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# Active control of a 20-storey building

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***Abstract*—This paper investigates the active control of a 20-storey building using three different control strategies: Active Mass Damper (AMD), Active Bracing System (ABS) and Connected Building Control (CBC). Various control laws are employed: the Integral Force Feedback, the Direct Velocity Feedback, the first and second order Positive Position Feedback and the "LEAD". The optimal location of the active device is determined for all cases and the effect of some design parameters on the damping are highlighted.**

***Keywords*—Active control, AMD, ABS, CBC, Feedback.**

## I. INTRODUCTION

Since Buildings are sensitive to strong winds and earthquakes, it is a necessity to control their different vibration modes by the use of highly reliable vibration control devices, which are generally classified as passive, active, semiactive or hybrid. These control strategies may be applied to different control designs: using the reaction of (i) a fixed point: Shear Control (ii) an auxiliary mass: Tuned, Active and Hybrid Mass Dampers (iii) an auxiliary structure: Connected Buildings Control (CBC). Active control of civil structures was first introduced by Yao [1] as a mean of protecting tall buildings against storms and became the subject of intensive research subsequently. Active Mass Damper (AMD) was proposed by Chang and Soong [2] as an extension of a passive Tuned Mass Damper to control the vibrations of tall buildings. Some of the interesting works on AMD control include those by Abdel-Rohman [3], Samali et al. [4], Wang and Lin [5] and Guclu and Yazici [6]. Vibration of buildings may be also mitigated by Active Bracing Systems (ABS) which consist in adding active elements between the ground and the first floor or between two successive floors. Good contributions on ABS control include those by Chung et al. [7], Loh et al [8], Lu [9] and Preumont et al. [10]. The active Connected Building Control of tall structures has been investigated by Seto et al. [11], Ying et al. [12], Christenson et al. [13] and Zhu et al [14]. The papers reported by Datta [15], Spencer and Nagarajaiah [16], Fisco and Adeli [17, 18] and Korkmaz [19] provide a detailed review of earlier and recent studies on structural control. By examining the huge amount of literature on active vibration control, the optimal location of the active device the effect of some design parameters on the damping are less investigated. This has brought a lot of confusion amongst the less experienced researchers and engineers. In this paper, we investigate the active control of a 20-storey building using three different control strategies (AMD, ABS and CBC) and various control laws (IFF, DVF, PPF and LEAD). The optimal location of the active device will be determined for all cases and the effect of some design parameters on the damping will be highlighted.

## II. MODELLING OF THE ACTIVE CONTROL

The governing equations of motion of a controlled building, modeled as a shear frame are expressed as follows:

$$[M]\ \{\ddot{x}\}+[C]\ \{\dot{x}\}+[K]\{x\}=\{B\}\ f-[M]\{1\}\ddot{x}_0 \quad (1)$$

where $M$, $C$ and $K$ are respectively the mass, damping and the stiffness of the building and depends on the active control strategies illustrated in Fig. 1. $\ddot{x}$, $\dot{x}$ and $x$ are respectively the acceleration, velocity and displacement vectors. $B$ is the influence vector indicating the location of the active strut and $f$ is the control force which depends on the control law used. $\{1\}$ is a unit vector and $\ddot{x}_0$ is the ground acceleration. Control laws and forces used in this study are given in Table 1 for different control configurations [20].

TABLE I
CONTROL LAWS AND FORCES

| Configuration | Control law | Control force |
|---|---|---|
| A force actuator combined with a displacement sensor | LEAD | $f=-g\,(\frac{s+p}{s+z})\ y$ |
| | DVF | $f=-g\,s\,y$ |
| | PPF1 | $f=\frac{g}{1+\tau s}\ y$ |
| | PPF2 | $f=\frac{g}{s^2+2\xi_f\omega_f s+\omega_f^2}\ y$ |
| A displacement actuator collocated with a force sensor | IFF | $f=K_a(B^T(x_i-x_j)-u)$ where $u=\frac{g}{s}\frac{f}{K_a}$ |

