlled systems (Bouafoura, Moussi *et al.* 2011). They have been proved to be the most fundamental set and have gained much popularity in diverse applications in the area of control systems. In structural active control a new method proposed based on BP functions evolves minimizing computational costs of analytical approaches (Ghaffarzadeh and Younespour 2014). Optimal control of distributed parameter systems via BP transform where discussed by Zhu and Lu (1988). Ghaffarzadeh and Younespour (2015) proposed an equivalent linearization method for deterministic excitation based on BP transform. In comparison with other basic functions or polynomials, the BPFs can result more readily to recursive computation in order to solve specific problems. It is important to develop efficient control force schemes for optimizing the performance of the variable damper to work effectively. A variety of semi-active control algorithms have been proposed for control of semi-active devices such as the clipped-optimal algorithm (Dyke, Spencer *et al.* 1996), optimal controllers (Yoshida, Dyke *et al*. 2002), decentralized bang-bang, maximum energy dissipation (Jansen and Dyke 2000) and others. These mathematical-based analytical methods are much more reliable schemes to determine the control forces that are generated for reducing seismic hazard.

The main objective of this study is the implementation of BPFs in semi-active vibration control of structures. The BPFs and their attributes are then presented in order to discuss formulation of BPFs for structural control. For detecting the required control forces during an earthquake, the feedback gain matrix is needed. The analytical proposed method for calculating feedback gain matrix by BPFs is presented. The moral of this story is that to propose an analytical control scheme for semi-active control based on BPFs to reach minor computational expenses. The feasibility of the proposed method is verified by numerical simulations for a building frame equipped with VODs. The uncontrolled and controlled responses of the structural system are obtained by the proposed method and compared to clipped-optimal control method results. Simulation results show that the newly proposed method is effective in reducing seismic responses of the building for selected earthquakes. Additionally, the effectiveness of the proposed method of response reduction in earthquake excitation is evaluated by comparing the controlled response against the results obtained from the uncontrolled case.

2. Variable orifice damper

Control strategies based on semi-active devices appear to combine the best features of both passive and active control systems. More attention received in this area in recent years can be attributed to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources. In fact, many of semi-active devices can operate on battery power, which is critical when a seismic load apply and the main power source to the structure may fail. One means of achieving a semi-active damping device is to use a controllable, electromechanical, variable orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. The variable orifice damper consists of a fluid viscous damper combined with a variable orifice on a bypass pipe containing a valve in order to control the reaction force of the device. A schematic of VOD is given in Fig. 1. The damping characteristics of a variable orifice can be controlled between two damping values (The device provides low damping when the secondary orifice is completely opened and the damping capacity of the damper is maximized when it is completely closed) by varying the amount of flow passing through the bypass pipe from one chamber of the piston in the other. In the intermediate positions of the valve opening process, the device produces a specific damping dissipation. The adjustment of the valve can be made usually electromechanically.

Sack and Patten (1993) conducted experiments in which a hydraulic actuator with a controllable orifice was implemented in a bridge to dissipate the energy induced by vehicle traffic, followed by a full-scale experiment conducted on a bridge to demonstrate this technology (Patten, Sun *et al.* 1999).

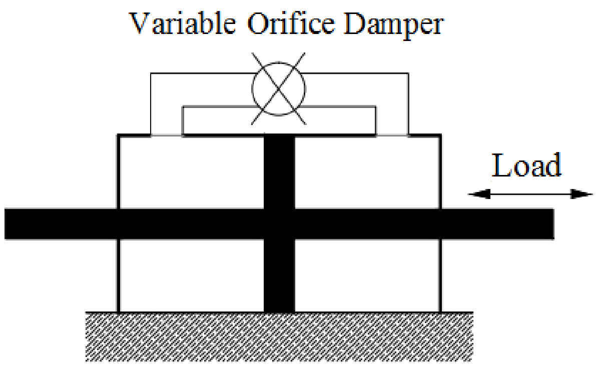

Fig. 1 Schematic of Variable-Orifice Damper

A case study of variable orifice dampers for seismic protection of structures was studied by Luca and Pastia (2009). They concluded that the variable orifice damper is more effective in reducing the displacement response of a SDOF system more in comparison to the response with a passive control fluid device.

