Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 4115-4121

ECCOMAS Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

AN APPROACH TO THE DYNAMIC CONTROL OF VIBRATIONS IN STRUCTURAL SYSTEMS SUBJECT TO EARTHQUAKES

Ileana Corbi[1], Ottavia Corbi[2], and Francesca Tropeano[3]

[1] Department of Structural Engineering and Architecture, University of Naples "Federico II", Italy
e-mail: ileana.corbi@unina.it

[2] Department of Structural Engineering and Architecture, University of Naples "Federico II", Italy
e-mail: ottavia.corbi@unina.it

[3] Department of Structural Engineering and Architecture, University of Naples "Federico II", Italy
e-mail: francesca.tropeano@unina.it

Keywords: Structural Dynamics, Dynamic Control, Algorithm, Response Mitigation.

Abstract. *The mitigation of the structural response under seismic action can be achieved , as well known, by introducing proper variations to the mechanical parameters of the structural system through the recourse to dynamic control strategies. In order to pursue some optimality in the setup of the problem, sometimes it is necessary to tune the coefficients of the motion equation in a measure that might result not compatible with the characteristics of current structural materials, thus pushing towards active control techniques, where the proper selection of the algorithm is of fundamental importance.*

As concerns the performance of base-isolation (BI) devices in mitigating inertia forces due to intense earthquakes, it strongly depends on the proper calibration of the own frequency of the BI system, that should be designed on the basis of the dynamic characteristics of both the structural system and the expected disturbance. Nevertheless the passive mode may fail, without guaranteeing the real effectiveness of the device.

The best improvement would, thus, require a resettlement of the problem and, possibly, the transformation into a more complex coupled system where some active component is allowed in order to refit the system to its optimality when required.

In the paper the design of such system is then proposed in order to respond to major requirements about the performance of the control action, with an active component selected in way to yield a powerful and simple approach, which appears particularly effective for mitigation of dynamic earthquake-induced motion.

doi: 10.7712/120117.5709.20175

1 INTRODUCTION

The research interest in the field of structural control of dynamic vibrations mainly relies upon the need of protecting the existing constructions or the new ones from damages caused by earthquakes, which might result even in the global collapse of the structure or give rise to local crises of parts of the structure.

Minor damages refer to decrease or loss of serviceability of the structure after the event, and disease/malfunctions during the occurring of the event because of significant displacements/accelerations, exceeding some thresholds.

The problem is deeply felt because of the wide seismic areas characterized by high earthquake hazard, spread all over the world. Additionally, the significant seismic risk in some geographic regions often superposes to an high vulnerability of the structures in the area to seismic events.

The last decades witness a large effort both from the scientists and from the factory, for developing a variety of systems, devices, technologies, reinforcement techniques devoted to increase the degree of prevention of structural damages against strong motions in civil structures. Also infra-structural systems and constructions with monumental/artistic/historical value, besides other class of special objects requiring preservation against dynamic motion, such as artistic objects in museums, statues, ancient columns, electrical equipment and so on have been attracting special attention for preserving their integrity.

Approaches to the problem of attenuation of the structural response vary from the setup of control devices for reducing the structural vibrations [1]-[10] to the development of reinforcement techniques, also involving new composite materials [11]-[14], for increasing the dynamic strength of the structure, even in masonry constructions [15]-[19].

Under the theoretical profile, they include the setup of analytic methods for the development of control algorithms and the compensation of errors and noises possibly occurring in active control systems, as well as the design of control systems, actuating and sensing devices also with reference to semi-active systems founded on the adoption of special smart materials, and coupling of passive or semi-active systems with active systems in integrated hybrid systems.

With reference to composite reinforcements, mainly preferred in existing or ancient constructions, theoretical and numerical tools have been developed for the setup and analysis of the mechanical model of the composite material and body, and its coupling with the structural material, as well as for the analysis and forecast of the unreinforced and reinforced structure, and the design of the reinforcement provision and the identification of the areas needing the adoption of the reinforcement.

On the other side, experimental investigations have been widely developed on structures scaled from the small dimension up to full/real scale case, setting up laboratory facilities and machines, such as shaking tables, as well as instruments for the real scale tests to be used in situ. In the following one presents some researches in course of execution in the field of structural control of seismic vibrations.

