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Full-scale measurement of wind pressure on the surface of an oscillating circular cylinders

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ABSTRACT

Under wind excitation, many slender structural members with circular cross sections have exhibited large-amplitude vibrations. The nature of some problematic vibrations remains to be fully understood. To investigate the excitation mechanisms that can cause the vibrations, an experimental campaign was conducted to measure simultaneously the wind pressure on the surface of a circular cylinder in the atmospheric boundary layer and the acceleration of this cylinder. The pressure and acceleration measurements were used to investigate the interaction between the cylinder and the turbulent wind in subcritical and critical Reynolds number ranges. The study revealed several effects of turbulence in wind in the atmospheric boundary layer on the critical transition, including the promotion of early critical transition, the attenuation of the single separation bubble, and the early cessation of the coherent vortex shedding. A coherent fluctuating axial flow component in the wake of circular cylinders yawed to the flow, which has been previously observed in wind tunnel tests in smooth flow and postulated to be critical for the onset of dry cylinder vibration at high reduced velocity, was not observed in the present experiment.

1. Introduction

Circular cylinders are among the simplest shaped bluff bodies. However, the interaction between circular cylinders and fluid flow is very complex primarily due to the fact that both where and how the flow separates from the cylinder surface depend on not only the mean and turbulent nature of the free-stream flow, but also the characteristics of the cylinder, such as its size, orientation relative to the flow, and elastic property. Numerous experiments, most of which being laboratory-based, have been conducted to study the flow around circular cylinders. In a two-volume book, Zdravkovich (1997, 2003) comprehensively reviewed many of these studies, detailing the observed nature of the flow around a circular cylinder and the corresponding characteristics of the loading on the cylinder over ranges of Reynolds numbers (*Re*) that are associated with a succession of transitions of the flow in the wake, the free shear layers, and the boundary layers around the cylinder from laminar to turbulent.

For many engineering applications involving the flow around circular cylinders, the Reynolds number is high, approaching or exceeding those at which the critical transition of the boundary layers begins (e.g., at $Re \approx 2 \times 10^5$ for uniform smooth free-stream flow perpendicular to the cylinder axis). Due to this, and also the perceived drastic change of the loading on the cylinder at the critical transition, many classical studies (e.g., Almosnino and McAlister, 1984; Bearman, 1969; Eisner, 1925; Fage, 1929; Farell and Blessmann, 1983; Güven et al., 1980; Humphreys, 1960; Schewe, 1983) have focused on the flow at high Reynolds numbers. The results from these studies have led to advances in fundamental knowledge of the evolution of the flow and the resultant characteristics of the force acting on the cylinder with increasing Reynolds number. Most notably, it was revealed that when the free-stream flow is uniform, smooth and perpendicular to the cylinder axis, the transition of the boundary layers from laminar to turbulent causes a drastic decrease of the drag coefficient, a condition known as the “drag crisis”. It was also observed that as the Reynolds number increases, the critical transition occurs on one side of the cylinder first, creating a separation bubble on this side and resulting in a net mean lift force, and then on both sides of the cylinder, forming two symmetric separation bubbles and generating zero mean lift. The previous studies also suggests that as the Reynolds number further increases, the flow enters the supercritical regime, over which the separation bubbles are disrupted and fragmented, resulting in irregular separation lines and the cessation of periodic vortex shedding. Subsequently, the flow enters the postcritical range (e.g., $Re > 4 \times 10^6$), over which

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straight separation lines are reestablished and periodic vortex shedding reappears (e.g., Bearman, 1969; Cincotta et al., 1966; Roshko, 1961). The Stouhal number (St) in the postcritical region was estimated to be greater than the nominal value over the precritical Reynolds number regime (i.e., $St \approx 0.2$).

Previous studies have also suggested that the flow around circular cylinders can be significantly influenced by turbulence and shear in the free-stream flow as well as by the roughness of the cylinder surface. It was observed that increasing the turbulence in the free-stream causes the laminar to turbulent transition in the free and boundary layers to occur at progressively lower Reynolds numbers (e.g., ESDU, 1980; Fage and Warsap, 1929; Kiya et al., 1982; Zasso et al., 2005), and that increasing surface roughness has a similar effect on the critical transition (e.g., ESDU, 1980; Fage and Warsap, 1929; Zasso et al., 2005). In particular, one group of researchers provided formulas (ESDU, 1980) that can be used to quantify the effects of the surface roughness and the free-stream turbulence (in terms of the turbulence intensity and the lateral integral length scale of the longitudinal turbulence) on the critical transition. Further, Blackburn and Melbourne (1996) revealed that for free-stream flow of low turbulence intensity (e.g., for a longitudinal turbulence intensity, I_u, of 4.6%, as in Blackburn and Melbourne, 1996), periodic vortex shedding occurs in the precritical and critical Reynolds number regimes, with a Strouhal number of 0.18, but ceases to exist in the supercritical Reynolds number regime. The same researchers also suggested that for free stream flow of high turbulence intensity (e.g., $I_u = 18\%$, as in Blackburn and Melbourne, 1996), organized vortex shedding exists beyond the critical Reynolds number regimes, with a Strouhal number of 0.23.

