Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 1816–1821

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Active control of art objects subjected to seismic excitation

Ilaria Venanzi[a,*], Laura Ierimonti[a], Annibale Luigi Materazzi[a]

[a]*Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti 93, Perugia 06125, Italy*

Abstract

The problem of the protection of statues and works of art is important in earthquake-prone regions. Among mitigation techniques, the base isolation demonstrates to be one of the most effective, as it creates a disconnection between the artwork and the floor that avoids the seismic acceleration transmission. Although passive base isolation systems, if well designed for a specific location and a specific piece of art, are efficient in protecting the artifact, they are not immediately adaptable for different artworks, different locations within the building and different seismic hazard conditions. For these reasons, in the present paper it is exploited the possibility of using a base active control strategy in which a force provided by an actuator counterbalances the seismic acceleration. The base active and passive control solutions are compared considering different seismic intensities and different characteristics of the artwork. Results demonstrate the robustness and adaptability of active control for the seismic protection of works of art.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Base active control; seismic protection; museum artifacts.

1. Introduction

During recent seismic events in 2016-17 in Central Italy several damages to statues and works of art housed in museums and expositions occurred (Figure 1). Strong earthquakes can produce irreparable damage and lead to inestimable losses to the historical and artistic heritage. For these reasons, large effort has been recently devoted to the development of methods for the seismic protection of museum artifacts [1–3].

The seismic response of an artifact is characterized by different types of mechanisms: sliding, rocking and combination thereof. When the statue is simply supported on its basement and it is free to rotate or slide, the motion can be adequately described using rigid body mechanics.

Passive protection techniques, like base isolators and mechanical sliding isolators, have been adopted in some cases. If well designed, they are effective in protecting an artifact with specific characteristics and location but, as the isolators' performance is dependent on the characteristics of the isolated structure, they are not immediately adaptable for different works of art and seismic hazard conditions. Moreover they can only reduce the sliding and rocking response but, in most cases, they cannot avoid at all the activation of the mechanisms. To improve the performance of the control device it is possible to adopt semi-active and active control techniques which are more robust with respect to loading conditions and uncertainties in the system modeling.

* Corresponding author. Tel.: +39-075-585-3908 ; fax: +39-075-585-3908.
E-mail address: ilaria.venanzi@unipg.it

1877-7058
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.096

a) b)

Fig. 1. Collapses of statues due to the seismic sequence in Central Italy (2016) (a) San Bartolomeo statue in Santa Maria della Consolazione temple (Todi, Perugia); (b) bronze statue by Cola dellAmatrice (Amatrice, Rieti).

In this paper it is exploited the possibility of using an active control device for the seismic protection of museum artifacts. An actuator connected to the basement of the work of art provides the required control force and accelerometers located on the basement measure the necessary feedback information. A linear velocity feedback (LVF) control law is adopted in order to avoid displacements and rotations of the artifact. Parametric analyses on the variation of the characteristics of works of art and on seismic intensity demonstrate the adaptability of the proposed control solution to different artifacts and its robustness with respect to the seismic input. In order to optimize the control strategy, preliminary investigations are also carried out to evaluate the possibility of using a Model Reference Adaptive Control algorithm for the same application.

2. Dynamics of the actively controlled system

2.1. Description of the model

The model adopted to investigate the base active control system consists of a museum artifact over a rigid case and subjected to base acceleration due to seismic excitation x_g (Figure 2). The system is supported by passive base isolators with stiffness k and damping coefficient c. The mass of the artifact and the basement are denoted as m_{art} and m_{case}, respectively. An electric servomotor allows the application of the control force u. Accelerometers measure the acceleration of the basement and the ground.
In seismic protection of works of art it is commonly assumed that the control system has to prevent the activation of the sliding and rocking mechanisms. Therefore the system is described by a single degree of freedom system (the displacement of the basement x), assuming that no relative motion between the basement and the work of art occurs. In particular, the sliding is not activated if the following inequality holds:

$$\ddot{x} + \ddot{x}_g \leq \mu g \tag{1}$$

where μ is the friction coefficient at the contact between the basement and the work of art and g is the acceleration of gravity. The rocking motion is not activated if:

$$\ddot{x} + \ddot{x}_g \leq \frac{B}{H} g \tag{2}$$

where B and H are the horizontal and vertical distances between the center of gravity and one of the extreme points of the base of the piece of art.

