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# Comparative Study of Different Active Control Systems of High Rise Buildings under Seismic Excitation

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**Abstract**

Large number of active vibration control systems existing in the literature has brought lot of confusion for engineers and junior researchers. This study deals with the comparison of different active control systems of a 20-storey building under seismic excitation for three control devices: Active Mass Damper (AMD), Active Bracing System (ABS) and Connected Building Control (CBC). Two different control configurations are considered to add active damping to the building. The first one employs force actuator and displacement sensor and is examined with first and second order Positive Position Feedback, Lead compensators and Direct Velocity Feedback. The second configuration employs a displacement actuator collocated with a force sensor and an Integral Force Feedback control law. A total number of 15 control cases are compared from the point of view of stability, robustness, performance and control effort.

**Keywords**

active control, Active Mass Damping, Active Bracing System, Connected Building Control, feedback controller, seismic excitation

## 1 Introduction

In the past decades, significant development has been made in the field of vibration control strategies for civil engineering structures in order to mitigate earthquake hazard. Vibrations may be reduced by passive method [1, 2], active method [3, 4], hybrid method [5] or semi-active method [6]. These control strategies have been applied to different control designs: using base isolation system, a bracing system, an auxiliary mass damper or an auxiliary structure (CBC: Connected Buildings Control). Active control was developed by Yao [7] to withstand tall structures against storms and became the subject of intensive research subsequently. Active Mass Damper (AMD) was developed as a means to extend passive Tuned Mass Damper (TMD) in order to control the vibrations of tall buildings. Significant researches have been published to validate the effectiveness of TMDs on high-rise and slender structures [8–13].

Abdel-Rahman [14] presented a rule to design active TMD in order to control a tall building subjected to stationary random wind forces. Samali et al. [15] studied the active vibration control of a 40-story building under strong wind excitations using an AMD and compared the results to the case of a classical TMD. Wang and Lin [16] used two controllers, the fuzzy sliding mode control and variable structure control, for seismic protected buildings equipped with AMD control systems. Guclu and Yazici [17] compared the effectiveness of Fuzzy Logic and PD controllers to control a 15-story frame equipped with AMDs on the first and 15th floors. Zhang et al. [18] studied experimentally the Fuzzy Control of seismic structure with an AMD. Tu et al. [19] tested numerically and experimentally the AMD control system based on Model Reference Adaptive Control algorithm.

Vibration of buildings may be also mitigated by Active Bracing Systems which consist in adding active elements between the ground and the first floor or between two successive floors. Based on the LQR theory, Chung et al. [20] developed a system to control a single-degree-of-freedom (SDOF) and 3DOFs structures by making use of tendons connected to a servo hydraulic actuator. Loh et al. [21] examined the effectiveness of control algorithms which are employed on a full-scale 3-storey steel structure with

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Active Bracing System installed at the first floor. The experimental verification includes three different control algorithms: modal control with direct output feedback, static-output-feedback LQR control, and static-output-feedback with variable gain. Lu [22] proposed a discrete-time modal control strategy which is very useful method to control the seismic response of building structures equipped with ABS. Preumont et al. [23] investigated the active bracing control of a seven story building using Positive Position Feedback (PPF) and Direct Velocity feedback (DVF) and Integral Force Feedback (IFF). Achour-Olivier and Arfa [24] studied the vibration control of a SDOF building based on Lyapunov method. Blachowski and Pnevmatikos [25] presented a neural network based vibration control method to reduce the vibrations of a 3D multi-storey building subjected to earthquakes and compared it to the classical linear quadratic regulator (LQR) in terms of displacement responses and control forces.

The active control of coupled adjacent tall structures under seismic excitation has been investigated by Seto et al. [26], Yamada et al. [27] and Christenson et al. [28]. The linear quadratic control method was applied to determine the control forces of coupled structures in those studies. The nonlinear optimal control method has been also used to reduce the seismic response of coupled buildings [29]. Based on the stochastic dynamical programming principle and stochastic averaging method, the stochastic optimal coupling control of adjacent building structures is studied by Ying et al. [30]. The papers reported by Housner et al. [31], Datta [32], Spencer and Nagarajaiah [33], Fisco and Adeli [34–35], Korkmaz [36] and Ghaedi et al. [37] provide a detailed review of earlier and recent studies on structural control as well as real applications.

By examining the huge amount of literature on active vibration control, the comparison between various control techniques is less investigated. This has brought a lot of confusion amongst the less experienced researchers and engineers. Preumont et al. [23] compared between the Integral Force Feedback (IFF), Positive Position Feedback (PPF) and Direct Velocity feedback (DVF) for the case of active bracing control of a 7 storey building. This work had motivated the authors to compare not only the control laws but also the control systems: AMD, ABS and CBC. Two different control configurations are considered to add active damping to the 20 storey building. The first one uses a force actuator combined with a displacement sensor and is examined with DVF, first-order PPF1, second-order PPF2 and Lead compensators. The second configuration employs a displacement actuator combined with a collocated force sensor and an Integral Force Feedback control law. A total number of 15 control cases will be compared from the point of view of stability, performance and control effort.