3. Block pulse functions

BPFs are a set of orthogonal functions with piecewise constant values and are usually applied as a useful tool within the analysis, identification and other problems of systems science. Also BPFs can be used in control system engineering for analysis and synthesis of dynamic systems. Studies show that BPFs may have definite advantages for problems due to their explicit expression and their simple formulations. Because the BPFs are orthonormal function, in comparison with other basis functions, the block pulse functions can lead more easily to recursive computations to solve concrete problems (Jiang and Schaufelberger 1992).

A set of BPF on a unit time interval [0, 1) is defined as (Babolian and Masouri 2008)

$$\varphi_i(t) = \begin{cases} 1 & \frac{i}{m} \le t \le \frac{i+1}{m} \\ 0 & otherwise \end{cases} \tag{1}$$

where $i = 0,1,2,...,m-1$ with a positive integer value for m and φ_i is the ith BPF.

BPFs possess disparate properties, the most salient characteristics are disjointness, orthogonality and completeness. The disjointness property can be clearly obtained from the definition of BPFs

$$\varphi_i(t)\varphi_j(t) = \begin{cases} \varphi_i(t) & , \quad i = j \\ 0 & , \quad i \ne j \end{cases} \tag{2}$$

where $i, j = 0,1,...,m-1$.

The other property is orthogonality, which can be stated as follows

$$\int_0^1 \varphi_i(t)\varphi_j(t)dt = h\delta_{ij} \tag{3}$$

in which δ_{ij} is Kronecker delta and $h = \frac{1}{m}$.

The third property is completeness. For every $f \in L^2([0,1))$ Parseval's identity holds

$$\int_0^1 f^2(t)dt = \sum_{i=1}^{m} f_i^2(t) \| \varphi_i(t) \|^2 \tag{4}$$

where

$$f_i = \frac{1}{h}\int_0^1 f(t)\varphi_i(t)dt \tag{5}$$

4. Clipped-optimal control strategy of VOD based on linear quadratic regulator

The force in the variable orifice damper is expressed as

$$f_d(t) = C(t)|\dot{x}|^{\alpha} \operatorname{sgn}(\dot{x}) \tag{6}$$

where $\dot{x}$ is the velocity of the piston rod, $C(t)$ is regulated damping coefficient. This coefficient can be varied from a minimum value, C_{min}, to a maximum value, C_{max}, and α is the velocity exponent within the values of 0.1 to 1.0, which are commonly used in seismic applications. In the design process of an LQR control algorithm, the equations of motion of a structure controlled with dampers can be written as

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(\mathrm{t}) = \Lambda\, f(t) + \delta\, \ddot{x}_g(t) \tag{7}$$

where M, C and K are n-dimensional matrices of mass, damping, and stiffness of the building structure, n is the number of building stories. Respectively; $x(t)$ is an n-dimensional vector of floor displacements and $f(t)$ is an r-dimensional vector of measured control forces of VODs, r is the number of VODs that used in the structure. Respectively; Λ is a $n \times r$ location matrix of control forces of VODs; and δ is a n-dimensional vector of the coefficient vector for earthquake ground acceleration $\ddot{x}_g(t)$. This equation can be written in state space form as

$$\dot{\mathbf{z}}(t) = A\mathbf{z}(t) + Bf(t) + E\ddot{x}_g(t) \tag{8}$$

where

$$\mathbf{z}(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix} \tag{9}$$

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad \mathrm{B} = \begin{bmatrix} 0 \\ M^{-1}\Lambda \end{bmatrix}, \quad \mathrm{E} = \begin{bmatrix} 0 \\ M^{-1}\delta \end{bmatrix} \tag{10}$$

A is a 2n-domensional matrix called system matrix. B is a $2n \times r$ control location matrix and E is a 2n-domensional excitation influence vector. $\mathbf{z}(t)$ is a 2n-domensional state vector. On–off clipping control is used concerning design the semi-active strategy. The following rule is usually adopted for this control algorithm: if the magnitude of the force, f_d, produced by the device is smaller than the magnitude of the desired optimal force, f_c, and the two forces have the same sign, the voltage applied to the current driver is increased to the maximum level so as to increase the force produced by the damper to match the desired control force. Otherwise, the commanded voltage is set to zero to provide the minimum damping. The command signal based on LQR theory is described by the following

