Journal of Fluids and Structures 68 (2017) 1–14

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

An efficient approach to the determination of Equivalent Static Wind Loads

L. Patruno, M. Ricci*, S. de Miranda, F. Ubertini

DICAM, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

ARTICLE INFO

Keywords:
Equivalent Static Wind Loads
Structural response
Buffeting
Envelope reconstruction

ABSTRACT

In this paper, a novel approach to the determination of Equivalent Static Wind Loads is presented. The envelope of the effects on the structure, representing the design load for each structural member and obtained by means of a complete buffeting analysis, is reconstructed, in a least square sense, by considering a series of statically applied load conditions. Such load conditions are obtained by combining Principal Static Wind Loads which, in turn, are obtained by means of the recently introduced Proper Skin Modes. By considering a smoothed version of the maximum/minimum operator, efficient, gradient based, optimization algorithms can be used in order to drive the least square minimization which conduces to the identification of the most significant wind load conditions. Such load conditions, statically applied, can be used in order to fully characterize the effect of the wind on the structure with very good approximation. No hypotheses are introduced regarding the shape of the envelopes, so rendering the procedure of general applicability. Very good results in terms of reconstruction rate and accuracy are obtained on a low-rise and a high-rise buildings.

1. Introduction

The determination of wind effects on structures represents an extremely demanding activity for wind and structural engineers. In particular, the response to wind loading results from the interaction between the turbulent flow encountered in the atmospheric boundary layer and the structure under consideration. The response is always characterized by unsteadiness due to the intrinsic unsteady behaviour of the incoming turbulence, the local flow conditions in the proximity of bluff bodies and the signature of surrounding buildings.

In order to characterize the wind effects on complex structures, wind tunnel tests are usually performed. The raw output of such tests is represented by pressure time histories at each measured pressure tap for each considered attack angle. Starting from such data, the structural response can be evaluated for each wind direction (Davenport, 1995; Dyrbie and Hansen, 1996; Xu et al., 1999; Gu and Zhou, 2009; Chen et al., 2013; Huang et al., 2015). Finally, for each effect on the structure, extreme values can be calculated, and envelopes defined, which contain the minimum and maximum design value obtained from all the considered wind conditions. Such calculation can be extremely cumbersome and impractical due to the coexistence of static, quasi-static and resonant components in the structural response (Davenport, 1995).

Recently, an efficient approach for the calculation of the structural response has been proposed, which allows to easily calculate the time histories of the effects on the structure starting from the recorded time varying pressure fields, the structural modes and the response to predefined, statically applied, pressure distributions (Patruno et al., 2016; de Miranda et al., 2015). Such pressure

* Corresponding author.
E-mail address: mattia.ricci10@unibo.it (M. Ricci).

http://dx.doi.org/10.1016/j.jfluidstructs.2016.10.003
Received 27 November 2015; Received in revised form 12 May 2016; Accepted 3 October 2016

distributions, called Proper Skin Modes (PSMs), depend only on the structure geometry and can be seen as an efficient modal approach to the determination of influence coefficients, traditionally adopted to characterize the structural response in the static and quasi-static regime. In particular, by following that approach, the modal base is adopted for the calculation of the static, quasi-static and resonant contributions to the structural response without any distinction while static/quasi-static corrections are developed, aiming at mitigating the errors introduced by the unavoidable truncation of the modal base.

Following such an approach, the effects envelopes can be easily extracted and adopted in the design process. Nevertheless, as observed by Blaise and Denoël (2012, 2013), structural engineers are often used to Equivalent Static Wind Loads (ESWLs), which represent the most convenient way to include in commercial structural analyses software the effects of wind and combine them with the effects generated by other load cases. Thus, ESWLs still represent an active research topic whose primary objective is to condensate, in a few static load cases, the complete response to wind from all considered directions.