2 MAIN ISSUES AND GENERAL SETTLEMENT OF THE PROBLEM

Many researches and real-scale applications do refer to the mitigation of structural vibrations through the recourse to Base Isolation (BI) devices.

The design of BI systems is usually aimed at two primary objectives: on one side, to move far from the main frequency range of the expected ground motion the dominant frequencies of the isolated structure; on the other side, to reduce the energetic transmission of the dynamic input, by realizing a damping filter and interrupting the continuity between the surface layers of the soils and the foundation of the structure.

The performance of base-isolation devices in mitigating inertia forces due to intense earthquakes thus strongly depends on the proper calibration of the isolation devices own frequency, that should take into account both the dynamical characteristics of the superstructure and the frequency content of the expected disturbance.

In the paper a BI design approach has been developed for optimally tuning the parameters of a seismic isolation device accounting for either the structure dynamic characters or the ground input expected macro-properties. In the approach one introduces a measure of the energy transmitted to the superstructure, compared to the energy filtered by the isolator, which is given a closed-form. An optimization procedure is then set up by searching for the optimal tuning of the BI in order to minimize the structural response and, in the meanwhile, to keep bounded the BI energy absorption.

Further improvement of the performance of the base-isolation system may be obtained by turning the passive isolator into an hybrid one. This is accomplished by coupling the passive isolator with an actuation device introducing an active force aimed at counteracting the incoming excitation. A new constrained optimization strategy is formulated to this purpose, where the active device is re-tuned in order to get the best performance of the hybrid combined system. The proposed control algorithm basically acts in the frequency environment managing the analytic expressions of the passively and actively controlled response gain functions, and achieving a proper distribution of the control effort over the frequency ranges where it is needed.

3 HYBRID STRATEGY BASED ON AN EQUIVALENT-MODEL SETUP

3.1 The BI structural system

As concerns to the overall formulation mentioned in the previous Sect.2, with reference to a mdof structural shear frame, in order to improve the overall performance of the control system and effectively counteracting the incoming dynamic excitation at the base of the building, one introduces in the dynamic equilibrium equation the active term **w**(t) in such a way to increase the reliability of the overall BI system

$$\begin{cases} \mathbf{M}\ddot{\mathbf{y}}(t)+\mathbf{C}\dot{\mathbf{y}}(t)+\mathbf{K}\mathbf{y}(t)+\mathbf{w}(t)=\mathbf{C}\dot{\mathbf{u}}_g(t)+\mathbf{K}\mathbf{u}_g(t)=\mathbf{f}^*(t) \\ \mathbf{y}(0)=\mathbf{0} \\ \dot{\mathbf{y}}(0)=\mathbf{0} \end{cases} \tag{1}$$

where **M** denotes the n×n mass diagonal matrix of the structural system, **C** and **K** denote the n×n symmetric positive-definite matrixes of damping and stiffness respectively.

Moreover **y**(t), with its first and second time derivatives marked by the superimposed dots, $\dot{\mathbf{y}}(t)$, $\ddot{\mathbf{y}}(t)$, denote respectively the n×1 vectors of the storey drift, velocity and acceleration. The vector of base acceleration $\ddot{\mathbf{u}}_g(t)$, with the related base velocity $\dot{\mathbf{u}}_g(t)$ and displacement $\mathbf{u}_g(t)$, is given in the form

$$\begin{cases} \mathbf{u}_g(t) = u_g(t)\mathbf{1} \\ \dot{\mathbf{u}}_g(t) = \dot{u}_g(t)\mathbf{1} \\ \ddot{\mathbf{u}}_g(t) = \ddot{u}_g(t)\mathbf{1} \end{cases} \tag{2}$$

with **1** the unit n×1 vector.

After denoting by $(\cdot)_1$ the quantities relevant to the isolation storey, let consider the active control force $w_1(\omega,t)$ acting at the isolation level, with the related control vector

$$\mathbf{w}(\omega,t) = q(\omega)\mathbf{B}\dot{\mathbf{y}}(t) \tag{3}$$

where $q(\omega)$ denotes the control coefficient to be suitably designed and depending on the frequency variable ω, and **B** is a suitable matrix governing the distribution of the control action and the dependence on the response variables.

3.2 Selection of the active component

With reference to the control expression in Eq. (3) and by referring to an equivalent-based-model strategy allowing some simplification of the mdof problem, the control parameter $q(\omega)$ is to be selected according to some optimization criterion in order to pursue a predefined set of objectives.

