Mechatronics 33 (2016) 108–120

Contents lists available at ScienceDirect

Mechatronics

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

A smart structure for wind tunnel investigation of a bridge deck's vortex-induced torsional motion

S. Cinquemani*, G. Diana, L. Fossati, F. Ripamonti

Politecnico di Milano, Dipartimento di Meccanica, Campus Bovisa Sud, via La Masa 1, 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 19 December 2014
Accepted 9 November 2015
Available online 2 December 2015

Keywords:
Smart structure
Wind tunnel
Control
Vortex induced vibration

ABSTRACT

The paper discusses the design and testing of a smart aeroelastic model of a suspended bridge that allows active regulation of torsional damping through the use of embedded piezoelectric actuators. Depending on test conditions, the structural damping of the model can be adjusted in a fast, precise and repeatable way in order to highlight the effects of the wind interaction. In particular, vortex-induced vibrations are taken into consideration. The main elements of the smart structure (sensors, actuators, control algorithm) have been designed on the basis of a numerical model of the system. Finally the aeroelastic model has been tested in a wind tunnel in different operating conditions and its dynamics have been assessed.

1. Introduction

Wind engineering is an important discipline in the analysis and design of large civil structures subject to significant wind loads, such as long-span bridges and high-rise buildings. The response of such structures needs to be predicted in advance, before they are actually built, rather than characterized "a posteriori" when the structure is, or should be, fully operative [1–4,16]. Moreover, the construction phase itself could represent a critical issue, for example in the case of cable-stayed bridges. Nowadays, their behavior is evaluated by means of small-scale models in wind tunnel tests. However, these models are not able to fully reproduce the real operating conditions, because it is not possible to match perfectly all the structural parameters involved in the phenomena under investigation. As a consequence, some problems arise when transposing the results obtained on a small-scale model to the full-scale prototype. Those issues are presented and analyzed in [5], specifically dealing with a reduced-scale bridge deck model. The possibility of carrying out tests on a model which correctly reproduces the aerodynamic behavior of the real structure and at the same time matches its dynamic response to wind loads would be very attractive. This can be achieved by implementing a smart structure capable of real-time (RT) tuning of its dynamic parameters such as natural frequencies and damping ratios. Very few contributions are found in the scientific literature concerning the use of smart structures for wind tunnel testing in the civil engineering field, where passive solutions are preferred [6–8], although in the aerospace field some applications have been developed and tested in recent decades: morphing wing [9], rotor control of wind turbines [10], smart flaps [11] and airfoil-actuator integration [12,13].

The aim of this work is to present the operative set-up and the main characteristics of a smart structure for wind tunnel testing purposes. It differs from a traditional aeroelastic model because of its ability to adapt the structural parameters to suit specific testing needs, which represents an improvement over the present scenario. The test case is a large sectional model of a bridge deck. The objective is a quantitative evaluation of the oscillatory motion that the aerodynamic force field is able to induce on the real bridge. Tuning of damping is useful to simulate a realistic bridge response as usually it is hard to know in advance the damping of the real structure that is to be tested.

Section 2 of this paper explains the most common issues of structures immersed in a fluid flow, focusing on vortex-induced vibrations, and summarizes the quantitative parameters used in engineering practice; the wind tunnel testing procedure is also briefly introduced.

List of symbols: V, Upstream wind velocity (m/s); V^*, Reduced flow velocity (–); D, Characteristic linear dimension, generic (m); C, Cross-wind dimension (m); μ, Dynamic viscosity of air (kg/(m · s)); ρ, Air density (kg/m^3); g, Gravity acceleration (m/s^2); m, Linear mass or mass per unit length (kg/m); M, Mass (kg); J, Moment of inertia (kg · m^2); f, Frequency (Hz); f_S, Strouhal frequency (Hz); f_n, Natural frequency of the n^{th} mode of vibration (Hz); Re, Reynolds number; Fr, Froude number; St, Strouhal number; Sc, Scruton number; B, Deck chord length (m); L, Bridge span length (m); ξ, Damping ratio (–); z, Oscillation amplitude at the edge (m); θ, Rotation of the section (rad); $\underline{q}(t)$, Modal coordinates vector, function of time t; $\underline{F}(t)$, Vector of external time-dependent forcing terms; $\mathbf{M}$, Modal mass matrix; $\mathbf{R}$, Modal damping matrix; $\mathbf{K}$, Modal stiffness matrix; $\mathbf{\Phi}$, Eigenmodes matrix (eigenvectors juxtaposed by columns); $\mathbf{\Lambda_F}$, Jacobian matrix which links the components of $\underline{F}$ to the physical coordinates.

* Corresponding author. Tel.: +39 0223998454; fax: +39 02 2399 8202
E-mail addresses: simone.cinquemani@polimi.it (S. Cinquemani), giorgio.diana@polimi.it (G. Diana), lorenzo.fossati@mail.polimi.it (L. Fossati), francesco.ripamonti@polimi.it (F. Ripamonti).

http://dx.doi.org/10.1016/j.mechatronics.2015.11.003

Section 3 describes the test-case structure and its modeling. The core considerations on the smart structure are presented in Section 4, where observability, controllability and stability issues are discussed and related to sensor and actuator placement and to the whole control loop configuration, including the control logic. Section 5 summarizes the results and performance obtained both in still air and in the wind tunnel; finally, Section 6 draws conclusions from this experience and suggests possible directions for future research.