$$v = V_{max} H\{(f_c - f_d) f_d\} \tag{11}$$

where v is the command signal, V_{max} is the maximum voltage applicable on the semi-active device such as VOD to obtain the maximum damping, H is the Heaviside step function, f_d is the measured control forces and f_c is the required control force. Unknown variables of state and control force vectors make the differential Eq. (8) unsolvable owing to the r additional unknown variables of control forces vector. Consequently, same as number of used VODs, extra equation is needed to solve the problem. The control is accomplished by measuring the actual relative velocity of the floor structure. The required control force is given by

$$f_c(t) = -K(t)\dot{x}(t) \tag{12}$$

where $K(t)$ is control gain matrix calculated by LQR theory. Control gain is determined by minimizing the following quadratic objective function

$$J = \int_0^T (\mathbf{z}(t)^T Q\mathbf{z}(t) + u(t)^T Ru(t))dt \tag{13}$$

where Q and R are the positive semi-definite constant matrices. Based on optimal control theory the control gain matrix is determined as

$$K(t) = R^{-1}B^T P(t) \tag{14}$$

where $P(t)$ is the Riccati matrix obtained from the following Riccati equation

$$A^T P(t) + P(t)A - R^{-1}P(t)B\,B^T P(t) + Q = 0 \tag{15}$$

5. Application of block pulse functions in semi-active control problems

The active and semi-active control devices performance are highly dependent on the control algorithm employed. Rather than relying on non-analytical methods for control problems such as fuzzy based or neural network methods, due to owing reliability and trustworthiness, the analytical methods are often used. One of the most challenging components of active and semi-active control is the development of an accurate analytical approach with minor computational expenses. Using orthogonal basis functions can be a useful tool in a numerical analysis. The predominant family of these functions is known as BPFs. Besides, These functions are orthonormal. In the proposed method, BPFs are used as an approximation tool to reduce computational difficulties.

The n-dimensional adjoint variable $P(t)$ satisfies the canonical equation (Bryson and Ho 1975)

$$\begin{bmatrix} \dot{\mathbf{z}}(t) \\ \dot{P}(t) \end{bmatrix} = F \begin{bmatrix} \mathbf{z}(t) \\ P(t) \end{bmatrix} \tag{16}$$

under the two-point boundary values $\mathbf{z}(0) = \mathbf{z}_0$ and $P(T) = 0$. In this canonical equation, the coefficient matrix F is

$$F = \begin{bmatrix} A & B\,R^{-1}B^T \\ Q & -A^T \end{bmatrix} \tag{17}$$

To avoid this two-point boundary value problem in solving Eq. (15) to find $P(t)$, we set the 2n-dimensional transition matrix of Eq. (17) as

$$\psi(T,t) = \begin{bmatrix} \psi_{11}(T,t) & \psi_{12}(T,t) \\ \psi_{21}(T,t) & \psi_{22}(T,t) \end{bmatrix} \tag{18}$$

where all the submatrices $\psi_{11}(T,t)$, $\psi_{12}(T,t)$, $\psi_{21}(T,t)$ and $\psi_{22}(T,t)$ are n-dimensional. Noticing that

$$\psi(T,t) \begin{bmatrix} \mathbf{z}(t) \\ P(t) \end{bmatrix} = \begin{bmatrix} \mathbf{z}(T) \\ P(T) \end{bmatrix} \tag{19}$$

and $P(T)=0$, we have

$$P(t)=\psi_{22}^{-1}(T,t)\psi_{21}(T,t) \tag{20}$$

The main problem is finding gain matrix $K(t)$.

With the gain matrix

$$K(t)=R^{-1}B^{T}\psi_{22}^{-1}(T,t)\psi_{21}(T,t) \tag{21}$$

In applying block pulse functions in this problem, a suboptimal solution with piecewise constant feedback gains can be obtained (Jiang and Schaufelberger 1992)

$$K(t)=\sum_{i=1}^{m}K_i(t)\varphi_i(t) \tag{22}$$

since the block pulse coefficients of the transition matrix $\psi_i(i=1,2,\ldots,m)$ can be computed iteratively from this series

$$\psi_{m-i}(t)=\sum_{i=0}^{m}\alpha^{i}\lambda\varphi_i(t) \tag{23}$$

and the matrices λ and α are

$$\lambda=\left[I-\frac{h}{2}F\right]^{-1} \tag{24}$$

$$\alpha=\lambda\left[I+\frac{h}{2}F\right] \tag{25}$$

6. A comparative numerical study

In order to compare the effectiveness of the semi-active control method described in the previous Section with other control method, numerical examples are used. The simulation consists of a 10-story building. Where the mass and stiffness parameters for each floor are listed in Table 1.

