

EXPLOITING MULTIPLE REFERENCE MODELS FOR ADAPTIVE CONTROL OF FLEXIBLE STRUCTURES

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Abstract. *Flexible structures like tall buildings are often equipped with active control systems which allow the reduction of structural vibration induced by wind and earthquakes. Wind gusts and earthquakes are different in terms of intensity level, frequency and duration of the excitation. In particular, wind induced vibrations are usually moderate and require a continuously operating control system whose main goal is to provide occupants' comfort in serviceability conditions. Conversely, earthquakes of significant intensity are rarely experienced by the structure and may produce structural damage that leads to deterioration in structural stiffness. The use of Model-Reference Adaptive Control (MRAC) has recently been considered for structural applications for its capability of dealing with systems's uncertainties and time dependence of parameters. The adaptive controller has two loops: the inner loop consists of an ordinary feedback control process while the outer loop adjusts the controller parameters through an adaptation rule in order to minimize the difference between measured output and model output. In this paper the use of MRAC in conjunction with a Lyapunov-based adaptation rule is investigated for the response mitigation of a tall building equipped on top with an active device and subjected to both wind and seismic hazards. Since the required structural performances in case of wind and earthquake-excited vibrations are different, in order to optimize the control effectiveness, a modified MRAC algorithm based on multiple reference models (M-MRAC) is proposed in which the switch between the targets is performed based on the measured feedback information. The main advantage of the proposed methods is its capability of providing power saving and limitation of the peak control force. Parametric analyses allow to identify proper threshold levels for the switching condition and optimal reference models providing a compromise between safety and economy. Results of the numerical analyses on a benchmark tall building show the effectiveness of the control strategy for several loading conditions.*

1 INTRODUCTION

Active control is an appealing technique, already adopted in many tall buildings for mitigation of wind- and earthquake-induced vibrations. The effectiveness of active control is closely linked to the selected control algorithm. The most widespread strategies are those based on linear optimal control or robust control [1, 2] but they can not fully manage uncertainties in modal parameters evaluation, loads variability, system's non-linearities and physical limits of actuators [3]. For these reasons adaptive control strategies recently have started to be used for structural control.

Model Reference Adaptive Control is an adaptive algorithm which updates the parameters of the controller for tracking the response of a reference model. The actual system's response is compared to the target response and the control parameters are modified as a function of the error. While many applications of MRAC are available in the mechanical and aeronautical fields, still a few studies exist for civil structures [4, 5, 6].

Tall buildings can experience different vibration levels when subjected to earthquake and wind hazards. Consequently, active control has to allow satisfaction of serviceability requirements under wind load and to avoid occurrence of severe damage under seismic load.

In this paper a modified MRAC algorithm based on multiple reference models (M-MRAC) is proposed, capable of switching between targets depending on the measured feedback information. The idea of switching between different models has recently been proposed in literature [7] but never exploited for civil engineering applications. A preliminary parametric analysis on a tall building equipped with an AMD on top and subjected to both seismic and wind loads allows to define the characteristics of multiple reference models. Analysis results demonstrate the effectiveness of the method in optimizing the control performance and in reducing the required control force.

2 ADAPTIVE CONTROL WITH MRAC

2.1 Dynamics of the structure and the reference model

The considered structure is a tall building modeled as a multi-degrees of freedom dynamic system, subjected to external excitation \mathbf{f} and to a control force \mathbf{u} . The equation of motion is:

$$\mathbf{M}_s \ddot{\mathbf{z}}_s + \mathbf{C}_s \dot{\mathbf{z}}_s + \mathbf{K}_s \mathbf{z}_s = \bar{\mathbf{E}}_s \mathbf{f} + \bar{\mathbf{B}}_s \mathbf{u} \quad (1)$$

where \mathbf{M}_s , \mathbf{C}_s and \mathbf{K}_s are the mass, damping and stiffness matrices of the building, $\bar{\mathbf{E}}_s$ and $\bar{\mathbf{B}}_s$ are the location matrices of the external excitation and the control force, respectively. In MRAC, a reference model is defined that is subjected to the same external disturbance \mathbf{f} whose dynamic behavior is the target. The equation of motion of the reference system is:

$$\mathbf{M}_r \ddot{\mathbf{z}}_r + \mathbf{C}_r \dot{\mathbf{z}}_r + \mathbf{K}_r \mathbf{z}_r = \bar{\mathbf{E}}_r \mathbf{f} \quad (2)$$

where \mathbf{M}_r , \mathbf{C}_r and \mathbf{K}_r are the mass, damping and stiffness matrices of the reference model, $\bar{\mathbf{E}}_r$ is the location matrix of the external excitation.