2.2. Control strategy

The control is activated when the ground acceleration is above a specific threshold ($\ddot{x}_g \geq \beta$). The thresholds β is set on the basis of the vibration level induced by other sources of excitation (different from the earthquake). The instant of time when the control is activated is the *activation time* and is denoted by t_0.

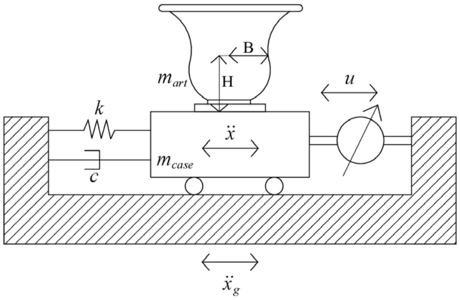

Fig. 2. Scheme of the actively controlled art object.

The control force has to counterbalance as much as possible the effects of the seismic excitation and to damp out the seismic acceleration at t_0. The equation of motion of the system is:

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g + u \quad (3)$$

where $m = m_{art} + m_{case}$ is the total mass of the system, u is the control force and $\ddot{x}(0) = \ddot{x}_g(t_0)$ is the initial condition. It can be written in state space form as follows:

$$\dot{z} = Az + Bu + E\ddot{x}_g \quad (4)$$

where $z = [x, \dot{x}]^T$, A is the state matrix, B and E are location vectors of the control force and the seismic loading, respectively.
Without loss of generality, the control force u is computed with a skyhook algorithm in which it is proportional to the velocity of the basement, obtained by integrating the measured acceleration:

$$u = GDz \quad (5)$$

where G is the control gain and $D = [0, 1]$.

3. Numerical analyses

To investigate the base active control of art objects, numerical analyses are carried out with reference to the model of a symmetric artifact whose characteristics are shown in Table 1. The artifact is considered subjected to an accelerogram corresponding to the ElCentro 1940 seismic ground motion record.
The threshold on maximum displacement is set to 10 cm, a value that is considered acceptable from the viewpoint

Table 1. Parameters used for the numerical analyses.

m_{art} (kg)	m_{case} (kg)	B (cm)	B (cm)	μ
200	100	0.33	1.00	0.40

of the exhibition set-up. The threshold on maximum acceleration is established based on the activation condition for rocking (Eq. 2) which is more restrictive than the one for sliding (Eq. 1), for the specific artifact under investigation. A parametric analysis is carried out on stiffness and damping of the base isolator. The contour plots in Figure 3 represent the peak displacements and accelerations normalized with respect to the threshold levels. Values of $k = 1000$ N/m and $c = 1000$ Ns/m are selected, ensuring safety to the system under the expected excitation. Figure 4 shows the normalized displacements and accelerations of the passively controlled system for two different heights of the building ($Z_0 = 10$ m and $Z_1 = 20$ m). The amplification factors of the seismic excitation for the two locations is computed according to the Eurocode 8 [4] as a function of the fundamental period of the structure and the floor's height. For Z_0 the response is smaller than one, showing that the passive control system, designed for a specific art object and a

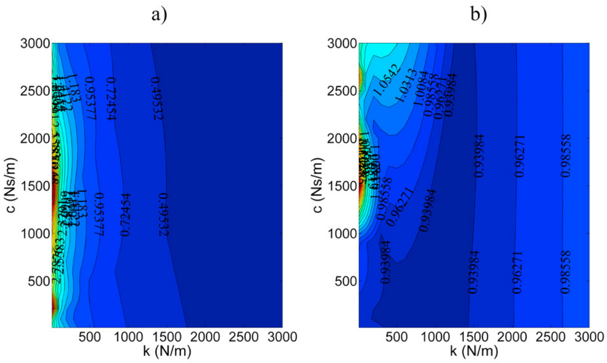

Fig. 3. Contour plots of normalized peak displacements (a) and accelerations (b).