The Mass and stiffness matrices are formed as follows

$$M=\begin{bmatrix} m_1 & & \cdots & & 0 \\ & m_2 & & & \\ \vdots & & \ddots & & \vdots \\ & & & m_9 & \\ 0 & & \cdots & & m_{10} \end{bmatrix} \tag{26}$$

$$K=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2+k_3 & -k_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ & & -k_9 & k_9+k_{10} & -k_{10} \\ 0 & 0 & \cdots & -k_{10} & k_{10} \end{bmatrix} \tag{27}$$

Table 1 Mass and stiffness values of test structure

Story	Mass	Stiffness
1-3	105,000 kg	1700×10^5N/m
4-6	95,000 kg	1600×10^5 N/m
7-9	90,000 kg	1400×10^5 N/m
10	85,000 kg	1100×10^5 N/m

Table 2 Properties of selected ground motions

Earthquake	Station	PGA (g)	PGV (cm/s)	PGD (cm)
Tabas	9101 Tabas	0.836	97.8	36.92
Northridge	24436 Tarzana	1.024	75.4	20.05
Duzce	Duzce	0.348	60.0	42.09

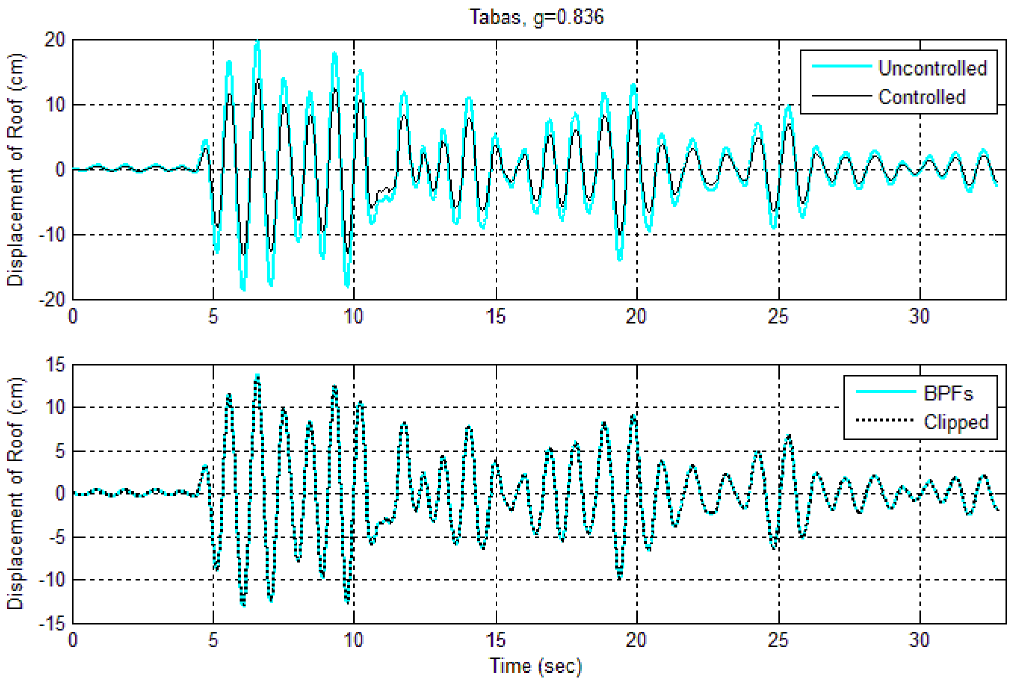

Fig. 2 Results of roof displacement time history in controlled structure (Tabas g=0.836)

The Rayleigh damping matrix is constructed using 3% modal damping for the first and second modes. It is assumed that one VOD dampers are in each floors. The velocity exponent parameter of VOD dampers is considered to be 0.8. The damping coefficient of dampers varies from a minimum value of C_{min}=200 N.s/mm, while the valve is fully opened, to a maximum value of C_{max}=1000 N.s/mm, when the valve is fully closed.