$g$ : controller gain; $s$ : *Laplace* variable; $p$ , $z$, $\tau$ : design parameters; $\omega_f$ : targeted frequency; $\xi_f$ : corresponding damping; $K_a$ : stiffness of the active strut and $u$ is its active displacement; $(x_i-x_j)$ : relative displacement between the extremities of the active strut; $y=(x_i-x_{i-1})$ is the relative displacement between the connected successive floors for the ABS case, $y=x_i$ is the absolute displacement of the $i^{th}$ floor equipped with an inertial mass for the AMD case and $y=(x_{i,1}-x_{i,2})$ is the relative displacement between building 1 and 2 at $i^{th}$ floor level for the CBC case .

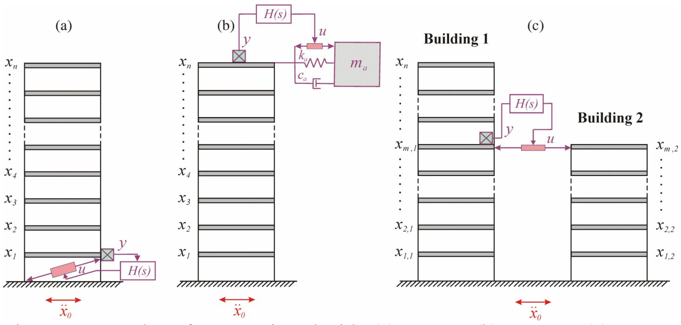


Fig. 1 n-storey shear frame equipped with: (a) an ABS (b) an AMD (c) a CBC.

## III. Numerical Example

Consider a building of twenty stories subjected to unidirectional seismic excitation (white noise). The same mass and stiffness are adopted for all floors and they are respectively equal to $6\text{x}10^5$ kg and $4.5\text{x}10^8$ N/m. A uniform modal damping of 1% is assumed for both buildings. Active damping is added to the structure using first or second order PPF, DVF, Lead or IFF.

### A. Active Bracing System

Using root locus technique, the maximum damping of modes 1 and 2 are determined for all the control laws when added to an Active Bracing System (ABS). Fig. 2 shows that the control using IFF, DVF and Lead produces maximum of damping for the first two modes when the active strut is located between ground and the first floor. For the case of the IFF The maximum damping of the first two modes increases by increasing the stiffness of the active struts as shown in Fig. 2.a and b. The damping of mode one decreases when the location of the active strut goes to the top floor. For the second mode, an increase of the damping is observed when the strut is located between ground and first floor and also when located on the 15th floor. The Lead has the same behavior as the DVF. In fact, when the z=0 and p→ ∞ the Lead becomes DVF. The damping is optimal when the active strut is located between the ground and the first floor as shown in Fig. 2.e and f. The maximum damping depends on the design parameter z which indicates the location of the zero on the real axis. By moving the zero to the left, the maximum damping of the first two modes decreases.

For the case of the First order PPF, the maximum damping of the first mode is reached when the active strut is located between the ground and the first floor as shown in Fig. 3.a and decreases when the Strut Location (SL) goes to the top floor. The maximum damping of mode one also depends on the design parameter τ. In fact, it increases by decreasing τ and a critical damping may be reached for many active strut locations (SL=1 to 7 in this case). PPF1 acts also on the second mode and critical damping may be reached for very small values of τ (see Fig. 3.b). The second order PPF can be target on a specific mode. When the PPF is targeted on the first mode, the damping is maximum for a strut located between the ground and the first floor. Unlike all the other control laws, when the PPF2 is target on the first mode it doesn't act on the second (see Fig. 3.d) and higher modes But when it is targeted on the second mode a critical damping can be reached for the mode1 for an active strut added to the first eleven floors and it acts also on mode2 (see Fig. 3.e and f). Targeting the PPF on the second mode seems more efficient than on the first mode. The damping depends also on the design parameter $\xi_f$ as shown in Fig. 3.c, d, e and f. Infact, by increasing $\xi_f$ the damping increases when the PPF2 is targeted on the first mode and decreases when the PPF2 is targeted on the second mode.