In state-space formulation, the equations of motion become:

$$\dot{\mathbf{x}}_s = \mathbf{A}_s \mathbf{x}_s + \mathbf{E}_s \mathbf{f} + \mathbf{B}_s \mathbf{u} \quad (3)$$

$$\dot{\mathbf{x}}_r = \mathbf{A}_r \mathbf{x}_r + \mathbf{E}_r \mathbf{f} \quad (4)$$

where

$$\mathbf{x}_s = [\mathbf{z}_s, \dot{\mathbf{z}}_s]^T \quad (5)$$

$$\mathbf{x}_r = [\mathbf{z}_r, \dot{\mathbf{z}}_r]^T \quad (6)$$

\mathbf{A}_s , \mathbf{A}_r are the system matrices of the structure and the reference model respectively, \mathbf{E}_s , \mathbf{E}_r and \mathbf{B}_s are the location matrices.

A linear feedback control law is adopted for computing the control force:

$$\mathbf{u} = \mathbf{K}\mathbf{x}_s \quad (7)$$

where \mathbf{K} is the vector collecting the states' gains.

2.2 Adaptation law

In MRAC control scheme both the structure and the reference model are subjected to the same external excitation \mathbf{f} which is supposed to be measured. To derive the adaptation law, the error vector \mathbf{e} is computed as follows:

$$\mathbf{e} = \mathbf{x}_s - \mathbf{x}_r \quad (8)$$

The knowledge of the states of the structure is considered available and the target response is computed through the reference model.

A stable adaptation law used to adjust the controller's parameters is computed based on the definition of a Lyapunov function as follows:

$$V = \mathbf{e}^T \mathbf{P} \mathbf{e} + \boldsymbol{\phi}^T \boldsymbol{\Gamma}^{-1} \boldsymbol{\phi} \quad (9)$$

where $\boldsymbol{\phi}$ is the parameter error vector, \mathbf{P} is a positive definite symmetric matrix, $\boldsymbol{\Gamma}$ is the positive definite adaptation gain matrix. In order to obtain an asymptotically stable adaptive system, the time derivative of the Lyapunov function \dot{V} , must be negative definite. Differentiating V yields:

$$\dot{V} = \mathbf{e}^T (\mathbf{A}_r^T \mathbf{P} + \mathbf{P} \mathbf{A}_r) \mathbf{e} + 2\mathbf{e}^T \mathbf{P} \mathbf{b}_I \boldsymbol{\phi}^T \mathbf{x}_s + 2\boldsymbol{\phi}^T \boldsymbol{\Gamma}^{-1} \boldsymbol{\phi} \mathbf{P} \mathbf{e} + \boldsymbol{\phi}^T \boldsymbol{\Gamma}^{-1} \dot{\boldsymbol{\phi}} \quad (10)$$

By applying the Lyapunov's equation ($\mathbf{A}_r^T \mathbf{P} + \mathbf{P} \mathbf{A}_r = -\mathbf{Q}$), positive definite symmetric matrices \mathbf{P} and \mathbf{Q} can be found such that the first part of Equation 10 is negative definite. By putting the last two terms of Equation 10 to zero, the adaptive law is obtained:

$$\dot{\boldsymbol{\phi}} = -\boldsymbol{\Gamma} \mathbf{e}^T \mathbf{P} \mathbf{b}_I \mathbf{x}_s \quad (11)$$

$$\dot{\mathbf{K}} = \dot{\boldsymbol{\phi}} \mathbf{M}_s^{-1} \quad (12)$$

The adaptive control gain vector \mathbf{K} is obtained by time integration.