The structure is subjected to the Tabas (1978), Northridge (1994), Duzce (1999) earthquakes to evaluate the performance of the proposed analytical method in reducing the structural responses under seismic loading. Table 2 lists basic characteristics of the earthquake recorded motions.

Fig. 2 shows time histories of the roof displacement for the uncontrolled structure compared with proposed method based on BPFs and proposed method compared with clipped-optimal control method under the Tabas earthquake.

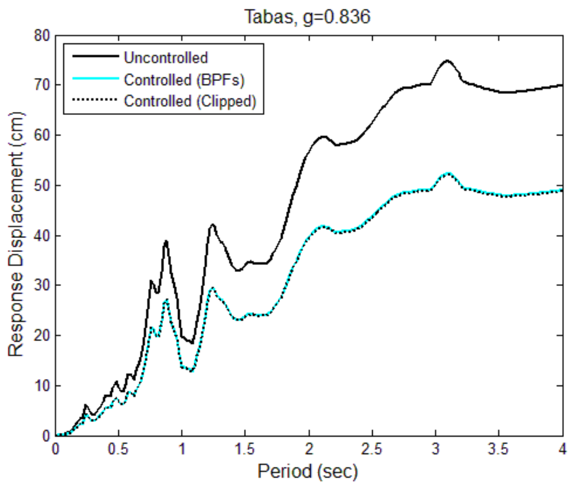

Fig. 3 Results of roof displacement time history in controlled structure (Tabas g=0.836)

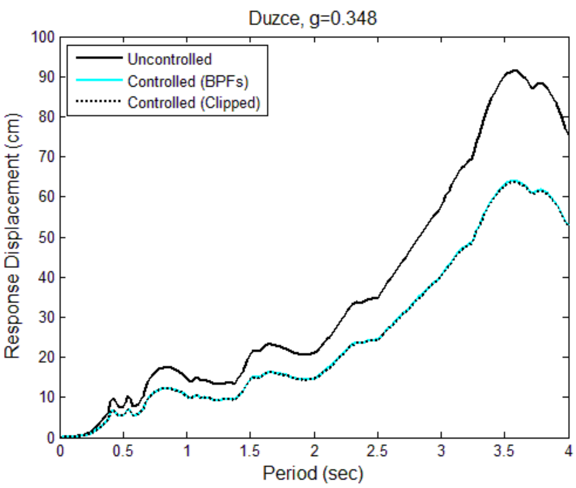

Fig. 4 Results of roof displacement time history in controlled structure (Duzce g=0.348)

Displacement response spectra of uncontrolled and controlled responses using the proposed method of comparsion to clipped- optimal control method for Tabas, and Duzce earthquakes are presented in Figs. 3 and 4. It can be seen that the proposed method is as efficient as clipped-optimal control method.

Figs. 5-7 are shown the same control trajectories of clipped-optimal and proposed semi-active control method based on BPFs.

Furthermore, the following indices to evaluate the control system performance are considered. These sets of performance indices compare the controlled response against the results obtained from the uncontrolled cases. There are different sets of evaluation criteria which are used in structural control to evaluate the performance of the control system applied to the buildings. The set of evaluation criteria used in this study to compare the performance of the structure are defined based on both maximum and normed responses (Ohtori, Christenson *et al.* 2004). The first evaluation criteria for the proposed method pertain to its ability to reduce inter-story drift. The second and third evaluation criteria relate to the ability of the proposed method to reduce the maximum displacement and acceleration of the floor. The fourth one relates to the ability of the new method to reduce the maximum force of the floor.