2. Wind-induced vibrations in civil structures

2.1. Fluid-structure interaction phenomena

Among the fluid-structure interaction problems occurring in engineering practice, the analysis is restricted to the case of a single-phase steady external flow. The vibration mechanisms that this kind of flow can produce are vortex-induced vibration (forced vibration, resonant vibration) and aeroelastic vibration (flutter, galloping - defined below) [15,16,32]. Several excitation mechanisms can potentially contribute to the forcing of the same structure:

- Vortex-induced vibration due to resonance at a specific flow velocity.
- Aeroelastic instability beyond a critical flow velocity.
- Turbulence excitation increasing with flow velocity.

The Vortex-Induced Vibration (VIV) phenomenon originates from the interaction between a structure and a surrounding fluid flow, and generates periodic irregularities in the flow itself (vortex shedding) as well as periodic oscillations (vibrations) of the structure immersed in it. Under certain conditions, the boundary layer which normally develops close to the contact surface because of the viscosity of a real fluid develops vortices that detach periodically from either side. This causes a periodic variation in the pressure distribution and consequently in the components of the aerodynamic force, thus leading to a motion mainly transverse to the flow [34,35]. The frequency of vortex shedding depends on the aspect ratio of the body cross-section and on the angle of attack of the flow. VIV can show up on streamlined bodies such as the decks of cable-stayed or suspended bridges. In this case they influence user comfort and the functionality of the structure as well as its fatigue life, since they can generate RMS levels of acceleration higher than the threshold imposed by standards [15,32,33]. Generally speaking, vortex shedding from the deck of long-span bridges does not lead to instability by itself, but large vibration amplitudes can arise when the vortex shedding frequency gets close to one of the natural frequencies of the structure. This condition is called “lock-in”. The synchronization between the motion of the system and the separation of the flow makes the energy transfer from the wind to the mechanical system more effective [14]. For these reasons, the early design stage of a structure subjected to VIV must include a preliminary evaluation of their relevance. This evaluation is normally carried out in a Wind Tunnel (WT) facility, where the phenomena of interest can be reproduced on a reduced-scale model. Synthetic indexes are used to describe these phenomena. The analysis of these indexes and of their governing factors is required for the design of a smart structure able to modify the system’s dynamic response under different testing conditions. This is finally summarized by expressing the variation of one or more of the indexes such as the Reynolds number (Re), the Froude number (Fr), the Strouhal number (St) and the Scruton number (Sc). Their definitions and physical meanings are given in Table 1.

Besides VIV, other fluid-structure interactions can lead to aeroelastic vibrations. Consider a body of chord length B and thickness C immersed in a cross-flow with a given upstream speed V and a given angle of attack (pitch) α as shown in Fig. 1. It will vibrate in the drag (x), lift (y) and torsional (θ) directions, which are its three degrees of freedom (dof) in this “in-plane” representation. Under certain conditions the aerodynamic force field may induce zero or negative net damping to one of the mentioned directions of vibration, thus leading to dynamic instability of the whole structure which can basically show up as a single-dof self-excited vibration (“galloping”, for bluff bodies) or as a coupled bending-torsional self-excited vibration (“flutter”, for streamlined bodies). Also in this case, in order to provide quantitative information about these phenomena, it is particularly convenient to refer to the dimensionless parameters previously introduced (Table 1).

Table 1
Non-dimensional parameters used in fluid dynamics.

Name	Definition	Description
Reynolds number	$\mathrm{Re} = \dfrac{\rho V D}{\mu}$	ratio between inertia and viscous force; involved in compressible fluid motion problems; allows flow pattern prediction at given conditions
Froude number	$\mathrm{Fr} = \dfrac{V^2}{gD}$	ratio between inertia and gravity force; allows for determining ratio of deflections under steady gravitational load to deflections due to aerodynamic and inertial loads
Strouhal number	$\mathrm{St} = \dfrac{f_S D}{V}$	ratio between local and average flow velocity; describes oscillating flow mechanisms and governs periodic vortex shedding phenomena; f_S = vortex shedding (Strouhal) frequency
Scruton number	$\mathrm{Sc} = 2\pi \dfrac{m\xi}{\rho D^2}$	ratio of structural vibrating mass to mass of air displaced by the structure

These excitations are driven by wind and are self-induced by the coupling between structure and fluid; they can show up even if the approaching undisturbed flow is turbulence-free and, indeed, they are often stronger in smooth flow than in turbulent flow. On the other hand, the vibrations produced by turbulence or other disturbances in the flow and not generated by the moving object itself are called buffeting vibrations.

2.2. Wind tunnel tests on civil structures

It is possible that a large and slender structure excited by VIV may experience acceleration levels so high that the transit has to be suspended for safety reasons. This is true in the case of high-rise buildings as well as long-span bridges, which often require some device for vibration suppression [6–8]. Dealing with civil structures, it is of course impossible to recreate the real operating conditions in a test rig. In fact, the experimentation relies a lot on dynamic models being able to reproduce at a reduced scale the behavior of the real object, under proper test conditions which must be carefully designed and finely tuned [36]. Fluid similarity as well as structural similarity has to be modeled, and this is achieved by matching the dimensionless parameters listed in the previous section. Every dimensional quantity (length, force, etc.) has its own scaling factor λ which is defined at the model design stage and can be used also to compare the values measured at model-scale (MS) to the corresponding values at full-scale (FS) in the analysis of the results. The similarity law that underlies the whole modeling procedure is expressed by the Buckingham theorem, or π theorem [17].

3. The test-case: the Third Bosphorus Bridge aeroelastic model

3.1. Preliminary considerations

In this work, the aerodynamic behavior of the Third Bosphorus Bridge (BB3) is investigated, and particular attention is paid to