Soil Dynamics and Earthquake Engineering 74 (2015) 79–88

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Algorithm design of an hybrid system embedding influence of soil for dynamic vibration control

A. Baratta, I. Corbi, O. Corbi *

Department Structural Engineering and Architecture University of Naples Federico II, Naples, Italy

ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form
18 March 2015
Accepted 19 March 2015
Available online 16 April 2015

Keywords:
Structural dynamics
Control algorithm
Base isolation
Hybrid device
Soil–structure interaction
Optimization

ABSTRACT

The paper outlines an approach for improving the effectiveness and reliability of base isolation devices in civil engineering structures that undergo exceptional dynamic conditions.

The strategy consists of designing the passive device in such a way to take into account the not-negligible soil–structure interaction effects. At this stage, the isolator is, then, designed in such a way to be optimally tuned on the basis of the characteristics of the structure and of the soil at the site. Anyway limits intrinsic in the effectiveness of the passive device cannot be completely overcome even when embedding in the design the influence of the soil filtering on the structural response. Therefore, at the second stage, an active vibration device is coupled to the basic isolator, which is, in turn, optimally designed for minimizing the structural response and control costs. The overall presented approach definitively produces an effective hybrid control base isolation, already optimized for the specific structure and soil in its passive component, and able to concentrate the active control effort only on the frequency ranges where it is required.

1. Introduction

The control of dynamic vibrations in civil structures subject to dynamic phenomena represents a basic issue for the international scientific community.

The research interest in the topic mainly relies upon the need of protecting the existing constructions or the new ones from damages caused by earthquakes, that may result even in the global collapse of the structure or give rise to local failures 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 the ordinary serviceability thresholds.

The problem is deeply felt because of the wide geographic regions distributed all over the world, characterized by significant seismic risk, to which often the high seismic vulnerability of constructions structures superposes.

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 equipments 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 set up of control devices for reducing the structural vibrations (see e.g. [1–7, 9–25], also including classical state-of-art reports relevant to Base-Isolation devices, and [26–34] for contributions by the authors on the topic of structural control and dynamics) to the development of reinforcement techniques, also involving new composite materials (see [35–40]), for increasing the dynamic strength of the existing and monumental constructions [41–47].

Under the theoretical profile, they include the set up 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.

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.

* Corresponding author.
E-mail addresses: alessandro.baratta@unina.it (A. Baratta), ileana.corbi@unina.it (I. Corbi), ottavia.corbi@unina.it (O. Corbi).

http://dx.doi.org/10.1016/j.soildyn.2015.03.011
0267-7261/

With regards to dynamic control devices, the performance of base-isolation systems in mitigating inertia forces due to intense earthquakes strongly depends on the proper calibration of the properties of the isolator.

In order to be effective the passive Base-Isolation (BI) device should be designed taking into account both the dynamical characteristics of the superstructure and the frequency content of the expected disturbance. The BI system should then be able to dissipate energy at frequencies dynamically interacting with the structure and to transmit only energy acting in a frequency range that poorly excites the structure.

One should also emphasize that the interaction effects between the structure itself and the soil at the site play a significant role, since the soil, behaving like a filter, mainly affects the frequency composition of the excitation.

In the following, in order to get the maximum performance of the passive control device, one thus designs the BI system starting from either the properties of the structure and the characteristics of the ground.

The problem is set up in the frequency domain as a constrained optimization based on the evaluation of properly selected energetic quantities of the structural response. Although an improvement of the BI system is noticed when accounting for soil properties, the limits intrinsic in the simple passive isolation system do not allow to guarantee a real effectiveness of the device for any type of soil.

Therefore, in the second part of the paper, an hybrid BI system is developed by coupling a active device with the BI system.

As it will be shown in the following, the proposed hybrid system is able to further significantly improve the performance of the passive system, while keeping bounded the energy requirement.

2. Design of base isolation systems accounting for soil effects at the site

2.1. Outline of the optimal design approach

In the present section an approach is outlined for optimally designing a seismic Base Isolation (BI) device by accounting for either the structure dynamic characters and the ground input expected macro-properties.

The optimal problem is set up in the frequency domain and starts from the analysis of the influence of the sub-soil mechanical properties at the site on the performance of base-isolation systems.

The earthquake disturbance is assumed to be modeled as a colored weakly stationary stochastic process, whose average spectral density is assumed to be a Kanai–Tajimi curve.

The shaping parameters of this spectrum can be related, as well known, to the macro-character of the surface ground layers. The energy transmitted to the superstructure, compared to the energy filtered by the isolator, can be measured by the cross/auto correlation functions of the response degrees of freedom. These functions are presented in the following in closed-form, allowing to prevent gross errors in the energy evaluation, and are calculated by integration of the spectral density functions.

In the procedure, once properly evaluated all of these (energetic) quantities as functions of the structure and soil characteristics, one sets up the optimal problem for the design of the BI system.

The strategy consists of searching for the optimal isolator parameters that minimize the energy introduced in the structure by the dynamic excitation, while keeping bounded the energy absorption in the isolator under a prefixed threshold.

2.2. Dynamic equilibrium

Let consider a base isolated multi-degree-of-freedom (mdof) shear frame with n degrees of freedom (including the isolation level) and subject to a ground acceleration $\ddot{u}_g(t)$.