3 MULTIPLE-MODEL REFERENCE ADAPTIVE CONTROL (M-MRAC)

Structures subjected to multiple hazards with different levels of excitation exhibit different performance. In order to guarantee the respect of various limit states under multiple hazard, it is convenient to define multiple reference models providing different target performance. The choice of the reference models is important for the determination of the best compromise between structural performance and power saving.

The reference model is a dynamic system described by the following equation:

$$\dot{\mathbf{x}}_r = \mathbf{A}_r(\sigma) \mathbf{x}_r + \mathbf{E}_r \mathbf{f} \quad (13)$$

where the state matrix $\mathbf{A}_{r\sigma}$ is a piecewise continuous function of time depending on the parameter characterizing switching conditions $\sigma(t)$. The multiple reference models' state matrix is defined as follows:

$$\mathbf{A}_r(\sigma) = \begin{cases} \mathbf{A}_{r,0} & \text{for } \sigma(t) < \sigma_1 \\ \mathbf{A}_{r,1} & \text{for } \sigma_1 \leq \sigma(t) < \sigma_2 \\ \dots & \\ \mathbf{A}_{r,n} & \text{for } \sigma(t) \geq \sigma_n \end{cases} \quad (14)$$

where $\sigma_1, \dots, \sigma_n$ are switching thresholds. The parameter σ can be a measured state of the system or a generic response parameter.

In the simplified case of two reference models, the switching rule becomes:

$$\mathbf{A}_{r,\sigma} = \begin{cases} \mathbf{A}_{r,0} & \text{for } \sigma(t) < \bar{\sigma} \\ \mathbf{A}_{r,1} & \text{for } \sigma(t) \geq \bar{\sigma} \end{cases} \quad (15)$$

where $\bar{\sigma}$ is the switching threshold.

In order to obtain good performance of the control system, the switching rule must be properly selected. Repeated switching may potentially lead to optimized performance but a too high commutation frequency can lead to improper system's behavior [8]. Nevertheless, due to the high natural periods of structures under investigation the critical dwell time is usually reasonably well below the switching time intervals.

4 THE CASE STUDY

4.1 Description of the tall building

The structure chosen as case study is the 76-story building, 306 meters high, proposed as a benchmark problem for response control under wind load [9]. It is a reinforced concrete building consisting of a concrete core, designed to resist lateral loads and concrete frames mainly devoted to support gravity loads. The building has a square cross section with chamfer at two corners, constant along the height. A simplified dynamic model of the building with 1DOF for each floor is considered in the analyses. Damping ratio for all modes is 1% and the first natural frequency is 0.16 Hz. Figure 1 shows the plan and elevation views of the structure.

4.2 Wind and seismic loads modeling

Wind loads adopted for the analyses were obtained by tests performed in the boundary layer wind tunnel facility at the Department of Civil Engineering at University of Sidney, Australia [10]. The rigid model of the building had a length scale of 1:400. Wind pressures were recorded for 27 seconds, corresponding to about 1 hour in prototype scale. Pressure coefficients were integrated and converted into across-wind forces at each story. The mean wind velocity at the top of the building was 47.25 m/s corresponding to a reference wind velocity $V_{ref} = 13.5$ m/s at 10 m above ground, representing serviceability conditions at which occupant's comfort and motion perception are important design criteria.

In order to consider uncertainties on measurement variability and to characterize statistically the wind load, 7 sets of time histories each one having a duration of 10 minutes are extracted from the measured time histories of the lateral wind forces and used to compute the structural response.

results:

$$J_1(\%) = \frac{\max|\text{IDR}|_r}{\max|\text{IDR}|_{lim}} \quad (16)$$

$$J_2(\%) = \frac{\max|\ddot{\mathbf{z}}|_r}{\max|\ddot{\mathbf{z}}|_{lim}} \quad (17)$$

$$J_3(\%) = \frac{\max|\mathbf{M}_b|_r}{\max|\mathbf{M}_b|_{lim}} \quad (18)$$

where IDR is the interstory drift ratio, $\ddot{\mathbf{z}}$ is the structural acceleration, \mathbf{M}_b is the bending moment at the base of the building. Subscript r refers to the reference model and subscript lim refers to the acceptable threshold levels.