### B. Active Mass Damper

Using IFF, the active control of the building using an auxiliary mass reaches a maximum of damping for the first mode when the AMD is located on the top floor and doesn't act on the second one as shown in Fig. 4.a and b. For the DVF case, a critical damping is obtained for the first mode when the AMD is located on the 10th to 20th floors (see Fig. 4.c) and for the second mode when the AMD is located on the 5th to 9th floor (see Fig. 4.d). When the AMD location changes from 9th to the 1st floor, the damping of the first mode decreases. The best location of the control device seems to be in the 10th floor providing a critical damping for the first mode and a damping of 44,9% for the second mode. As shown in Fig. 4.e, the AMD employing a Lead compensator is very efficient for the first mode when the AMD is located on the upper half of the building and may provide the structure with a critical damping for z ≤ 0.5 . When z = 1, the location of the AMD on the top floor doesn't have a critical damping anymore. For, z > 3 the best location is the 14th or 15th floor. Generally, By increasing z the damping of the first mode decreases but the damping of the second mode may increase or decrease depending on the AMD location. As a best location of the AMD, one can choose the 10th floor and z = 0.2 which provides large damping for the first two modes (100% and 71%).

The active damping using first order PPF, which depends on the design parameter τ and the location of the control device, is illustrated in Fig. 5.a and b. High performances may be obtained for mode 1 when τ=1/2.42. A maximum damping of 57.8% is obtained when the AMD is located on the 16th floor and τ=1/2.42 but doesn't act on the second mode. For the second mode, the damping increases by increasing τ and a maximum damping of 7.76% is obtained when the AMD is located on the 5th floor and τ=1/6. The optimal location, providing a damping of 45.5 % to the first mode and 6.97 % to the second mode, is the 5th floor and τ=1/2.42. When the PPF2 is targeted on the first mode, the damping of the first mode increases by locating the AMD on highest floors as shown in Fig. 5.c. The PPF2_1 doesn't act on the second (Fig. 5.d) and higher modes But when it is target on the second mode the maximum damping can be reached for the first mode for an AMD added to 3rd floor and for the second mode