## 2 Modeling of the active control systems

The governing equations of motion of the building, modeled as a shear frame and equipped with an active strut between two successive floors (shear control) or an active mass damper or connected to another building with an active strut are expressed as Eq. (1):

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{B\}f-[M]\{1\}\ddot{x}_0, \tag{1}$$

where $M$, $C$ and $K$ are respectively the mass, damping and the stiffness of the building and depends on the active control systems. $\ddot{x}$, $\dot{x}$ and $x$ are respectively the acceleration, velocity and displacement vectors. $B$ is the influence vector indicating the location of the active strut which creates two opposing forces on the connected points; $f$ is the control force which depends on the control law; Eq. (1) is a unit vector and $x_0$ is the ground acceleration.

### 2.1 Active Bracing System (ABS)

In case of shear control shown in Fig. 1, the mass matrix takes the following form:

$$\left[M\right]=\begin{bmatrix} m_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_n \end{bmatrix}. \tag{2}$$

The stiffness matrix is given by:

$$\left[K\right]=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2+k_3 & -k_3 & \cdots & \vdots \\ 0 & -k_3 & \ddots & -k_{n-1} & 0 \\ \vdots & \cdots & -k_{n-1} & k_{n-1}+k_n & -k_n \\ 0 & \cdots & 0 & -k_n & k_n \end{bmatrix}. \tag{3}$$

The damping matrix is as follows:

$$\left[C\right]=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & \cdots & 0 \\ -c_2 & c_2+c_3 & -c_3 & \cdots & \vdots \\ 0 & -c_3 & \ddots & -c_{n-1} & 0 \\ \vdots & \cdots & -c_{n-1} & c_{n-1}+c_n & -c_n \\ 0 & \cdots & 0 & -c_n & c_n \end{bmatrix}. \tag{4}$$

In general, the influence vector $B$ indicating the location of the ABS, which creates two opposing forces between the connected degrees of freedom, can be given by:

$$\boldsymbol{B}=\{\boldsymbol{0},\ldots,\boldsymbol{0},-\boldsymbol{1},\boldsymbol{0},\ldots,\boldsymbol{0},\boldsymbol{1},\boldsymbol{0},\ldots,\boldsymbol{0}\}^{T}_{1\times n}. \quad (5)$$

If the ABS is impemented between the ground and the first floor, the influence vector can be simply written as follows:

$$\boldsymbol{B}=\{\boldsymbol{1},\boldsymbol{0},\ldots,\boldsymbol{0}\}^{T}_{1\times n}. \quad (6)$$

### 2.2 Active Mass Damping (AMD)

In the case of the AMD shown in Fig. 2, the matrices M, C and K are of dimension $n + 1$ and the displacement vector $\{x\}$ has $n + 1$ entry. If the AMD is added to the last floor, the mass matrix becomes:

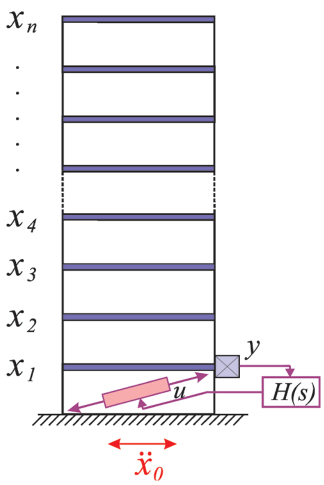


**Fig. 1** $n$-storey shear frame equipped with an ABS between the ground and the first floor

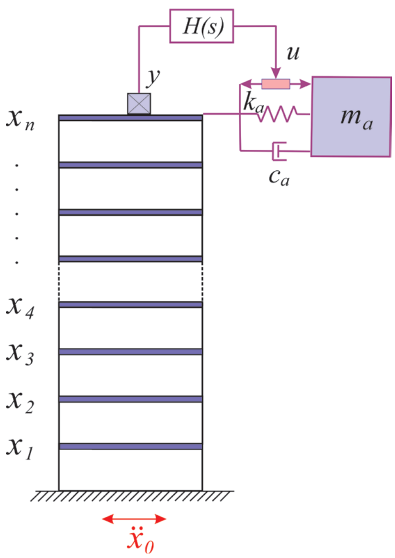


**Fig. 2** $n$-storey shear frame equipped with an AMD attached to the top floor

$$[M]=\begin{bmatrix}[M]_{n\times n} & \{0\}_{n\times 1}\\ \{0\}_{1\times n} & m_a\end{bmatrix}. \quad (7)$$

The damping matrix is:

$$[C]=\begin{bmatrix}[C]_{(n-1)\times(n-1)} & \{0\}_{(n-1)\times 1} & \{0\}_{(n-1)\times 1}\\ \{0\}_{1\times(n-1)} & C_{nn}+c_a & -c_a\\ \{0\}_{1\times(n-1)} & -c_a & c_a\end{bmatrix}. \quad (8)$$

The stiffness matrix is:

$$[K]=\begin{bmatrix}[K]_{(n-1)\times(n-1)} & \{0\}_{(n-1)\times 1} & \{0\}_{(n-1)\times 1}\\ \{0\}_{1\times(n-1)} & K_{nn}+k_a & -k_a\\ \{0\}_{1\times(n-1)} & -k_a & k_a\end{bmatrix}. \quad (9)$$

Where $m_a$, $c_a$ and $k_a$ are respectively the mass, the damping and the stiffness of the AMD.