The most important response components to limit in order to ensure comfort and avoid damage to non-structural components are interstory drifts and accelerations. For serviceability, according to [13], 1/400 of the story height can be set as the limit state threshold for maximum interstory drift. For the motion perception acceleration threshold, the following relation can be adopted [14]:

$$\ddot{\mathbf{z}}_{lim} = \frac{a_0}{f_0^{0.56}} \quad (19)$$

where f_0 is the dominant natural frequency, $a_0 = 6 \text{ cm/s}^2$, for office buildings.

Regarding the strength limit state, the threshold value of maximum bending moments at the base of the internal core is obtained as follows:

$$\mathbf{M}_{b,lim} = \varphi_{lim} EI \quad (20)$$

where EI is the flexural stiffness and φ_{lim} is the curvature at the elastic limit of the reinforced concrete central core. Since the control system is supposed to maintain the central core below its yielding limit, the hypothesis of linear elastic behavior is justified and the structural response is computed by linear analysis with time domain integration.

Table 1 shows mean values and standard deviations of the peak response components. Results are obtained for damping ratio equal to the 1% (the nominal value for the building), under wind and seismic loads. Results show that interstory drifts and base bending moments due to wind load are one order of magnitude smaller than those due to seismic load. Moreover, earthquake-induced accelerations are much higher than wind-induced ones. This results is in keeping with full scale observations. High accelerations in tall buildings were observed in response to the 2011 Tohoku earthquake, and shown to be due to higher mode effects [15].

	Wind		Earthquake	
	Mean value	Standard deviation	Mean value	Standard deviation
IDR_{max} (m)	1.70e-3	0.61e-3	1.72e-2	1.12e-2
$\ddot{\mathbf{z}}_{max}$ (m/s ²)	0.25	0.02	26.19	7.45
$\mathbf{M}_{b,max}$ (Nm)	5.39e6	1.85e6	6.06e7	3.39e7

Table 1: Mean values and standard deviations of peak response components for damping ratio of 1%.

Figure 2 reports the mean values of performance indices (computed adopting the 7 accelerograms and the 7 wind load time histories) for different values of damping ratio (1%, 5%, 10%,

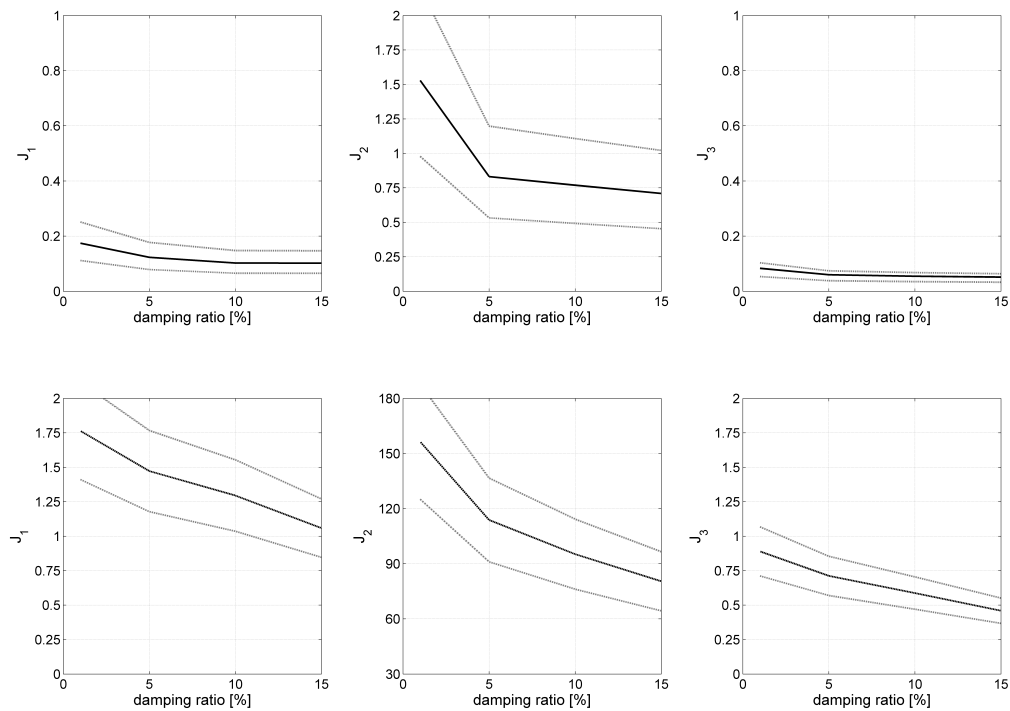


Figure 2: Performance indices as a function of damping ratio computed using wind load (top) and seismic load (bottom)

