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An efficient approach to the evaluation of wind effects on structures based on recorded pressure fields

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ABSTRACT

A well known peculiarity of the structural response to wind loading is that static, quasi-static and resonant effects are present, in general, without a clearly dominant contribution. In such conditions, the calculation of wind effects would require to consider a large number of modes due to the relevant contribution of high frequency ones. In the present paper, in order to alleviate inaccuracies in the evaluation of static and quasi-static effects, induced by the truncation of the modal base, an efficient approach to the evaluation of static and quasi-static corrections is developed. To this purpose, a new class of pressure modes, called Proper Skin Modes (PSMs), is introduced and the corrections are evaluated based on the structural response to such modes, statically applied. PSMs can be seen as a novel modal version of traditionally adopted influence coefficients and naturally arise from the adopted pressure interpolation technique. The obtained approach is compact and efficient leading to a reduced data exchange between structural and wind engineers and to an optimal organization of the software used to perform the analyses. The proposed procedure is tested on a low-rise and a high-rise building showing very good performances.

1. Introduction

The evaluation of wind effects represents a crucial point in the design of slender structures like high-rise towers and light roofs, being the wind action the dimensioning one for many structural members. Due to its relevance and complexity, wind loading is currently studied in atmospheric boundary layer wind tunnels, aiming at reproducing the flow conditions expected on site. The scaled building model is equipped with various hundreds of pressure taps and tests are run for a representative selection of wind incidence angles. The raw output of such experimental tests consists in simultaneous pressure measurements which must be elaborated in order to provide to the structural engineers indications regarding the effects on the structural members [1,2].

A variety of methodologies have been proposed in the literature aiming at efficiently calculating the structural response by means of reduced models both in a deterministic and, more often, in a stochastic framework [3–8]. On one side, this allows to reduce the remarkable computational effort needed to perform the computations and, on the other side, it facilitates the data exchange between structural and wind engineers, which represents an issue of utmost importance in practical applications. Traditionally, in order to build such reduced models, the structure is characterized by means of influence coefficients, obtained by applying unitary normal forces, and structural modes. Such two approaches are usually adopted in order to characterize the static/quasi-static and the resonant response, respectively. The choice between the two ways of proceeding is usually performed based on the structure typology.

In the present paper, a simple approach for the systematic post-processing of simultaneous pressures time histories is developed, in order to correctly take into account static, quasi-static and resonant effects in a compact and unified framework. The proposed procedure is designed to be computationally efficient and to minimize the data exchange between structural and wind engineers. On this regard, special attention is paid to ensure that all quantities required as input of the proposed calculations can be easily extracted by commonly used commercial softwares.

Due to its efficiency, the modal base is here adopted in order to reconstruct all the three aforementioned contributions to the structure response without distinction. In order to alleviate inaccuracies induced by the truncation of the modal base, static corrections [9–12], are introduced, so allowing to properly take into account the effects of high frequency modes and, thus, making the procedure applicable up to the static regime. A discussion

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regarding analogies and differences between various methods proposed in the literature to develop efficient static corrections can be found in [13,14].

In the present work, aiming at developing a technique tailored for wind load analyses, such corrections are developed based on the structural response to newly introduced pressure modes, hereinafter named Proper Skin Modes (PSMs), statically applied. PSMs naturally arise from the adopted pressure interpolation technique and depend only on the structure geometry. In particular, using PSMs can be seen as an enhanced modal version of the well known approach based on the evaluation of influence coefficients. The implementative and operational advantages of using PSMs are remarkable as problems related to pressure taps and influence coefficients collocation are naturally eliminated. The resulting methodology, which develops static corrections based on the structural response to static load cases, is formally equivalent to the one originally adopted in the seismic field by Hansteen and Bell [15].

The proposed procedure, here developed in the time domain, is characterized by high efficiency and provides results comparable to computationally demanding time marching algorithms. The extremely reduced amount of data needed to characterize the structural response can be easily and automatically extracted, so rendering the procedure suitable for use in the design practice.

The paper is organized as follows: in Section 2 the pressure interpolation technique adopted in the current work is described. In Section 3 some well known representation bases, used to characterize the structural response and the pressure field, are recalled and classical approaches to the calculation of the structural response are briefly discussed. Proper Skin Modes are proposed in Section 4, and, in Section 5, the proposed approach for the calculation of the structural response is detailed. Two case studies, a high-rise and a low-rise buildings are investigated in Section 6 showing the good performances of the proposed procedure. Finally, conclusions are drawn in Section 7.