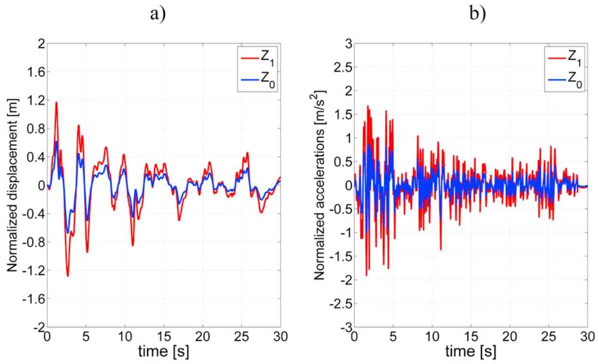

Fig. 4. Normalized response of passive system at Z_0 and Z_1: (a) displacements; (b) accelerations.

specific location can protect the system. Conversely, for Z_1 the passive control can no longer ensure safety. Another drawback of the passive protection technique is that it cannot fully manage the sources of uncertainty involved in the system's design, like the uncertainty in assessing buildings natural frequencies and modal dampings and uncertainty related to the possible variation of structural stiffness during the seismic event (due to damage). As the structure filters the seismic acceleration, all these sources of uncertainty influence the seismic input and can impair the performance of the passive base isolation.

3.1. Response of the active control system

The protection system is enhanced by the adoption of a servoactuator that can provide a control force to the basement. Figure 5 shows the response obtained with passive and active control at height Z_1. The gain G is 15000 and the acceleration at the activation time is 0.1 m/s^2. It is shown that the active control provides a significant reduction of the seismic response with respect to the passive system. Figure 6 shows the control force supplied when the artifact is located at Z_0 and Z_1, in both cases the control force is within the operational range of actual small size electric servomotors. As the active control device can in principle be reused for different locations and different artifacts, Tables 2 and 3 show the effect of varying the mass of the work of art, while maintaining the same characteristics of the control device, for the passive system and the active system, respectively. To the increase of mass corresponds a significant increase of maximum displacement that, in case of passive control, can lead to exceeding the displacement threshold. On the contrary the mass increase has a very limited influence on the acceleration and therefore on the possibility of activating the mechanisms. The adoption of active control significantly reduces the effect of mass uncertainty.

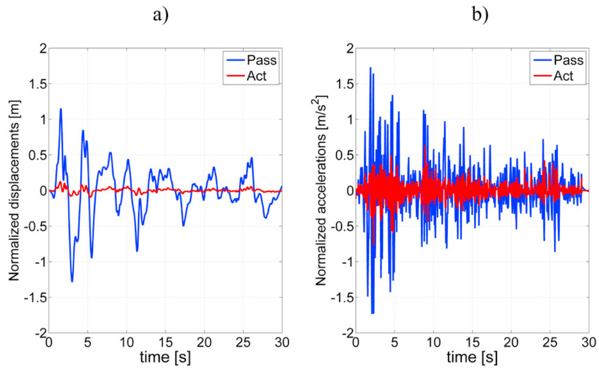

Fig. 5. Passive and active response at Z_1: (a) normalized displacements; (b) normalized accelerations.

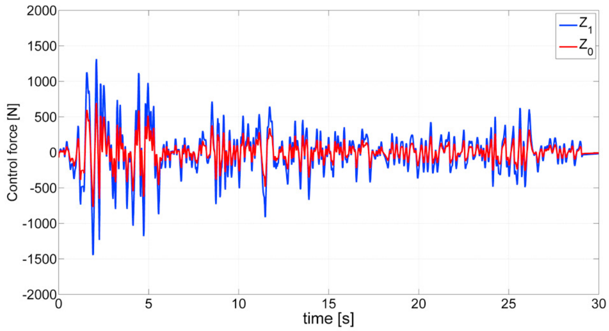

Fig. 6. Comparison between the control force supplied at Z_0 and Z_1.

Table 2. Passive system response as a function of the mass of the system (Z_0).

m_{art}	100 (kg)	200 (kg)	300 (kg)	400 (kg)	500 (kg)
x_{max} (cm)	6.8	8.1	8.9	9.4	10.5
$\ddot{x}_{max}$ (m/s^2)	2.96	3.02	3.03	3.03	3.02

Table 3. Active system response as a function of the mass of the system (Z_0).

m_{art}	100 (kg)	200 (kg)	300 (kg)	400 (kg)	500 (kg)
x_{max} (cm)	0.7	0.9	1.2	1.4	1.6
$\ddot{x}_{max}$ (m/s^2)	2.32	2.72	2.98	3.15	3.24

