Journal of Fluids and Structures 78 (2018) 52–68

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

A fully-coupled generalized model for multi-directional wind loads on tall buildings: A development of the quasi-steady theory

Wei Cui, Luca Caracoglia *

Department of Civil and Environmental Engineering, Northeastern University, Boston, MA, 02115, USA

HIGHLIGHTS

- A new generalized dimensionless approach for tall building aerodynamics is proposed.
- Inter-modal coupling due to fluid–structure interaction is explicitly analyzed.
- Wind tunnel HFFB results are incorporated into a generalized aerodynamic formula.

ARTICLE INFO

Article history:
Received 29 April 2017
Received in revised form 25 November 2017
Accepted 6 December 2017

Keywords:
Line-like structures
Quasi-steady aerodynamic theory
Tall buildings
Coupled modes
3D effects
Analytical formulation

ABSTRACT

This study examines in detail the quasi-steady aerodynamic theory, which is widely applied in wind engineering for the evaluation of wind loads. The authors propose an alternative approach and a novel generalized aerodynamic formulation for the wind-induced dynamic response of a bluff body. The proposed formulation is applied to the dynamic analysis of tall buildings, considering multi-directional wind loads, aerodynamic damping and aerodynamic stiffness effects, and inter-modal structural coupling. Dimensionless Fourier transformation is used in the formulation to provide a general "unified formula" and new insights on the modeling and estimation of wind loads. One numerical example is presented to verify the validity of the formula; numerical simulations are compared against literature data (wind tunnel test results) for a benchmark building structure.

1. Introduction

1.1. Foreword: advantages and limitations of the quasi-steady aerodynamic theory for the analysis of wind loads on vertical slender structures

The quasi-steady aerodynamic theory plays a fundamental role in the examination of wind loads, since the early stages of wind engineering research and the pioneering work by Professor Davenport (Davenport, 1961). In his original contribution, Professor Davenport demonstrated that the wind-induced structural response can be determined in the frequency domain by combining local wind climatology, local wind exposure (influenced by terrain roughness and topography), structural aerodynamic characteristics (governed by building shape) and structural dynamic properties (mass and stiffness distribution and damping ratios). The main steps of this approach are summarized by the Davenport Chain, which is illustrated in Fig. 1. This original idea has been employed in both wind engineering research and practice for several decades.

---

* Correspondence to: Department of Civil and Environmental Engineering, Northeastern University, 400 Snell Engineering Center, 360 Huntington Avenue, Boston, MA 02115, USA.

E-mail address: lucac@coe.neu.edu (L. Caracoglia).

https://doi.org/10.1016/j.jfluidstructs.2017.12.008
0889-9746/© 2017 Elsevier Ltd. All rights reserved.

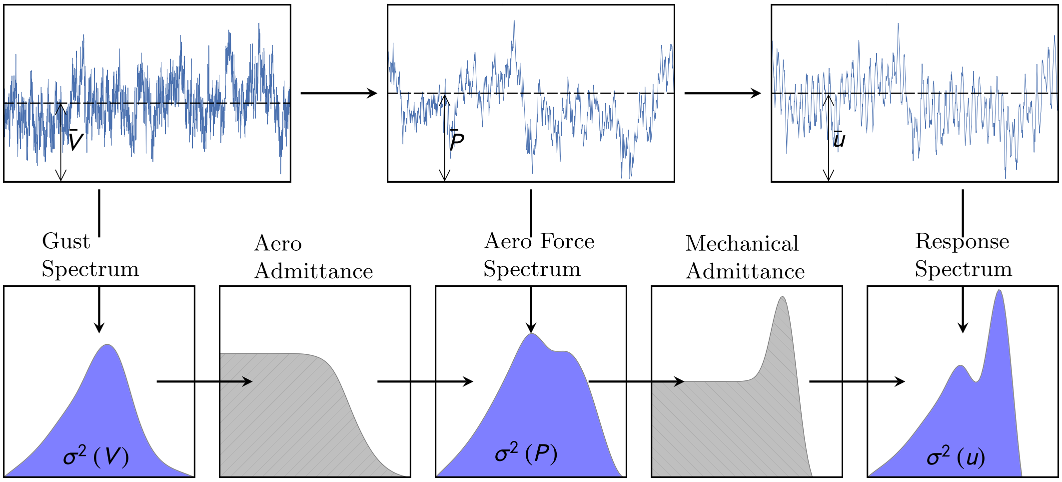

Fig. 1. Davenport Chain (Isyumov, 2012).