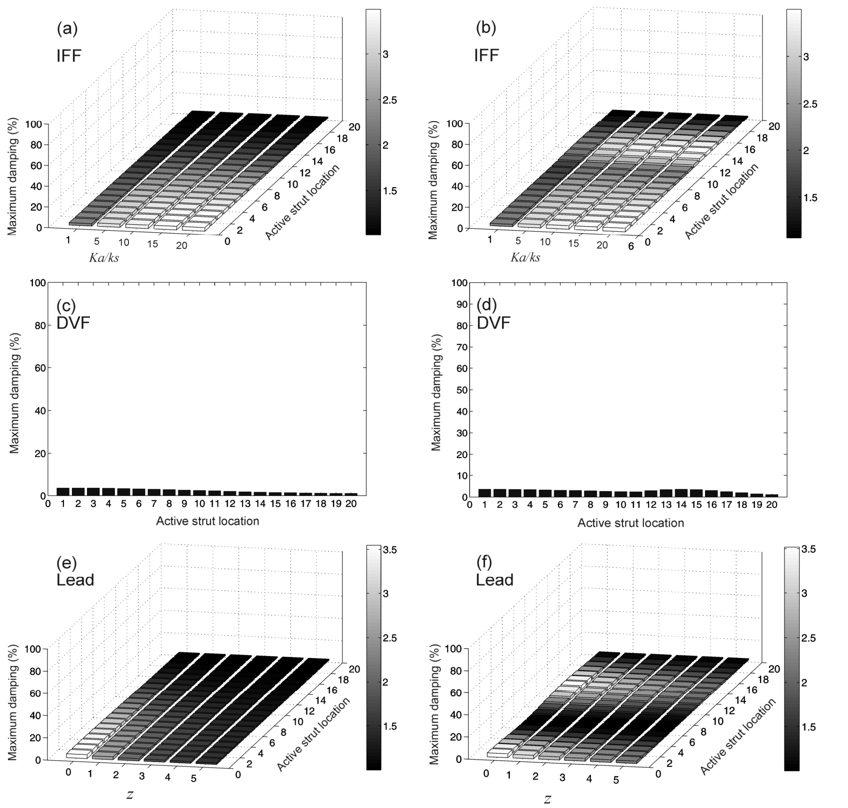


Fig. 2 ABS control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the IFF, DVF and Lead cases.

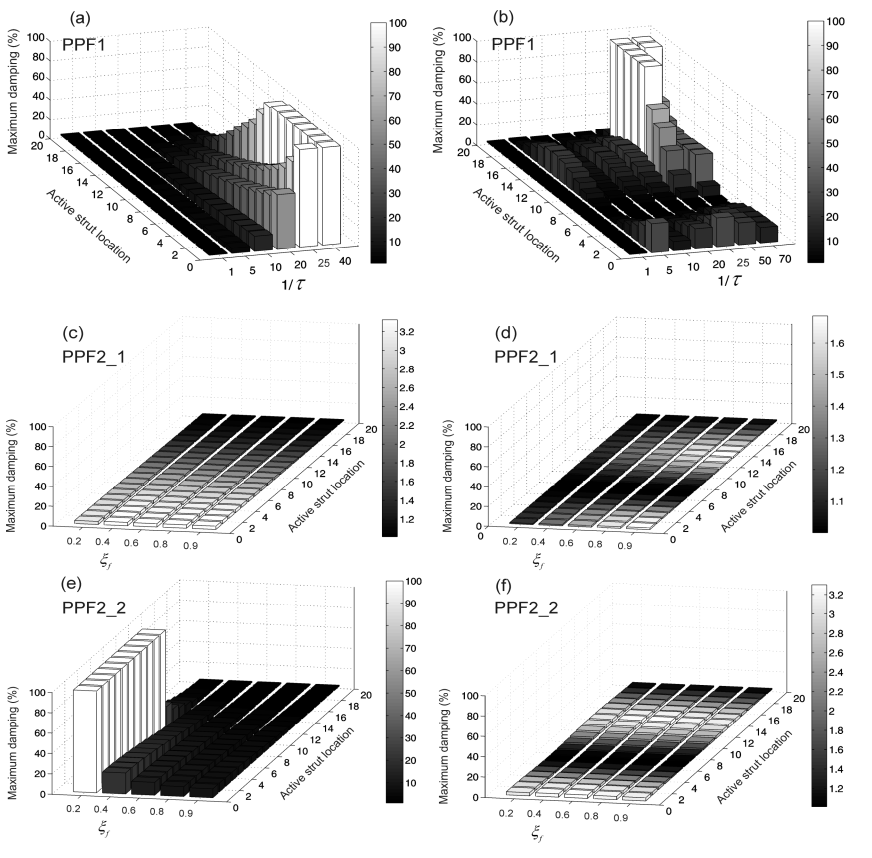


Fig.3 ABS control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the cases of the first order PPF (PPF1), the second order PPF target on mode 1 (PPF2_1) and on mode 2 (PPF2_2).

when the AMD is added to 6th floor as shown in Fig.s 5.e and f. respectively. Targeting the PPF on the second mode seems more efficient than on the first mode. The damping depends also on the design parameter $\xi_f$ . In fact, the damping is maximum for the case of a PPF2 targeted on the first mode when $\xi_f$ is equal to 0.9. For the case of a PPF2 targeted on the second mode, the damping is maximum when $\xi_f$ is equal to 0.4.