3.2. Model Reference Adaptive Control strategy

With the aim of optimizing the active system, the performance of LVF algorithm (Section 2.2) is compared to the one of the Model Reference Adaptive Control algorithm (MRAC). MRAC is an adaptive strategy that does not require information on the parameters of the system but only on the target the system has to track. It adjusts the controllers gains based on the error between the response of the system and the response of the reference model. The equation of motion of the system is described by Equation 4 and the one of the reference model is:

$$\dot{z}_r = A_r z_r + E_r \ddot{x}_g \tag{6}$$

where $z_r = [x_r, \dot{x}_r]^T$, A_r is the state matrix and E_r is a location vector. The reference system is uncontrolled but, in order to damp out the seismic vibration, it has a greater structural damping than the real system ($A \neq A_r$) [6].

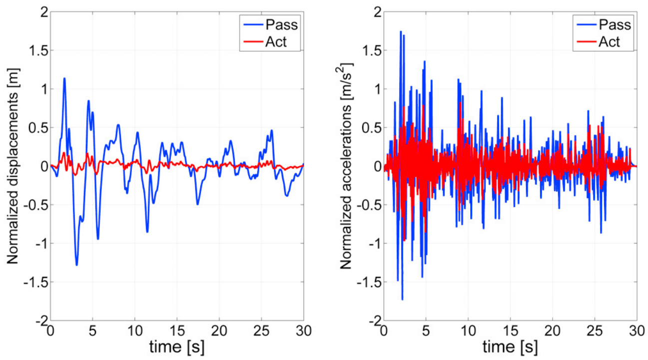

Fig. 7. Passive and active response with MRAC at Z_1: (a) normalized displacements; (b) normalized accelerations.

The MRAC control force can be written as $u = \bar{G}\phi^T z$ [5], where $\bar{G}$ is a constant gain and ϕ is the matrix collecting the adaptive controller's gains which are nonlinear and time-dependent. To derive the adaptation law, the error vector $e = z - z_r$ and its dynamics are computed. A stable adaptation law is derived using the Lyapunov approach. In particular it is defined a quadratic Lyapunov function $V = e^T Pe + \phi^T \Gamma^{-}1\phi$, where P is a positive definite symmetric matrix and Γ is the positive definite adaptation gain matrix. In order to obtain a closed loop bounded response, the time derivative of the Lyapunov function must be negative definite. This condition is satisfied provided that the following adaptation law for the error is selected [6]:

$$\phi = -\Gamma z e^T PB \tag{7}$$

Figure 7 shows the comparison between passive and active response with MRAC at Z_1 ($\Gamma = 10^9$) in terms of normalized displacements and accelerations. Preliminary results show that the MRAC is effective in properly reducing the response, although it has still to be more deeply investigated the choice of the best reference system and the best learning rate to provide a good performance in every loading condition. Additional quantitative comparison with LVF and other strategies' performance should also be carried out.

4. Conclusions

The effectiveness of base active control for the seismic protection of museum artifacts is investigated. The performance of the active solution is compared to the one of a passive base isolation system. While the base isolators properly reduce the response only for specific load and system's characteristics, active control can manage all the uncertainties in seismic excitation, amplification factors, systems parameters, avoiding the activation of the mechanisms with a suitable power supply demand. The intrinsic robustness and adaptability of active control allows in principle the utilization of the same control device for different works of art, different locations over the building's height and even different site exposures.

References

[1] I. Calió, M. Marletta, Passive control of the seismic rocking response of art objects, Eng. Struct. 25 (2003) 1009–1018.
[2] A. Contento, A. Di Egidio, Investigations into the benefits of base isolation for non-symmetric rigid blocks, Earth. Eng. Struct. Dyn. 38 (2009) 849–866.
[3] L. Berto, T. Favaretto, A. Saetta, Seismic risk mitigation technique for art objects: experimental evaluation and numerical modelling of double concave curved surface sliders, Bull. Earth. Eng. 11 (2013) 1817–1840.
[4] Eurocode 8 - Design of structures for earthquake resistance, European Commitee for Standardization (1998).
[5] H. Butler, Model Reference Adaptive Control - from theory to practice, Prentice-Hall, Englewood Cliffs, NJ (1992).
[6] I. Venanzi, M.L. Fravolini, L. Ierimonti, Multi-model robust adaptive control of tall buildings, Meccanica (2017) DOI: 10.1007/s11012-017-0619-z.