The original formulation was conceived to examine wind loads by focusing on a single (constant) wind direction at a time. Several authors have contributed to the further advancement of this theory for vertical slender structures such as tall buildings (e.g., Solari, 1993a,b; Piccardo and Solari, 1998a).

Because of the increasing slenderness and irregular shape in modern buildings, the approach for evaluation of wind loads has been significantly revised. For example Chen and Kareem (2005), exploiting theoretical derivations of the quasi-steady theory, proposed a general solution to evaluate the dynamic response of tall buildings by considering non-uniplanar mode shapes and inter-modal coupling. Piccardo and Solari (1998a, 2000) advanced a generalized formulation to evaluate the along-wind, cross-wind and torsional response of slender structures. In the presence of an irregular building shape, the eccentricity between mass and rigidity centers cannot be ignored. This eccentricity leads to structural coupling between lateral translation motion and rotation about the vertical building axis, first examined by Kareem (1985). Attention towards wind load analysis, accounting for a fully three-dimensional (3D) structural modeling, has been recently noted. For example, He and Macdonald (2016) proposed a method to examine generalized three-degree-of-freedom galloping instability of slender vertical structures through the extension of the quasi-steady theory, which is a derivation from a 2D model by Nguyen et al. (2015) considering the coupling between drag and lift forces for buffeting and aeroelastic response.

Finally, multi-directional wind load analysis, coupled with modal expansion with nonlinear mode shape functions, is often desirable in the presence of complex and unconventional buildings with large slenderness ratios, which often represent the modern architectural design trend. All the above aspects have been separately considered by most researchers; a generalized aerodynamic theory is still possibly needed for the design of future buildings.

1.2. Relevance of the quasi-steady theory in the context of performance-based wind engineering

Performance-based engineering is a well established probabilistic design methodology, routinely applied by structural engineers in seismic engineering (SEAOC, 1995). The basic idea is to ensure that a structure, subjected to different hazard levels, satisfies a set of minimum performance requirements (e.g., Inokuma, 2002). This methodology is a substantial evolution from the prescriptive structural design since it ensures that life safety and collapse prevention are preserved in the case of an extremely severe hazard, and occupancy disruptions are minimized in other cases.

In recent years, similar concepts have been put forward to derive a "basic theory" for performance-based wind engineering (PBWE) (Ciampoli et al., 2011; Ciampoli and Petrini, 2012). This topic has received much attention from the wind engineering community. The study by Smith and Caracoglia (2011) is among the first systematic implementations of PBWE to examine the wind-induced response of prismatic tall buildings; the quasi-steady aerodynamic theory was exploited to determine wind loads; the wind direction perpendicular to one of the vertical faces was only considered (as the most critical) and coupling of the structural modes was not examined (Smith and Caracoglia, 2011). Other examples include frameworks for the analysis of wind load variability (e.g., Bashor and Kareem, 2007; Chuang and Spence, 2017), a number of alternative methodologies for linear elastic building design (e.g., Norton et al., 2008; Jain et al., 2001; Spence and Kareem, 2014) and nonlinear inelastic structural response (Hart and Jain, 2013). In the case of wind load effects on low-rise buildings, structural failures can be related to capacity loss in key members or connections (Ellingwood et al., 2004; Ellingwood and Tekie, 1999).

Nevertheless, derivation of a possibly general (and practical) approach for PBWE, capable of investigating several performance objectives and limit states is not completely available, especially in the case of slender vertical structures such as tall buildings. As an essential part of PBWE, suitable formulas are desirable to calculate wind loads and structural response for variable wind speeds and directions. A unified formulation is consequently advantageous for a more systematic implementation of the PBWE.