The influence vector $B$ indicating the location of the active element between the top floor and the inertial mass can be written as follows:

$$\boldsymbol{B}=\{\boldsymbol{0},\ldots,\boldsymbol{0},-\boldsymbol{1},\boldsymbol{1}\}^{T}_{1\times(n+1)}. \quad (10)$$

### 2.3 Connected Building Control (CBC)

Consider two linear adjacent buildings with different numbers of stories subjected to a unidirectional seismic excitation. Buildings 1 has $(m + n)$ stories whereas Building 2 has only $(n)$ stories but both have the same constant height of floors (see Fig. 3). The buildings are modeled as shear frames and they are connected using an active strut located on the $i^{th}$ floor.

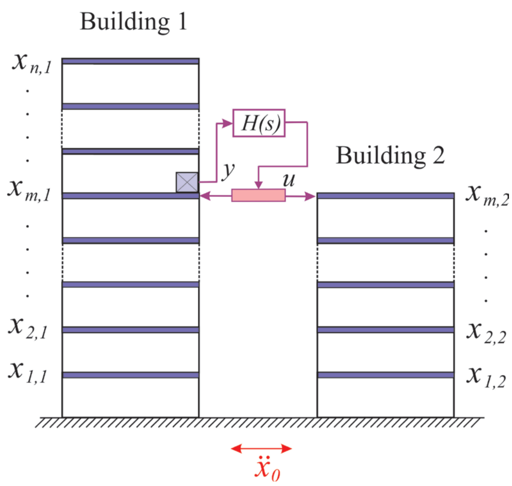


**Fig. 3** Model of two adjacent buildings connected with an active strut

The matrices $M$, $K$ and $C$ for the combined system are explicitly defined as follow

$$\underset{(n+m,n+m)}{M} = \begin{bmatrix} \underset{(n,n)}{[M_1]} & \underset{(n,m)}{[O_1]} \\ \underset{(m,n)}{[O_2]} & \underset{(m,m)}{[M_2]} \end{bmatrix}, \tag{11}$$

$$\underset{(n+m,n+m)}{K} = \begin{bmatrix} \underset{(n,n)}{[K_1]} & \underset{(n,m)}{[O_1]} \\ \underset{(m,n)}{[O_2]} & \underset{(m,m)}{[K_2]} \end{bmatrix}, \tag{12}$$

$$\underset{(n+m,n+m)}{C} = \begin{bmatrix} \underset{(n,n)}{[C_1]} & \underset{(n,m)}{[O_1]} \\ \underset{(m,n)}{[O_2]} & \underset{(m,m)}{[C_2]} \end{bmatrix}, \tag{13}$$

where, $[M_1]$, $[C_1]$and $[K_1]$ are respectively the individual mass, damping and stiffness matrices of Building 1. Similarly, $[M_2]$, $[C_2]$ and $[K_2]$ are the individual mass, damping and stiffness matrices of Building 2. $[O_1]$ and $[O_2]$ are null matrices.

The influence vector $B$ indicating the location of the control device which creates two opposing forces between Buildings 1 and 2 at the selected degrees of freedom, is given by:

$$\boldsymbol{B} = \{\mathbf{0},\ldots,\mathbf{0},\mathbf{-1},\mathbf{0},\ldots,\mathbf{0},\mathbf{1},\mathbf{0},\ldots,\mathbf{0}\}^{\boldsymbol{T}}_{\mathbf{1}\times(\boldsymbol{n}+\boldsymbol{m})}. \tag{14}$$

### 2.4 Control laws

Two different control configurations are considered to add active damping to the multistory building [23]:

#### 2.4.1 Using a force actuator combined with a displacement sensor

Four control laws are adopted for this case:

- The control force of the *Lead*:

$$f = -g_1\left(\frac{s+p}{s+z}\right)y, \tag{15}$$

where $g_1$ is the controller gain; $s$ is the *Laplace* variable, $a$ is a design parameter, $y = (x_i - x_{i-1})$ is the relative displacement between the connected successive floors for the case of ABS control, $y = x_i$ is the absolute displacement of the $i^{\text{th}}$ floor equipped with an inertial mass for the case of AMD and $y = (x_{i,1} - x_{i,2})$ is the relative displacement between the building 1 and 2 at $i^{\text{th}}$ floor level for the CBC case.