and 15%). The three top diagrams show response under wind load and the bottom ones show response obtained using the set of earthquakes. The grey dotted lines represent the performance indices obtained by varying PGA_{ref} and V_{ref} by the 40% ($\pm 20\%$) to account for randomness of the seismic intensity and the reference wind speed. Values of performance indices larger than unity indicate limit state crossing. Results show that index J_1 on interstory drifts ratio is smaller than unity for wind load and higher than unity for earthquake, unless damping ratios higher than 15% are adopted. Index J_2 on peak accelerations is significantly higher than unity for earthquake load, meaning that in seismic conditions limit state on motion perception is always exceeded and occupants comfort condition cannot be satisfied. In case of wind load, index J_2 can be reduced below unity for values of damping ratio higher than about 5%. Index J_3 related to yielding of the central core is smaller than unity for both wind and seismic load.

In order to ensure occupants' comfort, a reference model with 5% damping ratio can be used but to the extent of reducing drift-dependent damage to non-structural elements a reference model with 15% damping ratio must be adopted. Although the choice of reference models' damping cannot be generalized (as it depends on the building's dynamic characteristics and the specific site's conditions), the sensitivity analyses demonstrate that the optimal target damping is not unique for different limit states.

5.2 Analysis with M-MRAC

In order to evaluate the effectiveness of the modified MRAC procedure (M-MRAC), several analysis are carried out on a simplified 1 degree of freedom model having mass equal to the first

modal mass and natural period equal to the one of the selected tall building.

The two reference models are chosen on the basis of the preliminary analyses presented in Section 5.1. In particular, in order to ensure occupants' comfort in serviceability conditions, an uncontrolled target system with 5% damping ratio is adopted. In order to avoid damage to drift-sensitive non-structural elements, an uncontrolled target system with 15% damping ratio is selected.

The response component $\sigma(t)$ which determines the switching condition is the building's peak displacement that is related to drift dependent damage. In the present analyses, without loss of generality, the switch between different models is activated when the structural displacement is $\bar{\sigma} = 0.5$ m.

Figure 3(a) shows the response of the uncontrolled system (U), the reference model (R) and the controlled system with M-MRAC to a step loading with a short ramp. The reference model has no control system and a damping of 15%. In this case the applied load does not activate the switching condition. Structural responses and load are normalized with respect to their maximum absolute values. Results show very good matching between the target model and the real system. Figures 3(b) and (c) show the states errors and control force, normalized with respect to their maximum absolute values, which tend to zero with time. Figure 4 shows