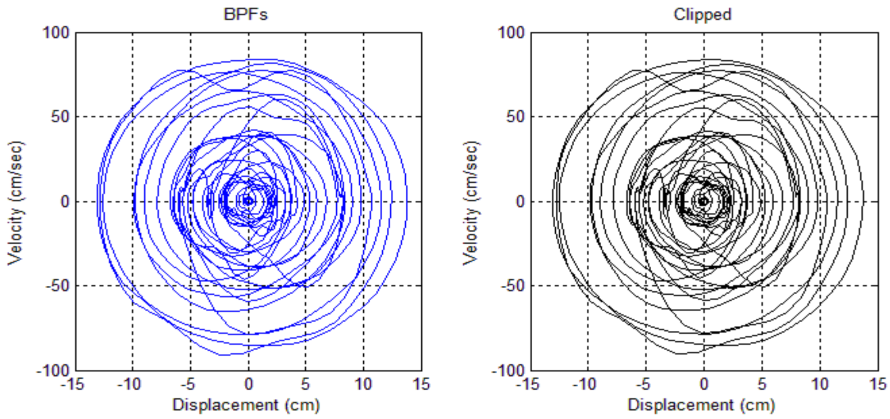

Fig. 5 Trajectory of proposed and clipped-optimal semi-active control method (Tabas g=0.836)

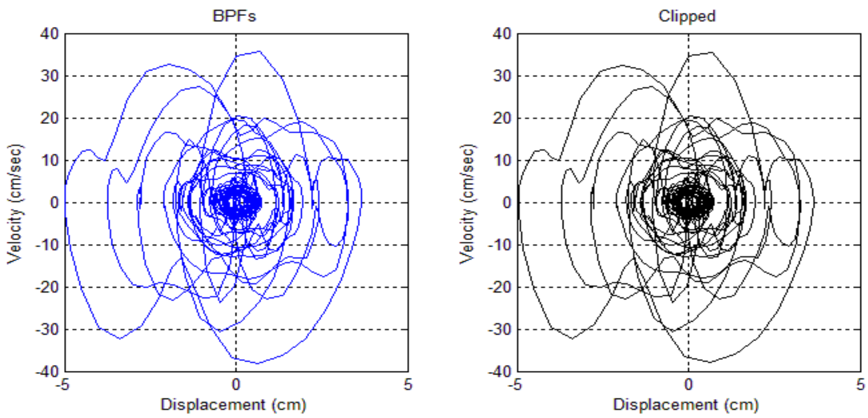

Fig. 6 Trajectory of proposed and clipped-optimal semi-active control method (Northridge g=1.024)

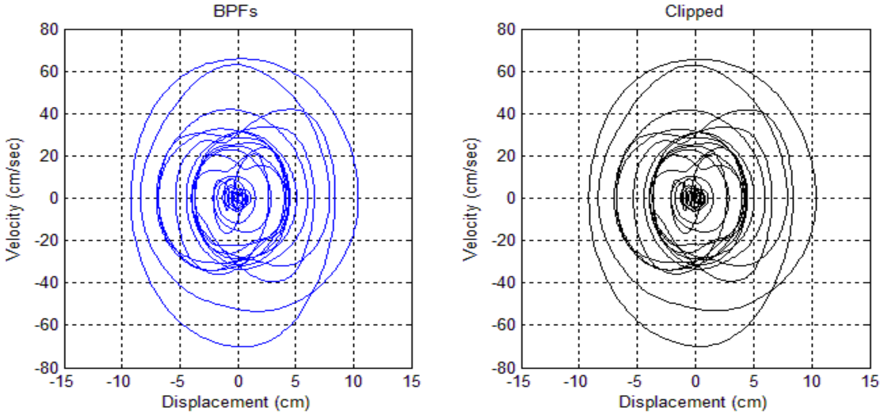

Fig. 7 Trajectory of proposed and clipped-optimal semi-active control method (Duzce g= 0.348)

$$J_1 = \frac{\max\limits_{t,i} \dfrac{\left|d_i^c(t)\right|}{h_i}}{\max\limits_{t,i} \dfrac{\left|d_i^u(t)\right|}{h_i}},\ J_2 = \frac{\max\limits_{t,i}\left|x_i^c(t)\right|}{\max\limits_{t,i}\left|x_i^u(t)\right|},\ J_3 = \frac{\max\limits_{t,i}\left|\ddot{x}_{ai}^c(t)\right|}{\max\limits_{t,i}\left|\ddot{x}_{ai}^u(t)\right|},\ J_4 = \frac{\max\limits_{t}\left|\sum\limits_i m_i \ddot{x}_{ai}^c(t)\right|}{\max\limits_{t}\left|\sum\limits_i m_i \ddot{x}_{ai}^u(t)\right|} \tag{28)-(31}$$