- The control force of the DVF, which is a particular case of the Lead, is:

$$f = -g_2 sy, \tag{16}$$

where $g_2$ is the controller gain.

- The control force of the first order PPF1 is:

$$f = \frac{g_3}{1+\tau s}y, \tag{17}$$

where $g_3$ is the PPF1 controller gain and $\tau$ is a design parameter which decides the damping ratio, defines the position of the pole of the PPF1 on the real axis and fixes the stability margin.

- The control force of the second order PPF2 is:

$$f = \frac{g_4}{s^2 + 2\xi_f \omega_f s + \omega_f^2}y, \tag{18}$$

where $g_4$ is the PPF2 controller gain.

#### 2.4.2 Using a collocated displacement actuator-force sensor

The control law adopted in this case is the IFF:

$$u = \frac{g_5}{s}\frac{f}{K_a}. \tag{19}$$

Where $K_a$ is the stiffness of the strut and $u$ is its active displacement and $g_5$ is the controller gain.

The control force in the active strut measures:

$$f = K_a(B^T(x_i - x_j) - u). \tag{20}$$

Where $(x_i - x_j)$ is the relative displacement between the extremities of the active strut.

The difference between the two configurations stems from the fact that the force actuator brings no stiffness in open-loop while the displacement actuator brings an extra stiffness $K_a$ to the structure.

The RMS control effort $u$, which eventually fixes the size of the actuator, can be assessed from:

$$\sigma_u = \left[\int_0^{\omega} \left|T_{u\ddot{x}_0}\right|^2 d\omega\right]^{1/2}, \tag{21}$$

where $T_{u\ddot{x}_0}$ is the transmissibility between the ground acceleration and the control input.

The mean square power of the control requirement of the DVF and IFF can be expressed as follows [23]:

$$\sigma_{DVF}{}^2 = E[u\dot{\Delta}] = gE[\dot{\Delta}^2] \sim \int_0^{\infty} g\omega^2 \left|T_{\Delta\ddot{x}_0}\right|^2 d\omega, \tag{22}$$

$$\sigma_{IFF}{}^2 = E[f\dot{\delta}] = E[\frac{g}{K_a}F^2] \sim \int_0^{\infty} \frac{g}{K_a}\left|T_{f\ddot{x}_0}\right|^2 d\omega. \tag{23}$$

Where $T_{\Delta\ddot{x}_0}$ is the transmissibility between the ground acceleration and the displacement sensor $\Delta$ and $T_{F\ddot{x}_0}$ is the transmissibility between the ground acceleration and the force sensor $f$.

## 3 Numerical example and discussions

Consider a building of twenty stories subjected to unidirectional seismic excitation. The same mass and stiffness are adopted for all floors and they are respectively equal to $6 \times 10^5$ kg and $4.5 \times 10^8$ N/m. A uniform modal damping of 1 % is assumed for both buildings. Active damping is combined with the structure using first or second order PPF, DVF, Lead or IFF. A comparison of these control techniques will be carried out to highlight their most salient features and to allow a more objective evaluation.

### 3.1 Stability

The stability of the control systems is studied using the root locus technique as shown in Fig. 4. For the case of CBC and ABS control the IFF, DVF and lead are unconditionally stable since all poles are on the left part of the imaginary axis where us the first and second order PPF are conditionally stable. For the AMD case, all the control laws are conditionally stable except the IFF. Normally, the DVF and the Lead are unconditionally stable, but in the case of the AMD, they become conditionally stable because the control system is not collocated [23]. In fact, the sensor measures the absolute displacement of the top floor whereas the actuator creates a pair of opposing forces acting on the top floor and on the inertial mass. The non-collocation of the system comes from the fact that the absolute displacement sensor (on the top floor) is not exactly located at the same place as the second force of the actuator (which is applied on the inertial mass).

### 3.2 Maximum damping

The maximum damping of the first two modes is plotted in Fig. 5 for all control systems (ABS, AMD, CBC) and different control laws (IFF, DVF, Lead, PPF1, PPF2). For the cases of IFF and PPF2, the CBC control is the best solution. For the case of DVF and Lead, the AMD is the best control method. For the case of PPF1, the ABS control is the best solution. A critical damping can be reached for the first mode for the following configurations: AMD + DVF or Lead, ABS + PPF1, CBC + PPF1 and CBC + PPF2. The AMD + DVF or Lead is the best configuration providing the building with large damping for first two modes.

### 3.3 Frequency function response

For all control systems and laws with respect to a maximum damping on the first mode, the transmissibility between the ground motion and the top floor acceleration, and between the ground motion and the shear force at the base are plotted in Fig. 6. The PPF1 has the best performances when an ABS control system is used and acts on all modes as shown in Fig. 6(a) but suffers from the negative stiffness problem which causes a large shear force at the base as illustrated in Fig. 6(b). When an AMD is added to the top floor, the DVF has the best performances and also acts on all modes and doesn't have a negative stiffness problem. For the CBC case the PPF1 has the best performances on the first mode but doesn't act efficiently on the other modes and also suffer from the negative stiffness problem.