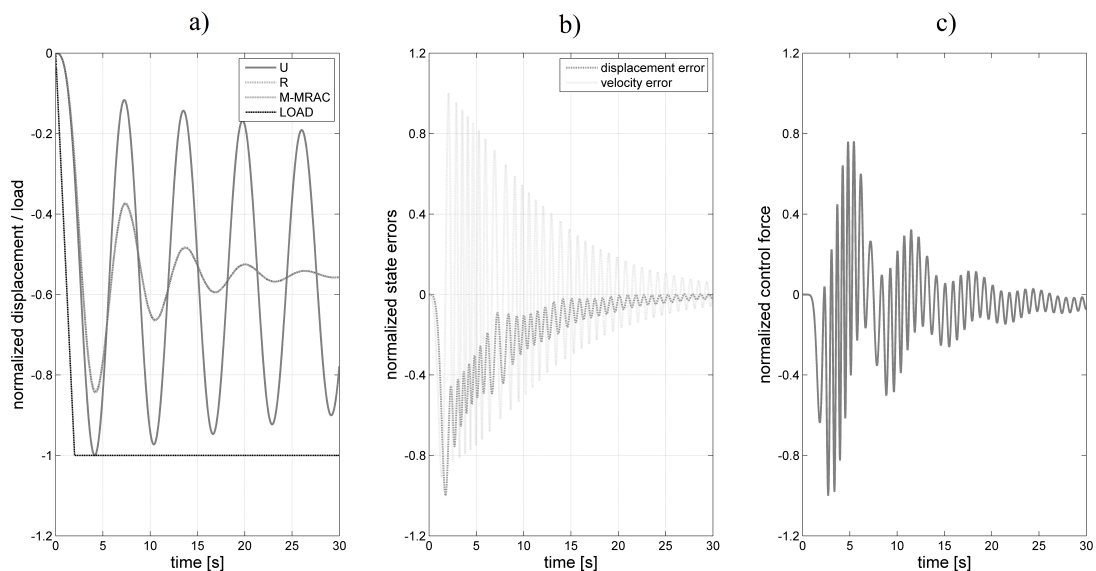


Figure 3: Controlled response obtained with M-MRAC to a step loading if reference model switching is not activated.

the performance of M-MRAC to a sinusoidal loading with natural frequency of 0.4 Hz and amplitude which increases up to its maximum value and after a slight impulsive variation is kept constant. Figure 4a shows the uncontrolled response (U), the response of the reference model (R) and the controlled response obtained with M-MRAC. Displacements are normalized with respect to $\bar{\sigma}$, showing that reference model switching is activated repeatedly. It can be observed that there is a very good matching between responses of the reference model and the controlled structure and that the system properly reduces peak displacements with respect to the uncontrolled case. Figure 4(b) compares normalized displacements obtained with the proposed M-MRAC and traditional MRAC. In this latter case, the reference model that the

system has to track is unique and has a damping ratio equal to 15%, corresponding to the damping required in case of seismic events. Figures 4(c) and (d) show the displacement error and control forces, normalized with respect to their maximum absolute values. It is possible to observe that state errors are kept limited and have the tendency to decrease with time. The control force required by M-MRAC is smaller than the one required by traditional MRAC, demonstrating the advantage of adopting multiple reference models.

