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Energy harvesting from wind-induced bridge vibrations via electromagnetic transduction

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ABSTRACT

Energy harvesting from wind-induced vibrations of long-span bridges through electromagnetic devices is herein addressed. A coupled model, describing the bridge structure excited by aeroelastic wind forces and equipped with harvesting devices mounted along the bridge girder, is derived by reducing bridge dynamics via a modal analysis. The model is employed to maximise the harvested power with respect to the stiffness and the electromagnetic damping parameter of the harvesting devices, depending on the characteristics of the approaching wind flow. Numerical results obtained in the case of a bridge-like structure similar to the Great Belt East Bridge are presented and discussed, showing model soundness and effectiveness. The influence of the dynamical coupling among principal structure and harvesting devices on the harvesting process is investigated. Moreover, in order to overcome possible feasibility drawbacks related to a real-time adjustment of harvester parameters, a simplified tuning procedure is proposed, resulting effective in a wide wind-speed range.

1. Introduction

Energy harvesting from structural vibrations has become a growing and challenging research topic in the last years, due to the possibility of obtaining renewable energy sources for powering wireless sensors, portable electronics and microsystems located in hostile and/or inaccessible environments. In particular, energy harvesting can be considered as a great challenge with respect to the powering of sensors and real-time monitoring systems for large scale structures, such as long-span suspended and cable-stayed bridges [1], avoiding the need of battery maintenance and replacement.

Energy harvesting can be obtained by exploiting a suitable transduction mechanism able to convert a part of the energy related to mechanical vibrations into electric energy. The most frequently used transduction mechanisms are based on the electrostatic, piezoelectric, or magnetic-induction conversion [2]. Due to the low frequency and large amplitude characteristics of the vibrations generally experienced in long-span bridges, the last mechanism is more frequently exploited for these structures [3], although attempts dealing with other transduction strategies can be found in the recent specialised literature. For example, piezoelectric harvesters for scavenging energy from bridges excited by traffic loads are studied in [4,5]. Furthermore, a magnetic shape-memory-alloy harvester is proposed in [6] for powering wireless sensors in bridge health monitoring.

As a matter of fact, the magnetic induction mechanism permits one to extract more power than the other mentioned mechanisms, and therefore it can be retained more suitable for wind-induced bridge vibrations, which can be generally considered as sources of large amount of harvestable power [7]. In this context, a simple solution was proposed in [8], consisting of an electromagnetic transducer only, inserted between a fixed reference point and a bridge position experiencing large enough oscillations. Nevertheless, such a strategy can suffer some feasibility drawbacks in the case of tall bridges and/or for bridge structures crossing rivers, lakes or sea. In these cases, alternative solutions have to be conceived. For example, it could be more convenient to employ devices based on the tuned-mass-damper (TMD) concept [9], simply replacing the dissipative element of a TMD with an electromagnetic transducer [10–12]. However, since these resonant devices are generally effective only over a narrow frequency band [2], a careful tuning process with respect to the main frequency content of the structure vibrations is required, in order to achieve an effective energy harvesting. As a matter of fact, bridge structures can oscillate with variable frequency contents depending on the traffic features [13] and on the wind characteristics [14], as well as on

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their coupling effects [9,15]. In order to improve harvesting performance of resonant devices many strategies have been recently proposed. For instance, nonlinear effects have been exploited and elicited by considering magnetic springs [16–18]. Other possible strategies are based on the use of multi-degrees-of-freedom harvesting arrangements. Such an approach has been investigated in [19] by considering electromagnetic devices. A similar concept has been used in [20], referring to a piezoelectric harvester connected to a vibration source by a multi-modal oscillating system. Dynamic magnifiers have been also proposed in a number of well-established studies for improving the amount of the harvested power and the effective bandwidth [21–23]. An exhaustive experimental characterisation of the harvesting performance in the case of an electromagnetic device mounted on a suspended bridge is reported in [24], highlighting the device effectiveness in a low-frequency range, up to 30 Hz. Energy harvesting feasibility for bridge-like structures and via an electromagnetic device is investigate also in [13], wherein tunability features are elicited through the use of a suitable control law.

