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Sensitivity of the stochastic response of structures coupled with vibrating barriers

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ABSTRACT

The sensitivity of the stochastic response of linear behaving structures controlled by the novel Vibrating Barrier (ViBa) device is scrutinized. The Vibrating Barrier (ViBa) is a massive structure, hosted in the soil, calibrated for protecting structures by exploiting the structure–soil–structure interaction effect. Therefore the paper addresses the study of the sensitivity of soil–structure coupled systems in which the soil is modelled as a linear elastic medium with hysteretic damping. In order to accomplish efficient sensitivity analyses, a reduced model is determined by means of the Craig–Bampton procedure. Moreover, a lumped parameter model is used for converting the hysteretic damping soil model rigorously valid in the frequency domain to the approximately equivalent viscous damping model in order to perform conventional time-history analysis. The sensitivity is evaluated by determining a semi-analytical method based on the dynamic modification approach for the case of multi-variate stochastic input process. The ground motion is modelled as non-stationary zero-mean Gaussian random process defined by a given evolutionary Power Spectral Density function. The paper presents the sensitivity of the response statistics of a model of an industrial building, passively controlled by the ViBa, to relevant design parameters. Comparisons with pertinent Monte Carlo Simulation will show the effectiveness of the proposed approach.

1. Introduction

Unpredicted vibrations due to ground motion earthquakes cause severe damages to the structural components that lead to the deterioration or collapse of buildings. Although several techniques and strategies of Vibration Control can be adopted for the seismic design of new structures or seismic retrofit of existing buildings, every approach is based on the direct design or intervention on the members or on the control systems belonging to the structure. Conversely, for heritage buildings, strong interventions are avoidable to preserve the authenticity and integrity of the historic character of the monument; moreover, most of the existing private buildings are seismically deficient requiring an important cost impact for their seismic protection. In this context, a novel passive control device called Vibrating Barrier (ViBa), has been recently proposed by Cacciola [6]. The Vibrating Barrier is a massive structure, hosted in the soil and detached from the other structures, calibrated for absorbing portion of the ground motion input energy. The aim is to reduce the vibrations of neighborhood structures by exploiting the structure–soil–structure interaction (SSSI) effect, i.e. the dynamic influence among vibrating structures caused by the wave propagation through the soil. To achieve this goal, the proper calibration of the ViBa parameters is required. Readers can refer to the work of Cacciola et al. [7] and Cacciola and Tombari [9] for an in-depth study of the ViBa. In this regard, uncertainty clearly plays a relevant role in the ViBa design. The uncertainties such as the random nature of the seismic action and the dispersion of the mechanical properties of both the structure and the soil result in a substantial difference between the actual and the computed seismic response. Therefore, sensitivity analysis is crucial to understand the impact of inaccurate model parameters on the structural response.

Probably one of the earliest contributions to sensitivity analysis in structural mechanics are due to Fox and Kapoor [15]. In the framework of stochastic mechanics several papers have been devoted to study the sensitivity of the response of structural systems subjected to stochastic excitations (see e.g. [16,17,18,2]). More recently, Bhattacharyya and Chakrabborty [3] extended Neumann expansion method within the framework of Monte Carlo simulation for sensitivity analysis of dynamic systems subjected to ground motion acceleration modelled by a stationary process. Chaudhuri and Chakraborty [4] determined the response

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sensitivity in the frequency domain of structures subjected to non-stationary seismic processes. Cacciola et al. [5] proposed a method to determine the sensitivity of second order statistics of linear structures forced by Gaussian excitation. Marano et al. [24] performed a parametric sensitivity analysis of the spectral response of a stochastic SDOF system subjected to a nonstationary seismic action with respect to uncertain soil parameters. [21,22] and Liu and Sensitivity [23] proposed numerical methods for calculation of the sensitivity and Hessian matrix of the response of structures subjected to uniformly modulated evolutionary random excitation. Johnson and Wojtkiewicz [19] proposed a high computationally efficient approach for the computation of the sensitivities of power spectral densities, and mean-square responses of a structural system. Recently, Sarkar and Ghosh [27] proposed a hybrid method to study the sensitivity of the stochastic response of linear behaving structures considering both uncertainties in the structural parameters and in the external input.