### 3.4 Control effort

For equal performances (3 % on first mode), the control efforts are compared and plotted in Fig. 7 for all the control systems and laws. The AMD is the best solution in term of energy requirements. The CBC needs a moderate energy whereas the ABS control needs a very large amount of energy. The Lead and DVF has almost the same control effort for AMD control and the DVF needs less of energy than the Lead for CBC and Shear Control cases. The second order PPF is the most expensive control law for the CBC and AMD cases. The DVF is the best solution in term of minimum control effort. Fig. 8(a) compares the power requirements of the DVF and the IFF.

The power requirement of the IFF is smaller than the one of the DVF for the three control systems. The time response of the top floor displacement of the 20-storey building subjected to El Centro earthquake is plotted in Fig. 8(b) for the ABS, AMD and CBC control systems using different control laws with respect to maximum damping.

### 3.5 Time response to seismic excitation

The time response of the top floor displacement of the 20-story building subjected to El-Centro earthquake is plotted in Fig. 8(b) for the ABS, AMD and CBC control systems using different control laws with respect to maximum damping. The first order PPF has the best performances in term of top floor displacement for the ABS and CBC control systems. For the case AMD control, the DVF shows the best capabilities in reducing the top floor displacement.

## 4 Conclusions

The active control of a 20-storey building under seismic excitation is investigated for three control systems: AMD, ABS and CBC and five control laws. A total number of 15 control cases are compared from the point of view of robustness, performance and control effort. It has been concluded that:

