Journal of Fluids and Structures 50 (2014) 512–527

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Analyzing the fluctuating pressures acting on a circular cylinder using stochastic decomposition

Y. Qiu [a], Y. Sun [a,b,*], Y. Wu [a,b], Y. Tamura [c]

[a] School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China
[b] Key Lab of Structures Dynamic Behavior and Control, Harbin Institute of Technology, Ministry of Education, Heilongjiang, Harbin 150090, China
[c] Tokyo Polytechnic University, 1583 Iiyama, Atsugi, Kanagawa 243-0297, Japan

ARTICLE INFO

Article history:
Received 25 November 2013
Accepted 7 July 2014
Available online 18 August 2014

Keywords:
Circular cylinder
Coherent structure
POD
Reynolds number
Spectral proper transformation

ABSTRACT

Fluctuating wind pressures acting on bluff bodies are influenced by approaching turbulence and signature (body-induced) turbulence. For a circular cylinder, the signature turbulence is closely related to the formation of Karman vortex shedding. In this paper, proper orthogonal decomposition (POD) and spectral proper transformation techniques (SPT) are applied to the pressure fluctuations acting on a circular cylinder. The physical relationships between the decomposed modes and vortex shedding are discussed to identify the dominant aerodynamic behavior (lift or drag) and to evaluate its contribution to overall behavior. The effect of Reynolds number (Re) is also addressed. It is found that the application of POD and SPT can separate the along-wind and across-wind effects on the cylinder model in both subcritical and supercritical regimes. In contrast to POD, the SPT mode is formulated in the frequency domain, and the dynamic coherent structures can be defined in terms of amplitude and phase angle, which allows detection of the advection features of vortex shedding. In addition, it is observed that the energy contribution of the shedding induced lift force increases with Re and gradually becomes a dominant aerodynamic force at Reynolds numbers in the supercritical regime.

1. Introduction

Fluctuating pressure field acting on a bluff body can be obtained through multi-channel pressure scanners in a wind tunnel test. A common purpose for analyzing aerodynamic behavior of bluff bodies is to quantify the global and local wind effects for design purposes, such as force and pressure coefficients. From a physical point of view, the pressure fields have a complex random nature due to the presence of approaching turbulence together with signature (body-induced) turbulence. Besides, the aerodynamic excitation (buffeting, vortex shedding, etc.) of the bluff body immersed in a turbulent flow is a result of the fluctuating pressure field over the body surface. This suggests that a physical interpretation of the aerodynamic pressure measurements or the mechanism of excitation may be obtained. However, the recorded pressure fluctuations are usually treated as a multi-variate stochastic problem, yet traditional statistical methods (e.g. correlation and coherence functions) are not applicable due to a strong spatial-temporal characteristic of the pressure field.

* Corresponding author at: School of Civil Engineering, Harbin Institute of Technology, Heilongjiang, Harbin 150090, China. Tel.: +86 451 86282080.
E-mail address: sunnyhit@hit.edu.cn (Y. Sun).

http://dx.doi.org/10.1016/j.jfluidstructs.2014.07.008
0889-9746/

Holmes et al. (1998) suggested a means for understanding turbulence in three broad categories: (a) investigating coherent structures in certain fully developed turbulent flows by experimental fluid visualization techniques; (b) finite-dimensional dynamical system theory in the analysis of the governing equations, where significant progress has been made, and (c) the introduction of statistical techniques such as stochastic decomposition method. Generally, counter-rotating vortices in turbulent flow can be termed coherent structures, which were originally found by direct observations of flow. Quantitatively extracting coherent structures and developing the corresponding dynamics are still subjects for research. In the last decade, the proper orthogonal decomposition (POD) approach has been widely used in many applications to characterize the dominant coherent structure hidden in apparently random fluctuations. This technique, originally proposed by Lumley (1970), allows decoupling of the fluctuating pressure field into a number of uncorrelated random scalar processes based on the orthogonal decomposition of the covariance matrix. Thus, the random pressure field can be represented by a sum of deterministic eigenvectors called modes, modulated by random coefficients called principal components.