The dynamic equilibrium equation, for rest initial conditions, can be written in the form

$$\begin{aligned}&\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{C}\dot{\mathbf{u}}(t)+\mathbf{K}\mathbf{u}(t)=-\mathbf{M}\ddot{\mathbf{u}}_g(t)=-\mathbf{m}\ddot{u}_g(t)=\mathbf{f}(t)\\&\mathbf{u}(0)=\mathbf{0},\dot{\mathbf{u}}(0)=\mathbf{0}\end{aligned} \tag{1}$$

with

$$\mathbf{M}=\begin{bmatrix}m_1&&&\\&m_2&&\\&&\cdot&\\&&&m_n\end{bmatrix},\mathbf{K}=\begin{bmatrix}k_1+k_2&-k_2&&\\-k_2&k_2+k_3&&\\&&\cdot&-k_n\\&&-k_n&k_n\end{bmatrix},$$

$$\mathbf{C}=\begin{bmatrix}c_1+c_2&-c_2&&\\-c_2&c_2+c_3&&\\&&\cdot&-c_n\\&&-c_n&c_n\end{bmatrix} \tag{2}$$

$$\mathbf{u}(t)=\begin{bmatrix}u_1(t)\\u_2(t)\\\cdot\\u_n(t)\end{bmatrix},\dot{\mathbf{u}}(t)=\begin{bmatrix}\dot{u}_1(t)\\\dot{u}_2(t)\\\cdot\\\dot{u}_n(t)\end{bmatrix},\ddot{\mathbf{u}}(t)=\begin{bmatrix}\ddot{u}_1(t)\\\ddot{u}_2(t)\\\cdot\\\ddot{u}_n(t)\end{bmatrix} \tag{3}$$

$\mathbf{M}$ is the $n\times n$ mass diagonal matrix, $\mathbf{C}$ and $\mathbf{K}$ the $n\times n$ symmetric positive-definite matrixes of damping and stiffness.

$\mathbf{u}(t)$, with its first and second time derivatives marked by the superimposed dots, $\dot{\mathbf{u}}(t),\ddot{\mathbf{u}}(t)$, denote respectively the $n\times 1$ vectors of the storey drift, velocity and acceleration.

The vector of base acceleration, with the related base velocity and displacement, is

$$\mathbf{u}_g(t)=u_g(t)\mathbf{1};\dot{\mathbf{u}}_g(t)=\dot{u}_g(t)\mathbf{1};\ddot{\mathbf{u}}_g(t)=\ddot{u}_g(t)\mathbf{1} \tag{4}$$

with $\mathbf{1}$ the unit $n\times 1$ vector.

The expression of the excitation vector is then given as follows

$$\begin{aligned}&\mathbf{f}(t)=-\mathbf{M1}\ddot{u}_g(t)=-\mathbf{M}\ddot{\mathbf{u}}_g(t)=-\mathbf{m}\ddot{u}_g(t)\\&=\begin{bmatrix}m_1&&&\\&m_2&&\\&&\cdot&\\&&&m_n\end{bmatrix}\begin{bmatrix}1\\1\\\cdot\\1\end{bmatrix}\ddot{u}_g(t)=-\begin{bmatrix}m_1\\m_2\\\cdot\\m_n\end{bmatrix}\ddot{u}_g(t)=\begin{bmatrix}f_1(t)\\f_2(t)\\\cdot\\f_n(t)\end{bmatrix}\end{aligned} \tag{5}$$

After rearranging Eq.(1) in the form

$$\mathbf{M}\left[\ddot{\mathbf{u}}(t)+\ddot{\mathbf{u}}_g(t)\right]+C\dot{\mathbf{u}}(t)+\mathbf{K}\mathbf{u}(t)=\mathbf{0} \tag{6}$$

it can be rewritten in terms of absolute displacements $\mathbf{y}(t)=\mathbf{u}(t)+\mathbf{u}_g(t)$ in the form

$$\mathbf{M}\left[\ddot{\mathbf{u}}(t)+\ddot{\mathbf{u}}_g(t)\right]+\mathbf{C}\left[\dot{\mathbf{u}}(t)+\dot{\mathbf{u}}_g(t)\right]+\mathbf{K}\left[\mathbf{u}(t)+\mathbf{u}_g(t)\right]=\mathbf{C}\dot{\mathbf{u}}_g(t)+\mathbf{K}\mathbf{u}_g(t) \tag{7}$$

Therefore one gets

$$M\ddot{\mathbf{y}}(t)+C\dot{\mathbf{y}}(t)+\mathbf{K}\mathbf{y}(t)=\mathbf{C}\dot{\mathbf{u}}_g(t)+\mathbf{K}\mathbf{u}_g(t)=\mathbf{f}^*(t) \tag{8}$$

2.3. Frequency response matrixes

Let consider an harmonic forcing action of the type $\mathbf{M}\,\ddot{\mathbf{u}}_\mathbf{g}\,(\omega,t)=\mathbf{M}\,\mathbf{1}\,\ddot{u}_{go}(\omega)\,e^{j\omega t}$.

One may select a particular integral of Eq. (1), of the type $\mathbf{u}(\omega,t)=\mathbf{u}_o(\omega)\,e^{j\omega t}$ and infer the gain matrix $\mathbf{H}(\omega)$ between the structure relative displacement vector $\mathbf{u}(t)$ and the base acceleration vector $\ddot{\mathbf{u}}_g(t)$.