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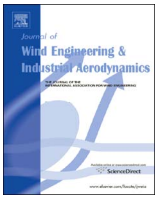

The effects of free-stream turbulence and angle of attack on the aerodynamics of a cylinder with rectangular 5:1 cross section

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ABSTRACT

The aerodynamics of a stationary two-dimensional cylinder with rectangular 5:1 cross section is the object of an international experimental and numerical benchmark study (BARC). The unsteady flow past such a bluff body is governed by the impinging shear-layer instability mechanism, which is also responsible for potential flow-induced vibrations. This paper discusses the characteristics of the high-Reynolds-number unsteady flow over the cylinder, investigated in the wind tunnel through pressure and force measurements on a sectional model in smooth and turbulent flows. In addition, hot-wire anemometry measurements of the velocity in the wake of the cylinder were carried out in smooth flow. The study is particularly focused on understanding the influence of free-stream turbulence and angle of attack on the aerodynamic behavior of the body. Key features are highlighted, such as a slight Reynolds-number dependence of force coefficients and Strouhal number in smooth flow, or the turbulence-induced variation of the length of the separation bubbles along the lateral sides of the cylinder. Incoming turbulence is also found to affect the vortex-shedding mechanism of impinging shear-layer instability, promoting the switch from a dominant mode to another. Finally, the wake measurements described some vortex-shedding features, confirming a slight Reynolds-number dependence of the Strouhal frequency.

1. Introduction

The rectangular shape is a recurring geometry in civil, military and industrial structures, and therefore it has often been the object of studies concerning its aerodynamics and proclivity to flow-induced vibrations. For instance, tall buildings are often shaped as elongated prisms and two-dimensional rectangular cylinders have commonly been considered as qualitative schematizations of bridge decks (Matsumoto, 1996). Many complex-shaped structures also present slender elements with rectangular cross sections. In addition, two-dimensional rectangular cylinders have often been considered as a reference to model the complex aerodynamics of rectangular underslung helicopter loads (Greenwell, 2011; Prosser and Smith, 2016).

For a theoretical cross section with perfectly sharp corners and smooth surfaces, the side ratio alone defines the rectangular geometry, which, due to its simplicity, clearly highlights interesting fluid dynamic phenomena and allows a detailed study of the aerodynamic features of the generated flow field. Moreover, depending on the side ratio and turbulent characteristics of the incoming flow, rectangular prisms are prone to different types of flow-induced excitation, such as vortex-induced vibration (e.g. Komatsu and Kobayashi, 1980; Shiraishi and Matsumoto, 1983; Nakamura and Nakashima, 1986; Naudascher and Wang, 1993; Marra et al., 2011, 2015), hard- and soft-type transverse galloping (e.g. Parkinson, 1965; Novak, 1972; Nakamura and Tomonari, 1977; Washizu et al., 1978), interference of vortex-induced vibration and galloping (e.g. Parkinson and Wawzonek, 1981; Bearman et al., 1987; Mannini et al., 2014, 2016), torsional galloping (or torsional flutter; e.g. Nakamura and Mizota, 1975; Matsumoto et al., 1997) and coupled flutter (e.g. Matsumoto, 1996; Bartoli and Righi, 2006). Consequently, it is extremely important from the practical engineering point of view to investigate the characteristics of flow past these simple geometries and to understand those mechanisms that can produce vibrations of elastic structures.

For these reasons, the BARC benchmark was launched in 2008 during the 6th International Colloquium on Bluff Body Aerodynamics and Applications (Bartoli et al., 2008), focusing on the stationary rectangular 5:1 cylinder, where the short side of the section faces the flow. This side ratio is particularly interesting, since in smooth flow the shear layers separating at the leading edges are known to reattach intermittently close to the trailing edges (as for all rectangular cylinders with side ratio between 3.2 and 7.6 in smooth flow, according to Parker and Welsh (1983)), so that a strong sensitivity of its aerodynamics on several geometrical features and flow conditions is expected. In addition, Ohya et al. (1992) noted that the vortex-shedding mechanism

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is less regular (and then challenging to predict) than for slightly smaller (such as 3:1 and 4:1) or larger (such as 6:1) side ratios.

A synopsis of the experimental and numerical results obtained in the first four years of benchmark activity has been recently published (Bruno et al., 2014). Therein, the good agreement between results in terms of near-wake flow, base pressure and drag coefficient was shown. By contrast, the comparison highlighted a significant dispersion of flow features and pressure distribution along the lateral sides of the cylinder. A collection of previous experimental results for drag coefficient and Strouhal number can be found in Mannini et al. (2011).

Among the main results achieved during the benchmark, it is worth reminding the measurements in a high-pressure wind tunnel performed by Schewe (2013), who investigated the Reynolds-number range between 4000 and 600,000 (based on the cross-flow section dimension). He found only a slight change of the main global aerodynamic parameters for a null flow incidence but a significant variation of the mean lift coefficient with the Reynolds number for small angles of attack (an increase of about 100% and 70% in the tested Reynolds-number range respectively for incidences of 2° and 4°). In particular, a quick change of mean lift coefficient and Strouhal number is clear for Reynolds numbers below about 10,000. In this respect, it is to note that for a rectangular 3:1 cylinder Okajima (1982) showed a strong Reynolds-number dependence of the Strouhal number for values below about 5000. The Reynolds-number effects observed by Schewe were explained by the two-dimensional unsteady Reynolds-averaged Navier-Stokes (URANS) computations carried out by Mannini et al. (2010), who emphasized the key role played by the separation bubble on the lateral side of the section where shear-layer reattachment occurs, the length of which reduces while increasing the Reynolds number. In that work, the Authors also highlighted the fact that the vortex shedding in the case of an angle of attack of 4° was much more regular at a Reynolds number of 370,000 than 5200.