In this paper the adaptive tuned-mass energy harvester (TMH) described in [11] is employed for harvesting energy from wind-induced bridge vibrations. The device is comprised of a seismic magnetic mass connected to a housing by a spring and moving with respect to a coil that is attached to the housing. The coil is connected in series with the harvesting circuit, which is here simply chosen as an electric resistance. Energy harvesting is pursued by considering a discrete distribution along the bridge deck of couples of such harvesting devices, connected to the opposite ends of some bridge deck sections, in order to take advantage from both bending and torsional bridge oscillations. Both stiffness and circuit resistance of harvesters are considered as design parameters to be optimised depending on wind characteristics. To this end, a comprehensive model accounting for the bridge structure, via a modal approach and as dynamically coupled to the harvesting devices, is derived and used for the optimisation process of the harvesting parameters. The bridge is assumed to be excited by the aeroelastic wind actions, coupled with the structural motion and modelled in the framework of the linearised Scanlan approach [14]. As induced by the wind-structure interaction, an intrinsic change in the effective damping and stiffness of the bridge results, as strictly depending on the shape of the bridge-cross section and on the wind features in terms of wind velocity and angle of attack. Accordingly, parameters of harvesting devices are herein optimised depending also on these excitation characteristics. Due to the nonlinear fluid–structure coupling, the optimisation is performed via a nonlinear approach based on the Nelder-Mead method [25]. As a matter of fact, the power is harvested at the expense of the bridge vibration energy, so two desirable targets can be simultaneously pursued: energy harvesting and vibration damping [26,27]. Although optimisation procedures with respect to both the requirements could be derived, in this study the optimisation is made with the aim of maximising the harvested power. In the optimisation process both a fully coupled model and a simplified one, the latter being defined by neglecting the influence of the harvesting devices on the bridge dynamics, are employed and the results they supply are compared. In order to overcome possible feasibility drawbacks, related to a real-time adjustment of the harvester parameters depending on the wind speed, a simplified tuning procedure is also proposed, considering only discrete sets of parameters equal for all the devices, each one prevailing in a certain interval of wind speed. As a case study, reference is made to a bridge-like structure whose main features are assumed similar to those of the Great Belt East Bridge in Denmark [28,29], showing soundness and consistency of the proposed optimisation approach, as well as the feasibility of the adopted harvesting technique.

The paper is organised as follows. In Sections 2.1 and 2.2 the modal model of the bridge and the wind-load model are presented, respectively. The equations governing the dynamics of the harvesting devices are derived in Section 2.3. In Section 2.4 the complete set of equations describing the coupled system comprising bridge and harvesting devices, and subjected to the aeroelastic wind excitation, is reported. A simplified model, defined by neglecting the influence of the harvesting devices on the bridge dynamics, is described in Section 2.5. Both simplified and coupled models are used in Section 3 for optimising design parameters of the harvesting devices. Numerical results, obtained by applying the proposed optimisation procedure to a case study based on a long-span bridge-like structure, are presented in Section 3.1 and discussed in Section 4. Finally, some concluding remarks are traced in Section 5.

2. Model

In this section the governing equations describing the coupled response of the system comprising a bridge-like structure excited by aeroelastic wind loads and equipped with energy harvesting devices modelled as mounted on its deck are derived.

2.1. Bridge model

The bridge is modelled as a beam-like structure of length ℓ (referring to the central span), with a constant cross-section along the span axis, and whose mass and torsional inertia moment per unit length are γ and I_α, respectively. The bridge girder is assumed to experience only flexural motion in the vertical plane and torsional motion around the span axis, which are decoupled from each other. Thereby, the actual bridge girder configuration is described by the vertical displacement $v(z,t)$ and the torsional rotation $\Theta(z,t)$, where z is the coordinate along the span axis and t is the time variable. By applying a modal reduction, and by accounting only for the first flexural mode and the first torsional mode, the following relationships hold:

$$\begin{aligned} v(z,t) &= \Psi(z)\,y(t), \\ \Theta(z,t) &= \Phi(z)\,\alpha(t), \end{aligned} \tag{1}$$

where $\Psi(z)$ and $\Phi(z)$ are the flexural and torsional dimensionless modal shapes, and $y(t)$ and $\alpha(t)$ are the corresponding modal coordinates.

Therefore, the bridge (namely, the primary structure) is reduced to the two degrees-of-freedom system depicted in Fig. 1. The following quantities are defined:

$$M = \int_0^\ell \gamma \Psi^2(z)\,dz, \qquad J = \int_0^\ell I_\alpha \Phi^2(z)\,dz, \tag{2}$$

where M is the modal mass and J is the modal torsional inertia moment. Furthermore, k_y and k_α are the flexural and torsional stiffnesses, respectively, and c_y and c_α are the modal damping coefficients associated to the flexural and torsional modes, respectively. Thereby, the natural circular frequencies corresponding to the considered modes of the primary structure are given by

$$\omega_y = \sqrt{\frac{k_y}{M}}, \qquad \omega_\alpha = \sqrt{\frac{k_\alpha}{J}}. \tag{3}$$

2.2. Modelling of wind loads

Let the bridge be approached by a wind flow orthogonal to the span axis, and let such a flow be assumed as perfectly correlated both along the girder axis and in the plane of the deck cross-