In this paper, the semi-analytical modal procedure proposed by Cacciola et al. [5] has been extended in order to consider multivariate Gaussian stochastic load process. The method allows the evaluation of the sensitivity of the nodal response of large MDOF systems in the modal space corresponding to the nominal values. In this regard, the method proposed in this paper allows the sensitivity analysis in the reduced model derived by means of the Craig–Bampton procedure [1]. The effects of interaction between the structure and the soil, namely the soil–structure interaction (SSI), are considered according to the substructure approach proposed by Kausel et al. [20] in which the soil is simulated by dynamic impedances subjected to seismic forces. The soil impedances are contained in the dynamic stiffness matrix computed by boundary element method (BEM) and accounts for hysteretic soil damping [26]. Furthermore, a lumped parameter model (LPM) composed of frequency-independent parameters is used for converting the exact soil–foundation reference hysteretic model formulated in the frequency domain to an approximately equivalent viscous model in the time domain. Time domain sensitivity analysis of the stochastic response through the LPM reduced model. Finally, numerical studies are carried out for investigating the stochastic response of a model of an Industrial Building passively controlled by the novel Vibrating Barrier device with respect to relevant design parameters.

2. Problem formulation of the global model

Consider the large global n-degree of freedom (n-DOF) structural linear system depicted in Fig. 1. The dynamic governing equations of motion are casted in the frequency domain as follows:

$$\left\{\mathbf{K}_{\mathrm{glob}}(\omega)-\omega^2\mathbf{M}_{\mathrm{glob}}+i\omega\mathbf{C}_{\mathrm{glob}}\right\}\mathbf{u}(\omega)=\mathbf{f}(\omega) \tag{1}$$

where $i=\sqrt{-1}$; $\mathbf{M}_{\mathrm{glob}}$, $\mathbf{C}_{\mathrm{glob}}$, and $\mathbf{K}_{\mathrm{glob}}(\omega)$ are the real $[n\times n]$ global mass, damping and stiffness matrices respectively; $\mathbf{u}(\omega)$ and $\mathbf{f}(\omega)$ corresponds to the $[n\times 1]$ vectors of the nodal absolute displacements and the applied forces in the frequency domain (ω is the circular frequency).

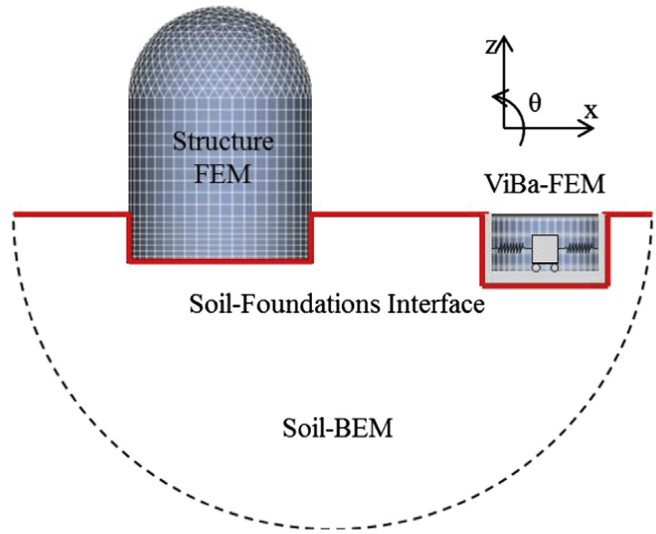

Fig. 1. Subdomains of the global problem considered in the paper.

The global system is partitioned in three subdomains or substructures, namely the structure to be protected hereafter referred in the paper by the subscript $[\bullet]_{\mathrm{str}}$, the ViBa device, indicated by the subscript $[\bullet]_{\mathrm{ViBa}}$, and the soil–foundations interface denoted by $[\bullet]_{\mathrm{SF}}$.