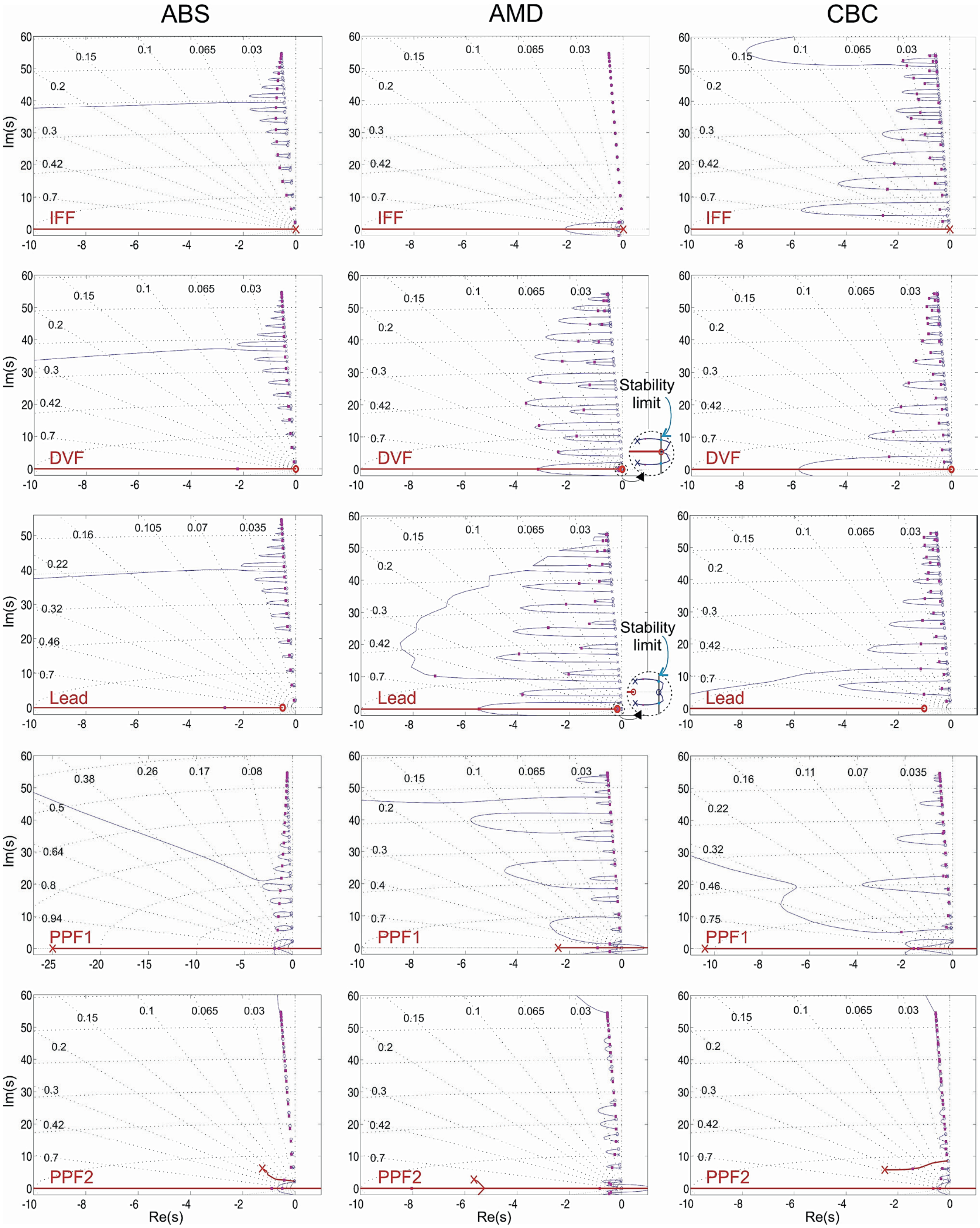


**Fig. 4** Root-locus of the different control laws for ABS, AMD and CBC control systems

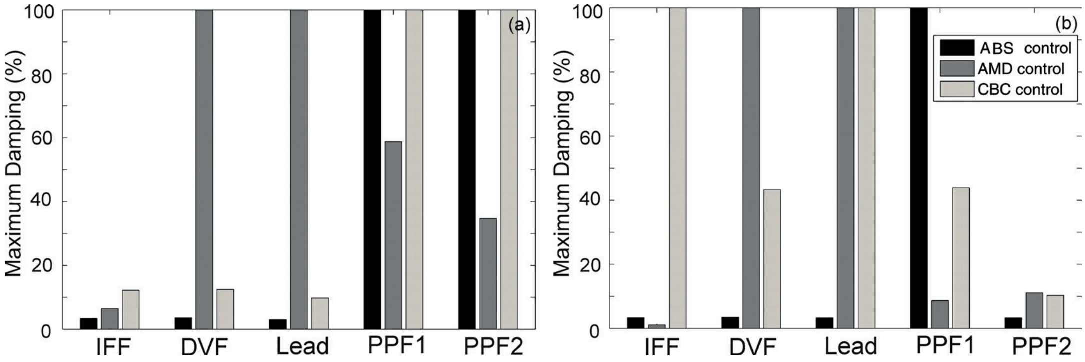


**Fig. 5** Comparison of the different control systems and laws: (a) maximum damping of mode 1 (b) maximum damping of mode 2