In engineering applications, the POD technique can provide an accurate description of the original fluctuating pressure field through a limited number of uncorrelated processes, which has been widely studied and used, and is efficient in reducing the necessary information for simulation purposes (Ricciardelli and De Grenet, 2002; Flores-Vera et al., 2008). Kikuchi et al. (1997) suggested that the first POD mode gives the best approximation of the pressure field in the mean square sense, and can be interpreted as the dominant coherent structure or the characteristic of the dominant flow around the bluff body. Thus, the POD approach has been widely used to obtain the lower-order POD modes, which are dominated by the most energetic turbulence in the flow, and to gain some physical insight into the nature of the pressure fluctuations (Kareem and Cermak, 1984; Holmes, 1990; Tamura et al., 1999). However, Holmes et al. (1997) applied this technique to analyze the fluctuating pressures acting on a low-rise building, and found that orthogonal modes failed to give any reasonable physical interpretation for some wind directions. Other authors suggested that there is no reason to assume the POD mode really provides a physical insight (Baker, 2000; Gilliam et al., 2004).

Although there is still some controversy concerning the use of stochastic decomposition techniques as identification tools, Ricciardelli (2005) discussed the capacity of the POD technique for separating physical phenomena. The author suggested that full decoupling of the multi-variate random processes is achieved only if its covariance matrix is diagonal. Generally, the fluctuating pressure fields are rather non-Gaussian and their correlation matrix is non-diagonal, so the application of POD provides only a partial decoupling of the multi-variate random processes. This constraint would, in fact, lead to a choice of eigenvectors which is not necessarily bringing the best separation of the physics. In other words, it does not necessarily mean that the application of POD can separate the physical phenomena from the pressure field. Carassale (2009) explained the reason why POD technique can separate the along-wind and across-wind effects on symmetric cylinders, is based on such a condition that, the measured pressure field and fluid-induced loads acting on the cylinders are statistically-symmetric. In addition, it should be noted that the eigenvectors cannot be uniquely determined in the sense of POD analysis (Tamura et al., 1999), possibly due to the sensitivity of eigenvectors to lacks of symmetry of the pressure field. The effect of lacks of symmetry can be strongly emphasized by the occurrence of two closely-spaced eigenvalues, and the consequent interaction between corresponding POD eigenvectors.

Another new analytical approach is based on the use of short-time Fourier transform combined with proper orthogonal decomposition in the frequency domain, namely spectral proper transformation (SPT). The application of SPT for extracting coherent structures from random pressure fields has received attention recently in wind engineering. Since the SPT eigenvalues and eigenvectors are functions of time and frequency, more information may be provided than the invariable POD modes. De Grenet and Ricciardelli (2004) applied the SPT technique to analyze the pressure fluctuations acting on a square cylinder and a bridge box deck. Their work reported that SPT modes allow a better separation of the aerodynamic components at different frequencies, and can provide a better reproduction of the energy of the pressure fluctuations than that obtained from the same number of POD modes. One related study is the work of Carassale and Marrè-Brunenghi (2011), they reviewed traditional and innovative statistical tools to study wind effects on bluff bodies, and found that SPT modes enable a temporal tracing of the coherent structures when the pressure field is generated by vortex advected by the mean flow. Carassale and Marrè-Brunenghi (2012) also pointed out that each SPT mode can describe many independent mechanisms of aerodynamic excitation at different frequencies, which provides more information than one POD mode does, and may be attractive for understanding the coherent structures hidden in the pressure field. Carassale (2012) extracted coherent structures from the random pressure field on a high-rise building immersed in a turbulent boundary layer. He concluded that the use of dynamic modes, like SPT, enables the detection of pressure features determined by the advection of vortices.

Several applications of POD and SPT for analyzing fluctuating pressure fields around two- or three-dimensional rectangular prisms can be found in the above literature. Since vortex shedding from a circular cylinder has been widely and thoroughly studied, the present paper aims to investigate the capacity of POD and SPT techniques for separating aerodynamic behavior from fluctuating pressure field and evaluating its role in overall wind-induced behavior. For this, wind tunnel tests with simultaneous multi-pressure measurements were conducted in the Reynolds number range 1.66×10^5–8.28×10^5. This paper primarily investigates the signatures of POD and SPT eigenvectors and eigenvalues in interpreting the advection features of vortex shedding in different flow regimes. In addition, the correspondence between POD and SPT modes is discussed. Finally, it is found that the shedding induced lift force becomes a dominant mechanism with respect to the overall behavior, with the flow condition changing from subcritical to supercritical.