In addition, previous studies have indicated that although shear along the cylinder axis in the free-stream flow does not significantly affect the critical transition (Davies, 1975), it does create secondary flows along the cylinder axis on both the windward and the leeward sides which cause the drag coefficient to vary along the cylinder axis (e.g., Masch and Moore, 1963; Shaw and Starr, 1972). It also has been observed that for this type of free-stream flow, vortex shedding occurs in a "cellular" pattern along the cylinder axis, with the shedding frequency being constant within each cell (Maull and Young, 1973). On the other hand, a limited number of studies (e.g., Kiya et al., 1980) have suggested that shear across the cylinder in the free-stream flow results in asymmetric pressure distribution on the cylinder surface. However, none of these studies were conducted at high Reynolds numbers. As a result, the effect of shear across the cylinder for flows at high Reynolds numbers is unclear.

Despite the extensive fundamental understandings gained from previous studies, several types of large-amplitude wind-induced circular cylinder vibration still cannot be adequately explained. For example, stay cables of many cable-stayed bridges have been observed to vibrate at excessively large amplitudes (i.e., of the order of multiple diameters of a cable) under the excitation of wind with simultaneous occurrence of rain (e.g., Hikami and Shiraishi, 1988; Matsumoto et al., 1998). Full-scale measurements (e.g., Hikami and Shiraishi, 1988; Matsumoto et al., 2003; Zuo and Jones, 2010) have revealed that these large-amplitude vibrations occur over a restricted range of reduced velocities that is significantly higher than that over which circular cylinders exhibit lock-in vortex-induced vibration. The same studies have also suggested that stay cables declining in the direction of the wind are more susceptible to this type of vibration than are cables of the opposite orientation. Initially, it was believed that the occurrence of rainfall is necessary for the onset of this type of vibration. However, a recent full-scale study has suggested that the characteristics of the large-amplitude vibrations occurring with rainfall, and the correlation of these characteristics with the wind characteristics, are similar to the corresponding characteristics and correlation of a class of dry stay cable vibration (Zuo and Jones, 2010). This indicates that the vibrations occurring with rainfall are likely related to the aerodynamics of dry circular cylinders.

Motivated by the observations in the field, many wind tunnel tests have been conducted to expressly study the wind loading of yawed or inclined circular cylinders (e.g., Cheng et al., 2008; Cosentino et al., 2003; Hikami and Shiraishi, 1988; Matsumoto et al., 1992, 2001; Zuo and Jones, 2009). However, the findings from these studies have varied. The tests that simulated rainfall or used solid strips to simulate the water rivulets on the cylinder surface during rainfall (e.g., Cosentino et al., 2003; Hikami and Shiraishi, 1988; Matsumoto et al., 1992) suggest that these rivulets play an important role in the onset of large-amplitude rain-wind-induced vibration, either by interacting with the oscillation of the cylinder or by aerodynamically modifying the cylinder surface. The studies that tested dry circular cylinders without artificial rivulets indicated that yawed or inclined dry circular cylinders can be susceptible to galloping over the critical Reynolds number range (Cheng et al., 2008), as well as a type of vortex-shedding related excitation at high reduced velocity due to the presence of an axial flow component (e.g., Cheng et al., 2008; Matsumoto et al., 2001; Zuo and Jones, 2009). Based on these studies, it has been suggested that the mechanisms which caused significant dry circular cylinder vibrations in the wind tunnels are also likely to be the causes for the large-amplitude stay cable vibrations.

In addition to the experimental work, numerical investigations based on computational fluid dynamics (e.g., Hoftyzer and Dragomirescu, 2010; Kawamura and Hayashi, 1994; Lucor and Karniadakis, 2003; Yeo and Jones, 2008) have also been conducted to study the wind flow around yawed circular cylinders. Some recent studies (Hoftyzer and Dragomirescu, 2010; Yeo and Jones, 2008) have particularly focused on the characteristics of an axial flow component in the wake of the cylinder, and it has been indicated that the interaction between this axial wind component and the vortex shedding into the wake of the cylinder can excite the cylinder to vibrate at large amplitudes.

Despite the extensive field, laboratory and computational studies that have been completed, the complex interactions between circular cylinders and wind that induce large-amplitude vibrations are still not adequately understood. In particular, since most of the wind tunnel and numerical studies were conducted based on uniform smooth flow, the effects of the wind shear and turbulence in the atmospheric boundary layer on the interaction are mostly unclear. Also, in the experiments in which the wind pressure on the surface of a circular cylinder was measured, with few exceptions (e.g., Jakobsen et al., 2012), the cylinder was held stationary. As a result, the interaction between the cylinder oscillation and the flow could not be fully assessed.

This paper presents the findings from a field experimental campaign conducted to measure simultaneously wind pressure on the surface of a slender circular cylinder and the resulting vibration of this cylinder. As a first step, the cylinder was oriented horizontally to facilitate an investigation of the effects of the turbulence and shear in the atmospheric boundary layer winds as well as the yaw angle of the cylinder on the cylinder-wind interaction. This paper details the characteristics of the wind pressures and the resultant forces acting on the cylinder in wind regimes of various mean and turbulent characteristics, as well as those of the corresponding cylinder response. The implications of observations on the excitation mechanism of large-amplitude dry circular cylinder vibration are also presented.

2. Experimental configuration

The experiment was conducted at the full-scale test facility at Texas Tech University in Lubbock, Texas, USA. This facility is