Therefore, Eq. (1) is restated as:

$$\left\{\begin{bmatrix}\mathbf{K}_{\mathrm{ViBa}} & 0 & \mathbf{K}_{\mathrm{ViBa,SF}}\\ 0 & \mathbf{K}_{\mathrm{str}} & \mathbf{K}_{\mathrm{str,SF}}\\ \mathbf{K}_{\mathrm{SF,ViBa}} & \mathbf{K}_{\mathrm{SF,str}} & \mathbf{K}_{\mathrm{SF}}\end{bmatrix}-\omega^2\begin{bmatrix}\mathbf{M}_{\mathrm{ViBa}} & 0 & \mathbf{M}_{\mathrm{ViBa,SF}}\\ 0 & \mathbf{M}_{\mathrm{str}} & \mathbf{M}_{\mathrm{str,SF}}\\ \mathbf{M}_{\mathrm{SF,ViBa}} & \mathbf{M}_{\mathrm{SF,str}} & \mathbf{M}_{\mathrm{SF}}\end{bmatrix}+i\omega\begin{bmatrix}\mathbf{C}_{\mathrm{ViBa}} & 0 & \mathbf{C}_{\mathrm{ViBa,SF}}\\ 0 & \mathbf{C}_{\mathrm{str}} & \mathbf{C}_{\mathrm{str,SF}}\\ \mathbf{C}_{\mathrm{SF,ViBa}} & \mathbf{C}_{\mathrm{SF,str}} & \mathbf{C}_{\mathrm{SF}}\end{bmatrix}\right\}\begin{bmatrix}\mathbf{u}_{\mathrm{ViBa}}(\omega)\\ \mathbf{u}_{\mathrm{str}}(\omega)\\ \mathbf{u}_{\mathrm{SF}}(\omega)\end{bmatrix}=\begin{bmatrix}0\\0\\ \mathbf{f}_{\mathrm{SF}}(\omega)\end{bmatrix} \tag{2}$$

The vector $\mathbf{u}(\omega)$ is hence divided into the $[p\times 1]$-vector of the ViBa, $\mathbf{u}_{\mathrm{ViBa}}$, the $[q\times 1]$-vector of the structure, $\mathbf{u}_{\mathrm{str}}$, and the $[r\times 1]$-vector of the soil–foundations system $\mathbf{u}_{\mathrm{SF}}$. The mass $\mathbf{M}_{\mathrm{str}}$, damping $\mathbf{C}_{\mathrm{str}}$and stiffness $\mathbf{K}_{\mathrm{str}}$ $[q\times q]$-matrices of the structure are derived by the traditional finite element approach as well the $[p\times p]$-matrices, $\mathbf{M}_{\mathrm{ViBa}}$, $\mathbf{C}_{\mathrm{ViBa}}$, $\mathbf{K}_{\mathrm{ViBa}}$ of the ViBa. The $[r\times r]$-matrices $\mathbf{M}_{\mathrm{SF}}$, $\mathbf{C}_{\mathrm{SF}}$, and $\mathbf{K}_{\mathrm{SF}}$ are the matrices of the nodes at the soil–foundations interface determined by the substructure approach proposed by Kausel et al. [20]; by defining $\mathbf{K}_{\mathrm{dyn}}(\omega)$ as the dynamic stiffness matrix, that can be decomposed in the real part (Re) and imaginary part (Im) as:

$$\mathbf{K}_{\mathrm{dyn}}(\omega)=\mathrm{Re}\left\{\mathbf{K}_{\mathrm{dyn}}(\omega)\right\}+i\,\mathrm{Im}\left\{\mathbf{K}_{\mathrm{dyn}}(\omega)\right\} \tag{3}$$

the following relations are derived: $\mathbf{M}_{\mathrm{SF}}=\mathbf{M}_{\mathrm{F}}$, $\mathbf{C}_{\mathrm{SF}}=\mathbf{C}_{\mathrm{F}}+\frac{\mathrm{Im}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\}}{\omega}$ and $\mathbf{K}_{\mathrm{SF}}=\mathbf{K}_{\mathrm{F}}+\mathrm{Re}\{\mathbf{K}_{\mathrm{dyn}}(\omega)\}$; $\mathbf{M}_{\mathrm{F}}$, $\mathbf{C}_{\mathrm{F}}$, and $\mathbf{K}_{\mathrm{F}}$ the mass, damping and stiffness $[r\times r]$-matrices of the foundation itself, respectively.

The dynamic stiffness matrix $\mathbf{K}_{\mathrm{dyn}}(\omega)$ is determined in order to take into account the effects of the soil, such as the soil–foundation interaction (SFI), the foundation–soil–foundation interaction (FSFI), the hysteretic damping as well as the radiation (or geometric) damping without resorting to a large finite element model of the soil. The dynamic impedance matrix is computed by condensing out the entire soil–foundations system onto the foundation interfaces in the frequency domain. It relates the displacements in the nodes on the structure–soil interface to the