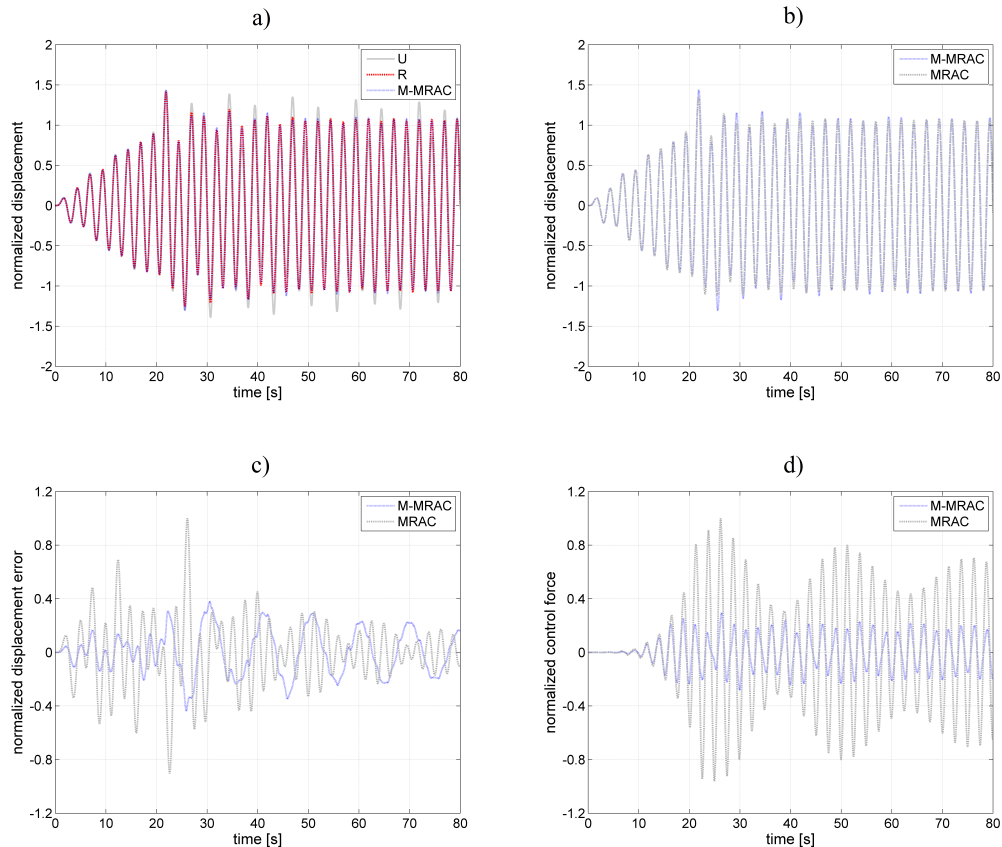


Figure 4: Performance of M-MRAC under sinusoidal loading.

In order to investigate the M-MRAC performance to real loading conditions, an earthquake capable of activating switching condition for several cycles is applied to the structure. Figure 5 shows the performance of M-MRAC to a base seismic accelerogram (represented in Figure 5(a)). Figure 5(b) shows the uncontrolled response and the response of the controlled systems with the proposed M-MRAC and traditional MRAC. Figures 5(c) and (d) show the displacement error and control forces, normalized with respect to their maximum absolute values. Also in case of extreme seismic loading, state errors tend to decrease with time and the control force required by M-MRAC is smaller than the one required by MRAC.

The effect of excitation frequency on M-MRAC performance is investigated by computing systems' responses to harmonic loads with frequency varying between 0.05 Hz and 1.00 Hz. As system's maximum response depends on frequency, the displacement threshold establishing switching condition is set equal to the 80% of the peak uncontrolled value. Figure 6(a) shows

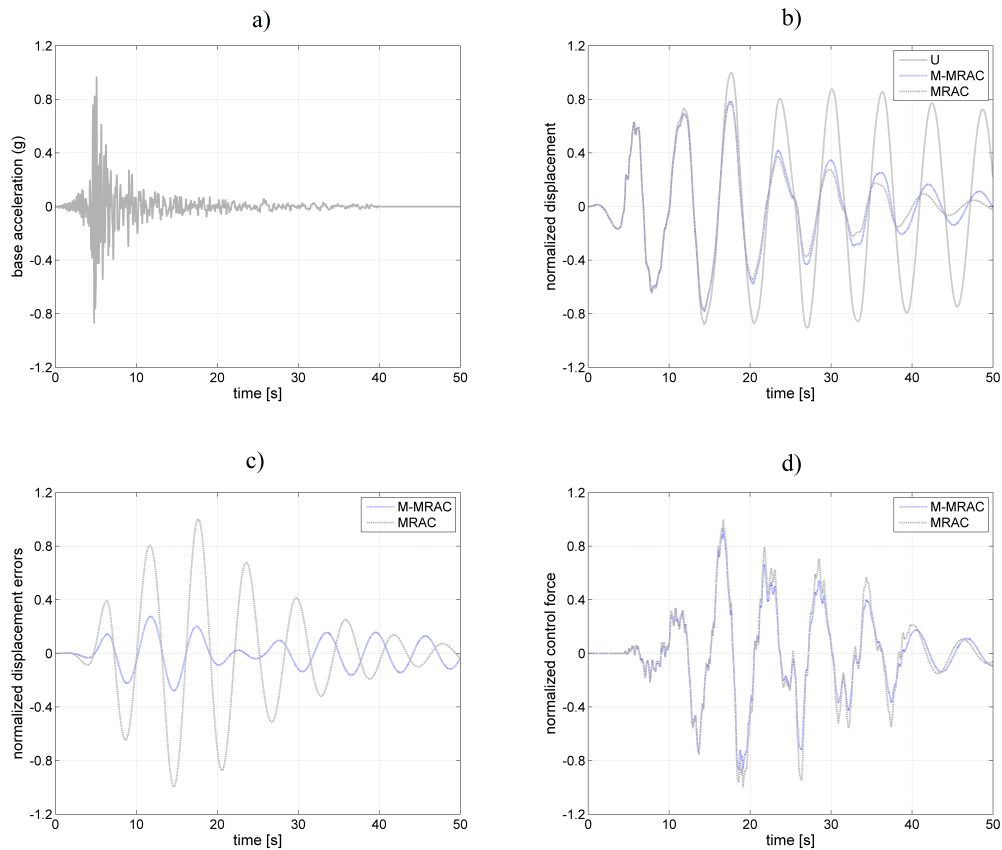


Figure 5: Performance of M-MRAC under seismic loading.