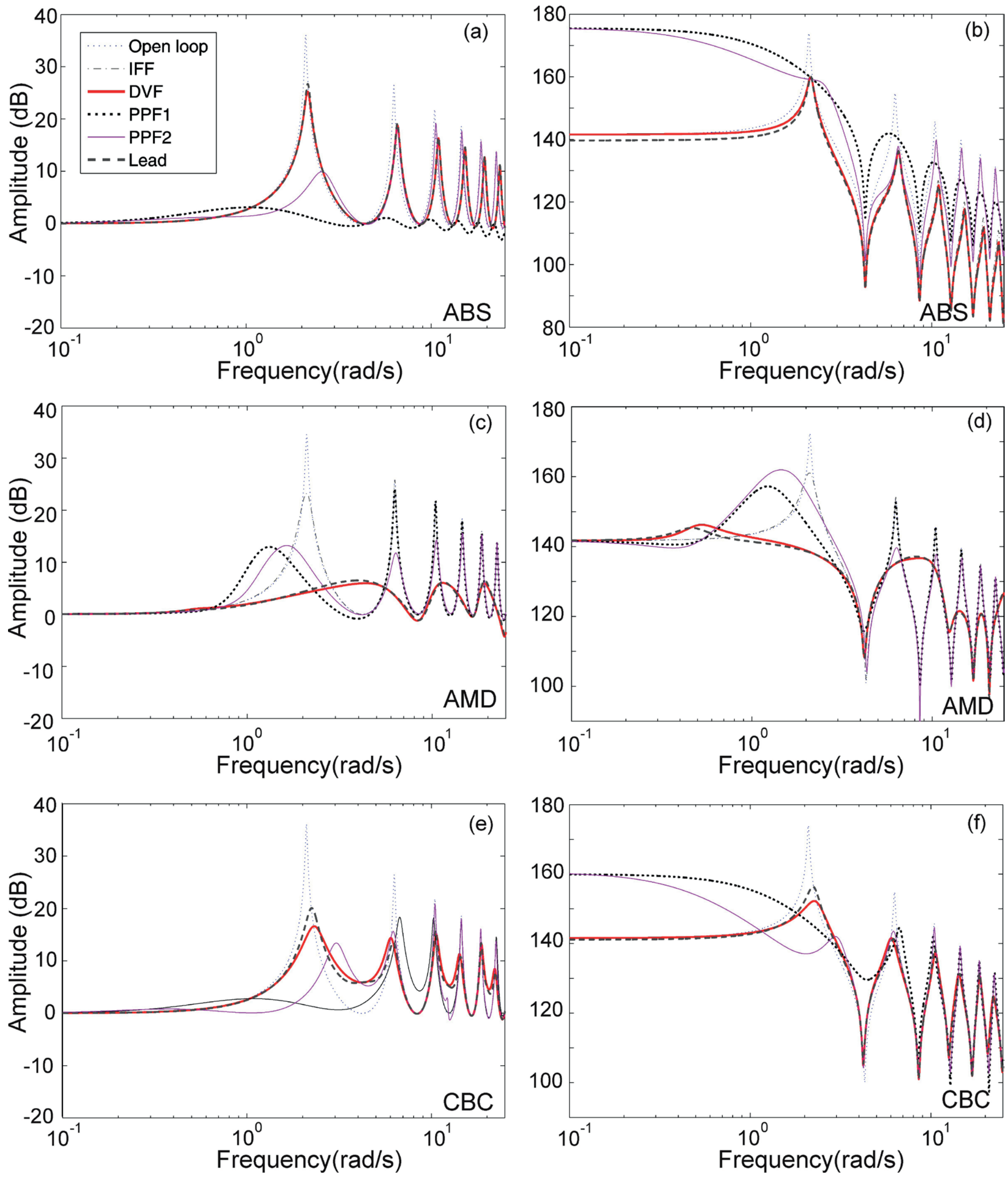


**Fig. 6** Transmissibility between the ground acceleration and: ((a), (c), (e)) the acceleration of the top floor ((b), (d), (f)) shear force at the base, for the ABS, AMD and CBC control and for the different control laws; with respect to the maximum damping on the first mode

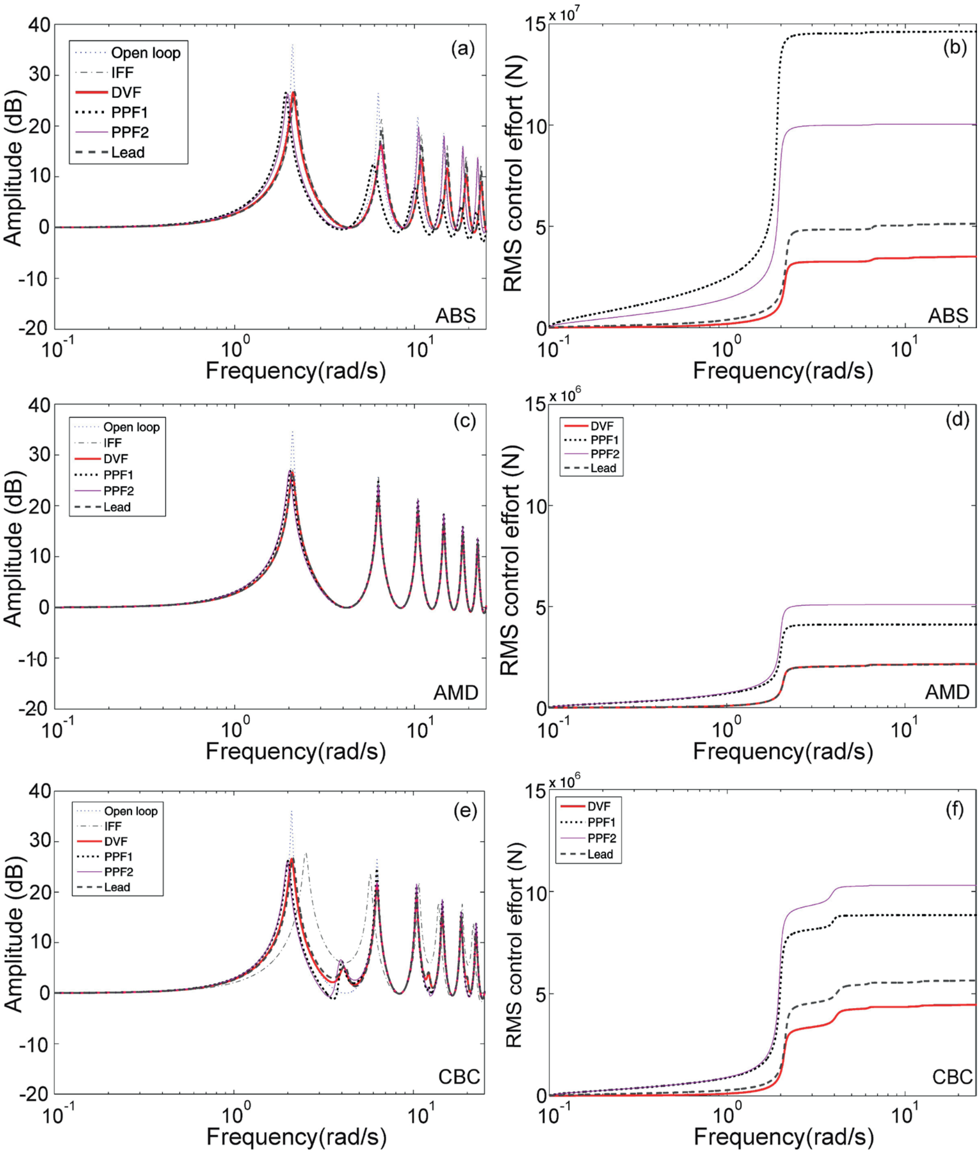


**Fig. 7** Comparison of the different control systems and laws: ((a), (c), (e)) Transmissibility; the gains have been selected to achieve similar performances for the first mode, ((b), (d), (f)) RMS control effort *u*