The evaluation criteria for the normed based forms control effort requirements of the method are given by the following criteria

$$J_5 = \frac{\max\limits_{t,i} \dfrac{\left\|d_i^c(t)\right\|}{h_i}}{\max\limits_{t,i} \dfrac{\left\|d_i^u(t)\right\|}{h_i}},\ J_6 = \frac{\max\limits_{t,i}\left\|x_i^c(t)\right\|}{\max\limits_{t,i}\left\|x_i^u(t)\right\|},\ J_7 = \frac{\max\limits_{t,i}\left\|\ddot{x}_{ai}^c(t)\right\|}{\max\limits_{t,i}\left\|\ddot{x}_{ai}^u(t)\right\|},\ J_8 = \frac{\max\limits_{t}\left\|\sum\limits_i m_i \ddot{x}_{ai}^c(t)\right\|}{\max\limits_{t}\left\|\sum\limits_i m_i \ddot{x}_{ai}^u(t)\right\|} \tag{32)-(35}$$

The last one is related to the control devices

$$J_9 = \frac{\max\limits_{t,l}\left|f_l(t)\right|}{W} \tag{36}$$

Where $x_i(t)$ is displacement of i-th story, $d_i(t)$ is drift of i-th story, $\ddot{x}_i(t)$ is acceleration of i-th story, $f_l(t)$ is control force produced by l-th device, m_i is mass of i-th story, h_i is height of i-th story and W is seismic weight of building. The term 'c' and 'u' refer to the controlled system and uncontrolled system. The norm $\|u\|$, is computed using the following equation

$$\|u\| = \sqrt{\frac{1}{t_f}\int_0^{t_f}(u)^2\,dt} \tag{37}$$

The performance of the system according to set of evaluation criteria for seismic records are presented in Fig. 8 for both proposed and clipped-optimal control algorithms. By comparison, between the results of evaluation criteria for ground motions it can be concluded the proposed control method based on BPFs is very close to clipped-optimal control algorithm.

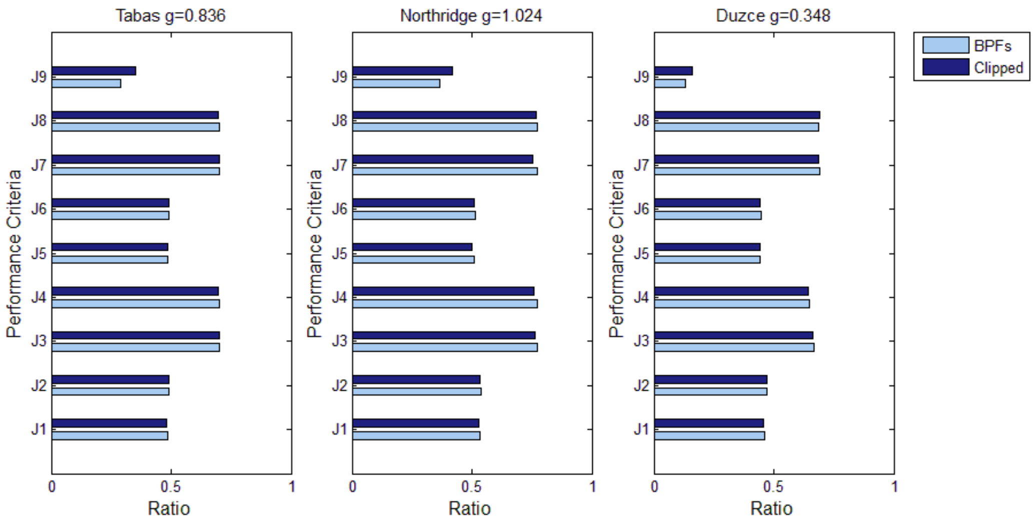

Fig. 8 Evaluation of performance criteria

7. Conclusions

This paper applied the idea of block pulse functions in the semi-active control problem. An approach based on BPFs is presented for the semi-active structural control. The results of the proposed method and clipped optimal control method were compared. The numerical simulation results illustrated that the proposed method gives satisfactory conclusions in the effectiveness of performance responses and feasibility of the proposed approach. The control trajectories for the clipped-optimal control method and the proposed method depicted the same performance for each approach. Also the proposed method exhibited satisfactory control performance for the evaluation criteria and the values of evaluation criteria revealed very competent control performance. The comparsion results depicted the present method is able to approximate the behavior of controlled system and is in agreement with other methods.

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