the peak displacements of the uncontrolled system and the controlled systems with M-MRAC and MRAC, normalized with respect to the maximum uncontrolled peak response. Figure 6(b) shows the peak control forces required by M-MRAC and MRAC normalized with respect to maximum peak control force. Results show that M-MRAC provides a significant reduction of the maximum required control force at the expense of an increase in structural response. This limited growth in structural response, which is less important in case of non-harmonic excitation (Figure 5), can be partially compensated by properly varying the gap between reference models' dampings.

6 CONCLUSIONS

The paper exploits the possibility of adopting multiple reference models for adaptive control of tall buildings subjected to multiple hazards. With this aim, the standard Model Reference Adaptive Control algorithm is modified through the adoption of multiple reference models. The motivation of the proposed algorithm enhancement is that flexible buildings require various damping levels to avoid the occurrence of different limit states. This problem is also more important when the tall building is subjected to multiple hazards, like wind and earthquake, having different characteristics in terms of frequency, amplitude and duration of load.

A benchmark tall building is chosen as case study to examine the effectiveness of the pro-

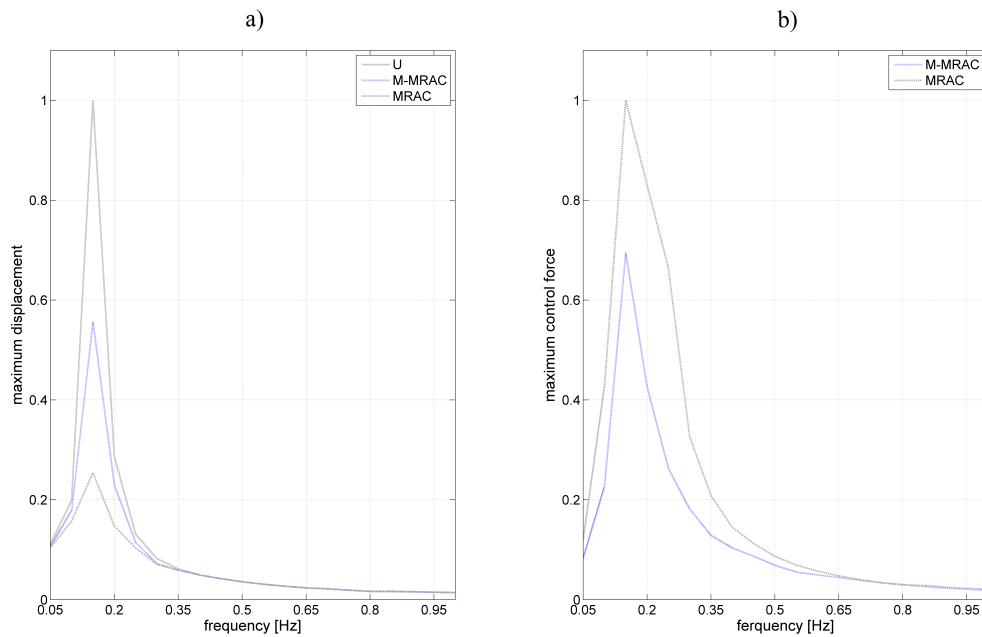


Figure 6: Peak displacements and control forces as a function of the harmonic excitation frequency.

posed control strategy. After preliminary parametric analyses for choosing the optimal reference systems, several investigations on the performance of M-MRAC are carried out. Results show the capacity of M-MRAC in tracking the target system and in reducing the structural response. Comparison between results obtained with traditional MRAC demonstrates that the main advantage of M-MRAC is the reduction of the required control force, at the expense of a slight reduction of control effectiveness.

Future developments of the work will deepen the effects of dwell time, reference models' characteristics, system's uncertainties and non-linearities.

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