Several approaches to the determination of ESWLs have been presented in the literature (Chen and Kareem, 2001; Katsumura et al., 2007; Blaise and Denoël, 2015). Between them, the most widely adopted are the Conditional Sampling Technique (CST) (Holmes, 1988; Tamura et al., 2002) and the Load-Response Correlation method (LRC) (Kasperski, 1992; Tamura et al., 2002). In particular, CST individuates ESWLs as the average of the pressure distribution acting in correspondence of a maximum effect recorded on the structure while LRC individuates them as the most probable pressure distribution corresponding to the maximum expected value of the considered effect. All such methods are able to individuate loading conditions which are particularly critical to the structure but they do not lead, strictly speaking, to an envelope reconstruction procedure. Furthermore, their applicability is limited to the quasi-static regime and, as regards LRC, a Gaussian framework has been adopted, which might limit its applicability (Blaise and Denoël, 2015; Tamura et al., 2002).

The first procedure aimed at reproducing the extreme effects experienced by the structure without introducing restrictive hypotheses on its dynamic behaviour has been proposed by Katsumura et al. (2007). In the same spirit, the definition of Principal Static Wind Loads (PSWLs) (Blaise and Denoël, 2012, 2013) represented a major step toward the development of general procedures, able to provide ESWLs for arbitrarily complex structures. In those works, Singular Value Decomposition (SVD) has been adopted aiming at identifying the most relevant load distributions which might be combined in order to reconstruct the envelope. Unfortunately, due to the inherent strongly non-linear nature of envelope calculation procedures, the identification of ESWLs is still an opened issue which is usually tackled by means of inefficient, and sometimes unreliable, Monte Carlo or evolutive optimization techniques.

In this paper, aiming at proposing an efficient approach to the determination of ESWLs, PSWLs are calculated starting from PSMs due to their efficiency and ease of use. Then, a new approach for the identification of the ESWLs starting from the calculated PSWLs is proposed. In particular, by substituting the sharp maximum/minimum operator, typical of envelope calculations, for their smooth version, efficient, gradient based optimization algorithms can be used in order to drive the least square minimization. The methodology is computationally efficient and avoids the need for Monte Carlo simulations and the definition of predefined PSWLs combinations as proposed by Blaise and Denoël (2013).

In order to assess the performance of the proposed approach, ESWLs are extracted for a low-rise and a high-rise building showing extremely encouraging results.

The paper is organized as follows: in Section 2 a brief description of PSMs is provided and a simple example on their use in the calculation of the structural response is proposed. In Section 3, PSWLs are briefly recalled while a new efficient envelope reconstruction procedure is proposed in Section 4. The proposed approach is used in order to extract ESWLs for a low-rise building and a high-rise building in Section 5. Finally, some conclusions are drawn in Section 6.

2. Proper skin modes

Proper Skin Modes have been recently proposed by Patruno et al. (2016) and can be considered an efficient alternative to the evaluation of influence coefficients, traditionally used in order to characterize the structural response in static and quasi-static conditions and based on the application of unitary normal forces. In particular, it is assumed that the structure can be wrapped by a computational mesh which reproduces the shape of the surfaces exposed to the wind action (surfaces composing the building might be conveniently separated if they are strongly angled).

In order to extract PSMs, a Laplacian operator is discretized on each surface composing the structure envelope, separately, leading for each of them to a matrix $\boldsymbol{K}^{\nabla^2}$ which represents the discretized differential operator. Then, the generalized eigenvalue problem is solved:

$$(\boldsymbol{K}^{\nabla^2} - \sigma^{\nabla^2}\boldsymbol{A})\boldsymbol{\phi}^{\nabla^2} = \boldsymbol{0}, \tag{2.1}$$

where $\boldsymbol{A}$ is a diagonal matrix collecting the area associated to each mesh node, σ^{∇^2} is an eigenvalue and the eigenvector $\boldsymbol{\phi}^{\nabla^2}$ is the PSM (i.e. it represents a modal shape of the aforementioned discretized operator). The PSM defined in such a way can be interpreted as a pressure distribution over the considered surface. Pressure modes defined in such a way are $\boldsymbol{A}-$ orthogonal by construction and can be properly normalized in order to obtain an orthonormal representation base, suitable for describing pressure distributions. Notice that, the same Laplacian operator used for extracting PSMs can be used in order to interpolate pressures from the tap locations to the computational mesh nodes, leading to an optimal organization of the code used to perform the analyses.

Examples of PSMs associated to a rectangular and a semi-ellipsoidal surfaces are reported in Fig. 1. It is noticed that the first PSM is always associated to a constant pressure field while the subsequent ones are characterized by decreasing wavelength and,