*C. Connected Building Control*

The effects of active Strut Location (SL) and Number of the Stories of the auxiliary Building (NSB) on the maximum damping of the first two modes is investigated for different control strategies using the root locus technique. As shown in Fig. 6 and 7, for the various control strategies, the damping of mode one increases by moving the active strut to the level of top floor of the auxiliary building. The damping depends also on the number of the stories (stiffness) of the auxiliary building and weak controllability is observed when both buildings have the same frequencies. For the case of IFF, DVF and Lead, the maximum damping is reached when the number of stories is ten to twelve and the strut location is on the top level of the adjacent building. By observing the damping of the second mode, one can see that the case of ten stories is better than the one of twelve stories. For the case of IFF, Critical damping can be obtained for mode 2 when the number of stories is equal to 14 and 16 and the strut location is on the level of the 12th floor. Using DVF, the maximum of damping of mode 2 is reached when the number of stories is 16 and the active strut is located on the level of the 8th floor. For the control using first order PPF, a critical damping of mode 1 can be obtained for any strut location and story number of the auxiliary building except the case when both buildings have the same frequencies. This means that it is less sensitive to the location of the active device and the stiffness of the adjacent building. But the difference will be in the control effort which will be showed later. By observing the damping of the second mode, the best location is the 5th floor and NSB = 5.

For the second order PPF case, when the control is targeted on the first mode the best location which provides the principal building with maximum of damping on mode 1 is the 10th floor and NSB=10 as shown in Fig. 6.c. The damping increases by increasing $\xi_f$ and the PPF2 doesn't act on the second and higher modes (see Fig.s 7.a and b). when the PPF2 is targeted on the second mode and the locations of the active struts on the top floor of the second buildings having 5 to 18 floors, a critical damping may be reached for $\xi_f$ =0.2 to 0.4 (Fig. 7.c). By increasing $\xi_f$ until 0.9, the damping of mode one decreases. The PPF2 acts on mode 2 whose damping depends on $\xi_f$ and maximum damping is obtained when NSB=10, the active strut is located on top floor of the auxiliary building and $\xi_f$ =0.4 (Fig. 7.d).

*D. Conclusions*

The active control of a 20-storey building is investigated using three different control strategies (AMD, ABS and CBC) and various control laws (IFF, DVF, PPF and LEAD). The optimal location of the active device is determined for all cases and the effect of some design parameters on the damping are highlighted. It has been concluded that the damping is sensitive to the control laws, the active strut location and the design parameters.

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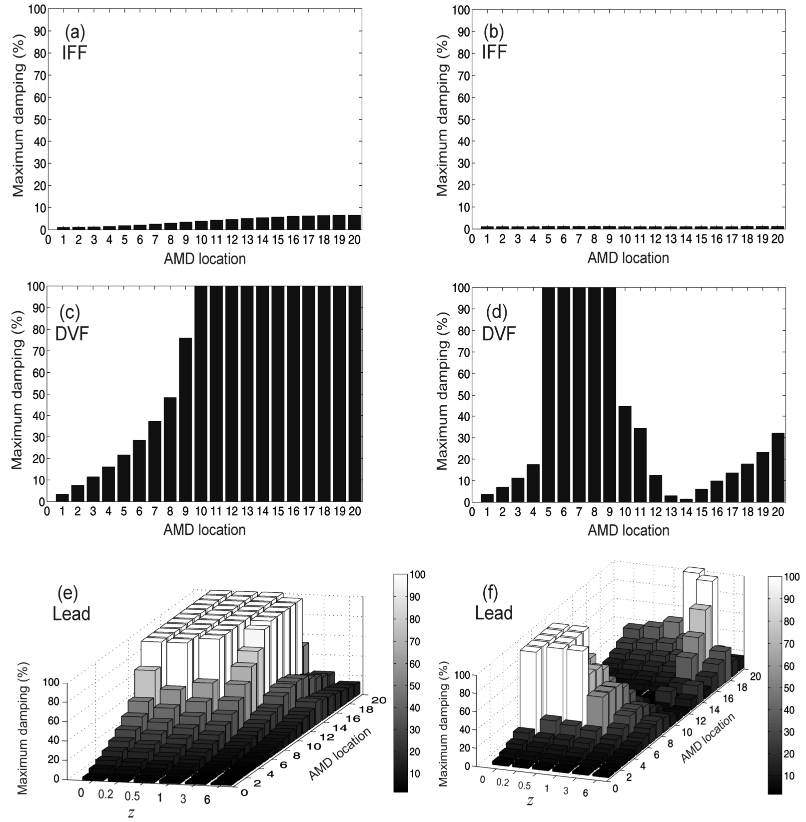