- The first order PPF has the best performances in term of top floor displacement and acceleration for the ABS and CBC control systems but suffer from the negative stiffness problem which may produce large shear force at the building base.
- For the case AMD control, the DVF has the best performances in term of top floor displacement and acceleration without any negative stiffness problem.
- The IFF has the minimum of power requirements when compared with the other control laws for the ABS, AMD, and CBC systems but it is less efficient in term of maximum damping of the first mode.
- The AMD needs less of energy than the ABS and CBC control for all control laws.
- The AMD equipped with a DVF seems the optimal solution with respect to the acceleration and displacement performances, stability and power requirements.

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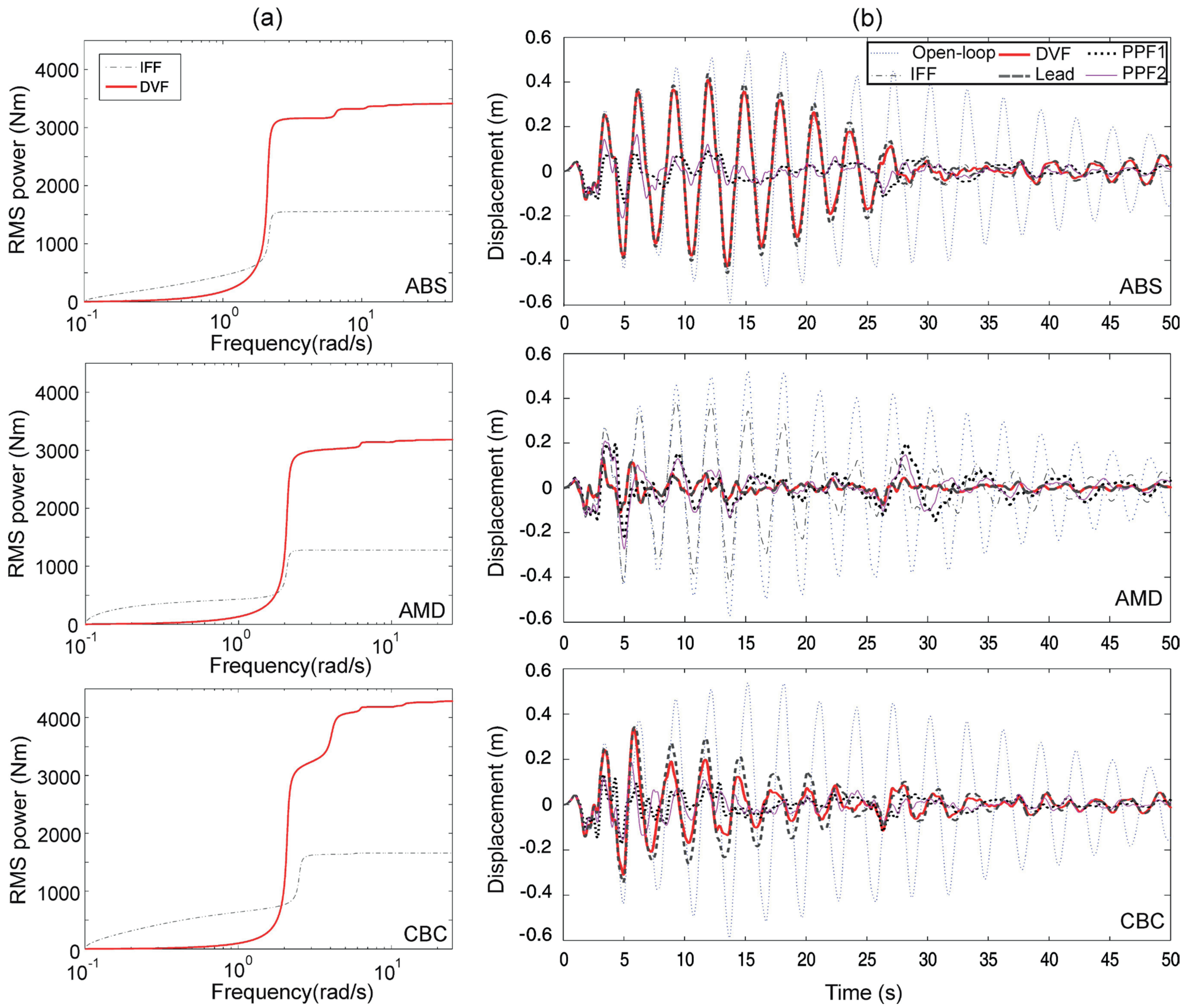


**Fig. 8** (a) Cumulative MS of the power requirements of the IFF and the DVF (b) Time response of the top floor displacement of a 20-storey building subjected to El-Centro earthquake for different control systems and laws

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