In the specific case, as specified in the above, the primary objective consists of improving the performance of the BI system in terms of mitigation of structural vibrations, while containing the active component at its minimum. The choice of a suitable control strategy designed in the frequency domain can successfully lead to an effective device, since one may employ all the response data monitored up to the instant of control application and control the single harmonics, also keeping contained the active control component.

The definition of $q(\omega)$ is then pursued by solving an optimum problem where one aims at minimizing the employed control force, while keeping the isolator absolute acceleration under a prefixed percentage (defined through the function $\alpha(\omega)\in[0,1]$) of the uncontrolled isolator acceleration $\ddot{y}_{o,1}(\omega\,|\,0)$.

Therefore, after introducing the excitation and response frequency functions, in the frequency domain one has

$$w_1(\omega,t) = w_{o,1}(\omega\,|\,q)e^{j\omega t} = q(\omega)\dot{y}_{o,1}(\omega\,|\,q)e^{j\omega t} \tag{4}$$

with

$$w_{o,1}(\omega\,|\,q) = -jq(\omega)H_{is}(\omega\,|\,q)\ddot{u}_{go,eq}(\omega\,|\,q) \tag{5}$$

where $H_{is}(\omega\,|\,q)$ is the BI gain in the equivalent model and $\ddot{u}_{go,eq}(\omega\,|\,q)$ the relevant excitation .

The final problem is then set in the form

$$\begin{cases} \text{Find} \qquad w_{o,1}(\omega \mid q) = \min \\ \\ \text{Sub} \quad \ddot{y}_{o,1}(\omega \mid q) \leq \alpha(\omega)\ddot{y}_{o,1}(\omega \mid 0) \end{cases} \tag{6}$$

After a number of further developments, one may get the expression of the optimal control parameter in the form

$$q(\omega) = -c_1 + \frac{1}{\omega}\sqrt{\frac{k_1^2 + \omega^2 c_1^2}{\alpha^2(\omega)\ddot{H}_{is}^2(\omega|0)} \frac{\ddot{u}_{go,eq}^2(\omega \mid q)}{\ddot{u}_{go}^2(\omega)} - \left(k_1 - m_1\omega^2\right)^2} \tag{7}$$

which represents the optimally tuned shape at the considered frequency, which is then reassembled in order to fit the forcing function.

3.3 Performance of the control system

A numerical investigation is developed on a 5-storey shear-frame structure subject to a white noise base acceleration with zero mean and unitary variance, which is scaled in such a manner to have a peak acceleration of 0.4g, with the first floor coinciding with the BI-level, shows the effectiveness of the hybrid system with comparison to the passive one.

In Figure 1, as an example concerning the performance of the control system, one reports a sample drift diagram vs the time variable referred to the BI floor, showing the significant response reduction for the coupled optimized control system.

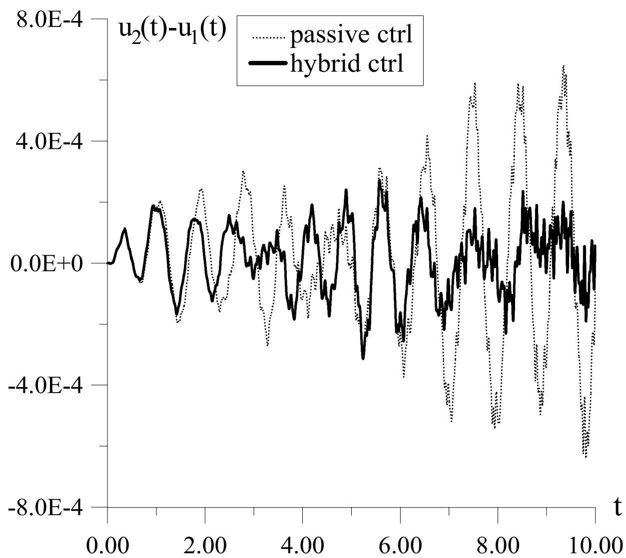

Figure 1: Inter-storey drifts of the structural frame equipped with the passive or hybrid BI device.

4 CONCLUSIONS

Passively controlled structural systems may exhibit a rare capability in resisting dynamic actions under adverse special or unexpected conditions. In the paper improvements of the overall performance of a passive BI system are obtained by introducing some additional control device, coupling different technological solutions and moving to mixed systems. In the specific case, the performance of a base isolation system is increased by embedding in the control layout an active device, controlled by a properly designed control algorithm.