Other interesting numerical studies were conducted in the framework of the BARC benchmark, discussing also technical aspects related to the numerical approach. In particular, Bruno et al. (2010) carried out a three-dimensional large-eddy simulation (LES), which enabled the identification of five topological mean flow structures around the cylinder (“inner region”, “recirculation region”, “main vortex”, “reattached flow” and “reversed flow in the wake”). In addition, the mechanisms of vortex formation close to the upstream sharp edges, vortex coalescence and convection are described in details. Mannini et al. (2011) performed three-dimensional detached-eddy simulations (DES) and emphasized the crucial influence on the results of the amount of numerical dissipation introduced to stabilize the central-difference discretization scheme and of the spanwise extension of the computational domain. The latter issue was further investigated through LES computations in Bruno et al. (2012) together with the effect of refining the mesh in the spanwise direction. The results pointed out the great importance of these two parameters for the accuracy of the results. Recently, Patruno et al. (2016) concentrated on the influence of small angles of attack on the resulting flow field and aerodynamic quantities, comparing URANS and LES numerical strategies. Ricci et al. (2016) studied the sensitivity of LES results to a low level of incoming turbulence. Finally, Mariotti et al. (2016) carried out URANS simulations with aleatory parameters (angle of incidence, and free-stream longitudinal turbulence intensity and length scale) and investigated the probabilistic propagation of the uncertainty.

For the BARC section, and in general for rectangular cylinders with side ratios in the range between 3 and 15, the vortex-shedding mechanism is not of Kármán type, i.e. triggered directly by the interaction between upper and lower shear layers in the region behind the body, but it is due to the “impinging shear-layer instability” or “edge tone” (Rockwell and Naudascher, 1979; Nakamura et al., 1991; Ohya et al., 1992). This phenomenon is also known as “impinging leading-edge vortices” (Naudascher and Wang, 1993) and is produced by the “impinging” of a shear layer on an obstacle downstream, namely the afterbody in the trailing edge region in the case of rectangular cylinders. This generates a feedback control through pressure pulses that travel upstream at the speed of sound. This feedback may be an order of magnitude stronger than that in the absence of impingement and is able to trigger large flow fluctuations at the leading edge. In fact, Nakamura and Nakashima (1986) showed that both vortex shedding and vortex excitation are possible for rectangular, H and T shapes also in the presence of a splitter plate, thus meaning that a single shear layer can be unstable in the presence of a downstream corner. Nevertheless, in the absence of a splitter plate, the separation bubble grows and envelops the trailing edge, allowing the fluid within the bubble to pass into the vortex formation region behind the body (Parker and Welsh, 1983). Clearly, the interference with the vortex forming on the opposite side of the cylinder has an effect on the vortex street.

Tan et al. (1998) and Hourigan et al. (2001), through two-dimensional and three-dimensional direct numerical simulations, and Mills et al. (2002, 2003), through flow visualizations and PIV measurements in wind and water tunnels, studied the interaction phenomena between leading- and trailing-edge vortices and their phasing in rectangular cylinders with long afterbody. Nakamura et al. (1996) experimentally observed transition from Kármán vortex street to impinging shear-layer instability mechanism for a Reynolds number around 250 (350 according to two-dimensional direct numerical simulations). In addition, impinging shear-layer instability exhibits different modes of vortex shedding depending on the side ratio, which in some cases can also coexist (Nakamura et al., 1991; Ohya et al., 1992; Naudascher and Rockwell, 1994). As a consequence, the Strouhal number presents evident jumps in correspondence of the side ratios for which a switch to a higher vortex-shedding mode occurs.

Another key issue that deserves great attention is the role played by free-stream turbulence in the aerodynamics of the BARC section. In these respects, one of the earlier investigation on the effects of incoming turbulence on the flow around bluff bodies was carried out by Vickery (1966), while Mulhearn (1973) visualized the reattachment lines on a square cylinder and highlighted their different location in smooth and turbulent flow. Kiya and Sasaki (1983) undertook a thorough study of the steady and unsteady characteristics of the separation bubble in the case of a long plate with blunt front corners. In their review, Bearman and Morel (1983) identified three basic mechanisms by which free-stream turbulence and the high-Reynolds-number mean flow over bluff bodies interact: i) anticipated transition to turbulence in the shear layers; ii) enhanced mixing and entrainment, which produce an increased growth of the free shear layers and a more pronounced curvature inward towards the body, leading to a stronger tendency to reattach; iii) distortion of free-stream turbulence by the mean flow. In the particular case of rectangular cylinders with sharp edges, the first mechanism was recognized to play a minor role. The thicker shear layers in turbulent flow were visualized by Laneville et al. (1977) for a rectangular 2:1 cylinder. Gartshore (1973), Nakamura and Ohya (1984) and Nakamura and Ozono (1987) distinguished between the effect of small-scale turbulence, i.e. comparable with the thickness of the shear layers, and large-scale turbulence, i.e. comparable with the body size. The former enhances the mixing and the entrainment of fluid from the near wake and accelerates the growth of the shear layers promoting their earlier reattachment; in contrast, the latter weakens regular vortex shedding by reducing the spanwise correlation of the process. This distinction is in line with the analysis of Gerrard (1966), who noted that there are two simultaneous characteristic lengths that contribute to the definition of vortex-shedding frequency for a bluff body, namely the scale of the formation region and the thickness of the shear layers when they diffuse. Haan Jr. et al. (1998) emphasized the importance of length scales of the incoming turbulence of the order of one tenth of the cross-section depth.

In the literature, a great effort has also been devoted to study the effect of the integral length scale of free-stream turbulence (Hillier and Cherry, 1981; Courchesne and Laneville, 1982; Bearman and Morel,