1.1. Some remarks

Aiming at highlighting the idea underlaying the introduction of static and quasi-static corrections, a sketch of how structural modes are excited by the wind action is given in Fig. 1. In particular, Fig. 1 shows a spectrum typical of pressures recorded on a building envelope in wind tunnel tests, p, and the module of transfer functions, H_i, typical of low-frequency, intermediate and high-frequency modes (characterized by modal stiffness equal to K_{qi}), as a function of the frequency, f.

It is noticed that, when structures are immersed in the atmospheric boundary layer, only few structural modes, whose natural frequency matches the energy containing zone of the incoming wind spectrum, are excited in a resonant way [16]. Additionally, the finite frequency adopted for sampling pressures, f_s, is often inadequate in order to sample pressure fluctuation which might excite in a resonant state structural modes characterized by natural frequency higher than 2.0–3.0 Hz.

In particular, low frequency modes, characterized by transfer functions similar to $H_1(f)$, are excited by the wind in a resonant condition so that dynamic amplification must be correctly taken into account in the calculation of their effects. On the other hand, considering high-frequency modes, characterized by transfer functions similar to $H_3(f)$, it can be observed that dynamic effects are negligible in the whole range of frequencies which contain energy and, thus, their effects can be correctly reproduced in a quasi-static framework. In the intermediate range, represented by the transfer function $H_2(f)$, the dynamic amplification is generally not null but a quasi-static assumption can be considered acceptable, due to the

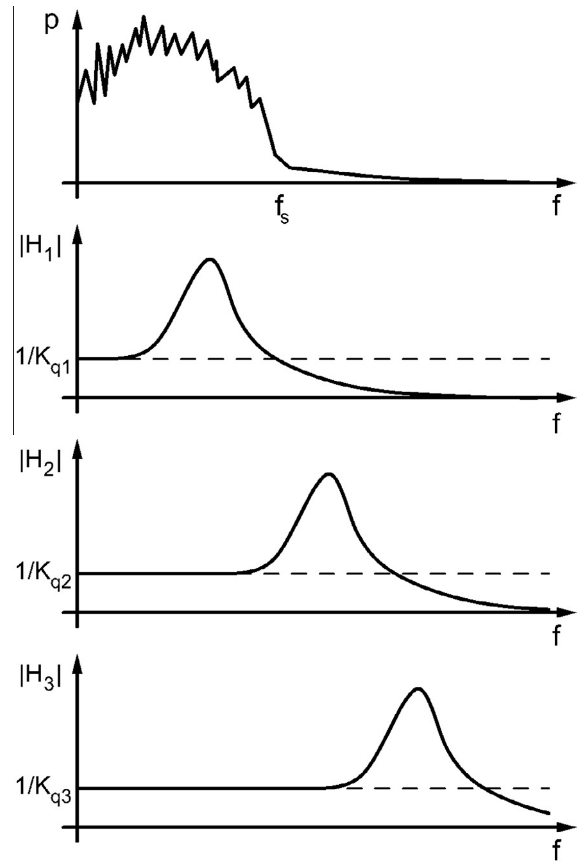

Fig. 1. Typical measured pressure spectrum (p) and transfer functions of the structural modes in resonant (1), intermediate (2) and quasi-static (3) conditions.

great simplifications which can be obtained in the calculation of the structural response. Such not uniform energy distribution in the recorded pressure field spectrum renders the adoption of static corrections particularly well suited for wind load analyses.

2. Pressure interpolation

Before proceeding to analyze the structural response, a first problem is always represented by the interpolation of pressures which are usually known only at the pressure taps. The interpolation of scattered pressure taps has been tackled in the literature in several ways, ranging from inverse distance weighting [7] and other *ad hoc* developed methods [17]. More often, cumbersome and time consuming manual procedures are applied, leading to the discretization of the surfaces exposed to the wind action in elemental facets characterized by the corresponding normal and tributary area.

In this paper, it is assumed that the structural engineer can wrap the structural model by using a thin membrane which acts as a skin of the underlying structure without changing its mechanical properties. Such skin can be easily obtained by wrapping the structural model with plate elements connected wherever possible to the main structure and assigning to them extremely low stiffness and mass. In such a way, a computational mesh is generated which can be used for subsequent calculations and represents the interface between structural and wind engineers.

In the proposed approach, in order to derive a smooth interpolation of pressures on such computational mesh, the interpolation problem is treated in analogy to a diffusion problem in which data measured at the pressure tap locations are imposed values while