5 ACKNOWLEDGEMENT

The present research has been supported by the Dept of Civil Protection of the Italian Government through the ReLuis Pool (DCP/ReLUIS 2017).

REFERENCES

[1] Baratta, A., Corbi, I., Corbi, O., Algorithm design of an hybrid system embedding influence of soil for dynamic vibration control, *J. Soil Dynamics and Earthquake Engineering*, 74, 79-88 (2015).

[2] Baratta, A., Corbi, I., Corbi, O., Mastorakis, N., Strategies for the protection from structural failures under seismic events, *International Journal of Mechanics*, 9, 69-75 (2015).

[3] Corbi, I., Corbi, O., Macro-mechanical modelling of pseudo-elasticity in shape memory alloys for structural applications, *J. Acta Mechanica*, 1-9, DOI: 10.1007/s00707-016-1624-3 (2016).

[4] Baratta, A., Corbi, O., Dynamic Response and Control of Hysteretic Structures, Intern. *Journal of Simulation Modeling Practice and Theory*, 11, 371-385 (2003).

[5] Constantinou, M.C., Whittaker, A.S., Kalpakidis, Y., Fenz, D.M., Warn, G.P., Performance of Seismic Isolation Hardware under Service and Seismic Loading; Technical Report MCEER-07-0012; *Multidisciplinary Center for Earthquake Engineering Research*, State University of New York at Buffalo: Buffalo, NY, USA (2008).

[6] Corbi, I., Rakicevic, Z.T., Shaking table testing for structural analysis, *International Journal of Mechanics*, 7(4), 459-466 (2013).

[7] Corbi, O., de Barros, R.C., Seismic protection of civil buildings by visco-elastic magneto-rheological fluids, *International Journal of Mechanics*, 7(4), 518-525 (2013).

[8] Corbi, O., Zaghw, A.H., Properties and design of dissipative viscorecentring SMA members for civil structures, *International Journal of Mechanics*, 7(3), 285-292 (2013).

[9] Corbi, O., Zaghw, A.H., Elattar, A., Saleh, A., Preservation provisions for the environmental protection of egyptian monuments subject to structural vibrations, *International Journal of Mechanics*, 7(3), 172-179 (2013).

[10] Sang-Hoon O., Sang-Hoon S., Sang-Ho L., Hyung- Joon K., Seismic Response of Base Isolating Systems with U-Shaped Hysteretic Dampers, *Int J Steel and Structures*, 12(2), 285-298 (2012).

[11] Baratta, A., Corbi, I., Topology optimization for reinforcement of no-tension structures, *J. Acta Mechanica*, 225 (3), 663-678 (2014).

[12] Baratta, A., Corbi, O., An approach to the positioning of FRP provisions in vaulted masonry structures, *J. Composites Part B: Engineering*, 53, 334-341 (2013).

[13] Corbi, I., FRP reinforcement of masonry panels by means of c-fiber strips, *Journal Composites Part B*, DOI: 10.1016/j.compositesb.2012.11.005 (2012).

[14] Corbi, I., FRP Composites Retrofitting for Protection of Monumental and Ancient Constructions, *Open Construction and Building Technology Journal*, 6, 361-367 (2012).

[15] Corbi, I., Corbi, O., Analysis of bi-dimensional solids with internal unilateral constraint coupled to structural elements with different degree of connection, *J. Acta Mechanica*, 228(2), 607-616 (2017).

[16] Corbi, I., Corbi, O., Theorems for masonry solids with brittle time-decaying tensile limit strength, *J. Acta Mechanica*, 228(3), 837-849 (2017).

[17] Corbi, I., Corbi, O., F. Tropeano, Stability assessment of an historical masonry bridge through the LA kinematic theorem for NT structures, *Int. J. Mechanics*, 10, 305-311 (2016).

[18] Baratta, A., Corbi I., Corbi, O. , Stability of evolutionary brittle-tension 2D solids with heterogeneous resistance, *J. Computers and Structures*, 174, 133-138 (2016).

[19] Baratta, A., Corbi, I., Corbi, O., Analytical Formulation of Generalized Incremental Theorems for 2D No-Tension Solids, *J. Acta Mechanica*, 226 (9), 2849-2859 (2105).