Fig.4 AMD control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the IFF, DVF and Lead cases.

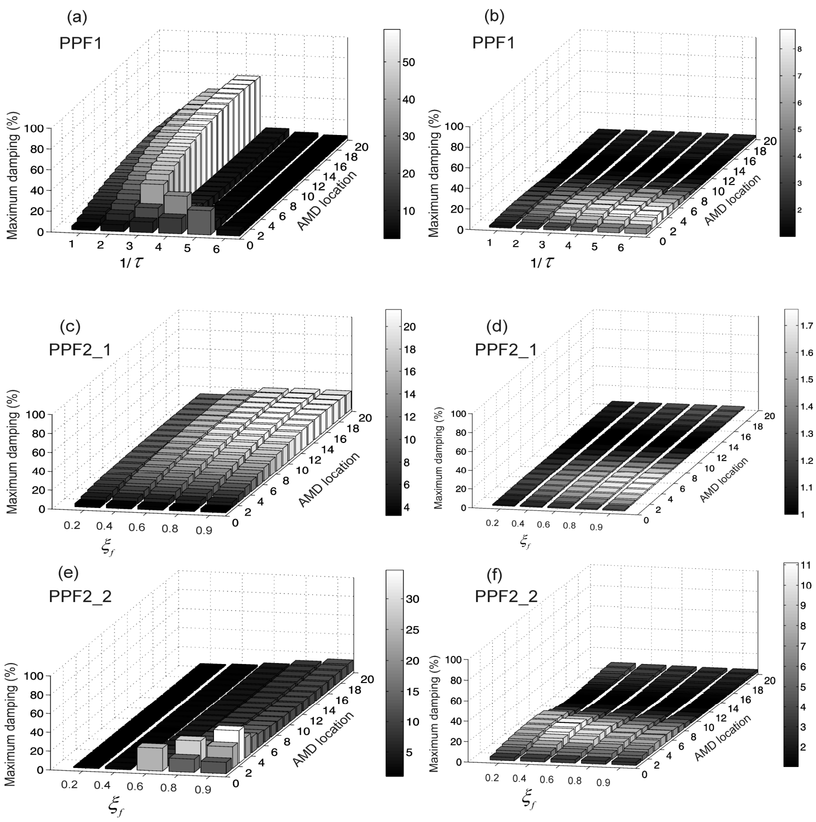


Fig. 5 AMD control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the cases of the first order PPF (PPF1), the second order PPF target on mode 1 (PPF2_1) and on mode 2 (PPF2_2).

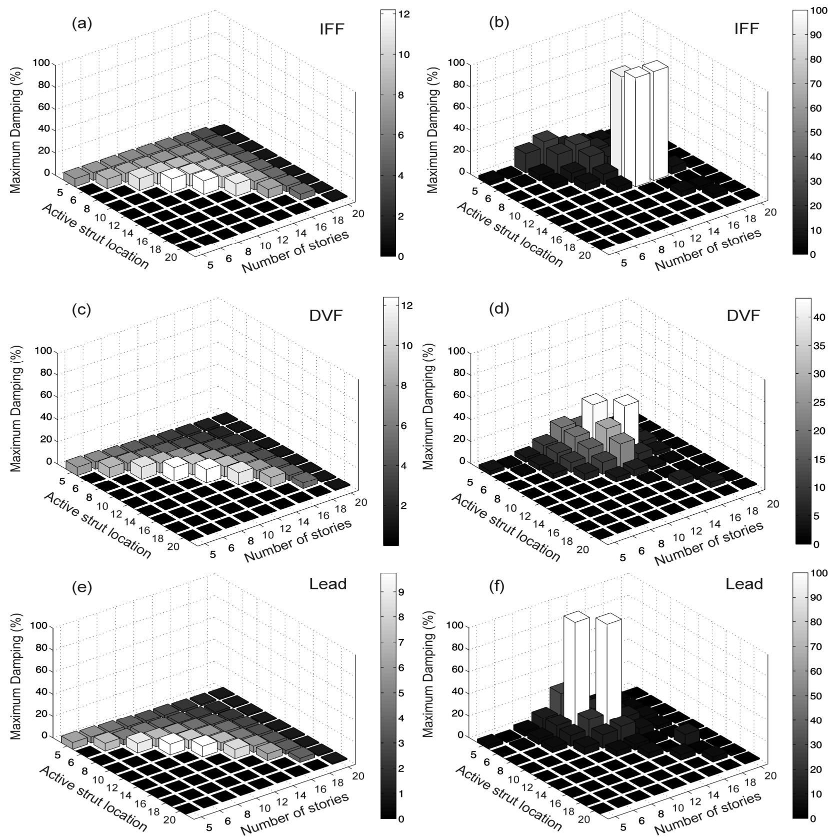


Fig. 6 CBC control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the IFF, DVF and Lead cases.

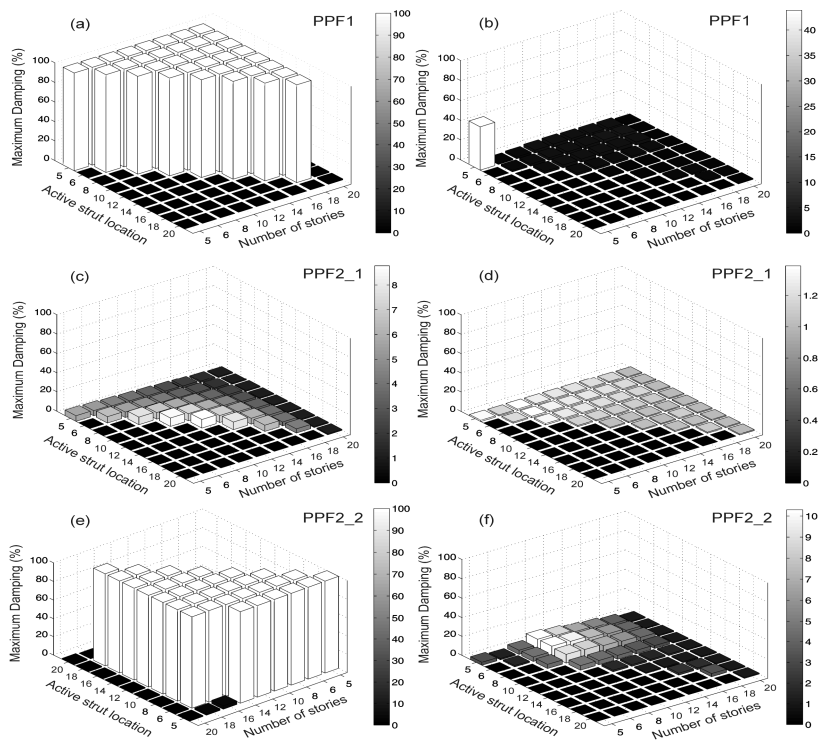


Fig. 7 CBC control: Maximum damping of mode 1 (a, c, e) and mode 2 (b, d, f) for the cases of the first order PPF (PPF1), the second order PPF target on mode 1 (PPF2_1) and on mode 2 (PPF2_2).