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Experimental investigation on the combined effects of surface roughness and corner radius for square cylinders at high Reynolds numbers up to 10^7

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ABSTRACT

In this study, the aerodynamics of 2D, slightly rough, square-section cylinders with rounded corners is experimentally investigated for Reynolds numbers up to about 12×10^6. The cylinders have a mean relative surface roughness of $k/D = 1 \times 10^{-3}$, a corner radius of either $r/D = 0.16$ or 0.29 and are positioned at an angle of incidence of 0° or −45° in cross-flow direction. The results show that a larger corner radius induces lower drag coefficients and higher vortex shedding frequencies for all flow regimes, but at lower shedding intensities. Changing the angle of incidence from 0° to −45° results in all coefficients and the wake profile to become nearly independent of the Reynolds number. The critical flow state furthermore shifts to higher Reynolds numbers and decreases in length, whereas the supercritical flow state reduces to a single point. An increase of the surface roughness height from $k/D = 5 \times 10^{-6}$ to $k/D = 1 \times 10^{-3}$ induces a shift of the flow regimes towards significantly lower Reynolds numbers. The values of the coefficients show a lower dependency on the Reynolds number in all flow regimes, whereas in the upper transition a strong recovery of all coefficients towards subcritical values takes place.

1. Introduction

Since the middle of the last century, numerous investigations have been conducted to study the aerodynamic behaviour of cylindrical structures with bluff cross-sections, which are found in numerous research fields, such as aerospace, civil, marine and mechanical engineering, and wind engineering. The flow around this type of bluff body is, to a large extent, characterised by complex phenomena close to the cylinder surface and in its near wake, e.g. shear-layer instabilities, flow separation and reattachment, vortex shedding, unsteady aerodynamic loads and flow-induced aeroelastic vibrations. Knowledge of these aspects in relation to the object's shape and surface texture is therefore of benefit to the design process of complicated structures.

1.1. Influence of cylinder corner radius

Due to the rounded and continuous surface shape of circular cylinders, the Reynolds number dominates the behaviour of the flow over this kind of bluff body. This dependency results from the variation of the boundary layer separation angles along the upper and lower side of the cylinder surface with changing Reynolds number defined as $Re_D = \rho U_\infty D/\mu$ with ρ, U_∞ and μ the density, free-stream velocity and dynamic viscosity of the fluid and D the reference length of the cylinder, respectively. In combination with the movement of the boundary layer transition points, this results in a strong influence on the mean and fluctuating drag and lift forces and vortex shedding process (Roshko (1961), Achenbach (1968), Bearman (1969), James et al. (1980), Schewe (1983), Zdravkovich (1997)). In contrast to circular cylinders, the location of the upstream separation points of square-section cylinders with sharp corners is fixed at the windward corners. Because of this the developed flow is relatively insensitive to a Reynolds number variation for angles of incidence up to the critical angle of ±13° (Delany and Sorensen (1953), Polhamus (1958), Vickery (1966), Bearman (1972), Lee (1975), Okajima (1982), Norberg (1993), Lyn et al. (1995), Tamura and Miyagi (1999), Dutta et al. (2003), van Oudheusden et al. (2007)). These structures are, however, more prone to a change in the impact angle of the flow, because for augmenting positive or negative angles of incidence, the flow field around the cylinder becomes increasingly asymmetric and a one-sided reattachment of the boundary layer takes place above the critical angle of incidence (Bearman and Obasaju (1982), van Oudheusden et al. (2005), Huang et al. (2010), Huang and Lin (2011), Carassale et al. (2014)).

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In some cases, the use of circular cylinders or square-section cylinders with sharp edges is unfavourable. Constructions based on the latter shape, for example, are prone to galloping and have a high drag force over a wide range of Reynolds numbers. In order to minimise the risk of galloping instabilities, square-section cylinders with rounded corners are often used for this type of structure. Because the cross section of the latter structure can be seen as transition geometry between the two aforementioned extreme cases, it is to be expected that the behaviour of the flow around rounded square-section cylinders is a combination of both extremes, whereby the extent to which the corners are rounded plays an important role. Various experimental and numerical studies have been conducted in the past decades to investigate the influence of the cylinder corner radius on the aerodynamic and aeroelastic behaviour of square-section cylinders. Delany and Sorensen (1953) and Polhamus (1958) observed that for rounded square-section cylinders up to $\mathrm{Re}_D = 2 \times 10^6$ a decrease of the corner radius results in a shift of the critical Reynolds number regime towards much higher values and in higher drag coefficients, especially in the critical and supercritical regime. The latter observation was confirmed for various Reynolds number regimes in later experiments by Tamura et al. (1998) and Dalton and Zheng (2003), who additionally found that this increase in the drag coefficient is accompanied by a shift of the fluctuating lift to higher values, both of which they attributed to a decrease of the wake pressure. Due to the subsequent reduction of the wake width and the better communication of the separated shear layers in the near wake, there is an increase in the vortex shedding frequency (Bokaian and Geoola (1984), Hu et al. (2006), Carassale et al. (2013, 2014)). Tamura and Miyagi (1999), Letchford and Mason (2011), Carassale et al. (2013, 2014) all measured that for higher free-stream turbulence levels, a larger cylinder corner radius promotes the reattachment of the separated shear layers on the side surfaces even at an angle of incidence of 0°. In an earlier publication (van Hinsberg et al. (2017)) we experimentally investigated the influences of the angle of incidence and corner radius on the aerodynamic behaviour of smooth, rounded square-section cylinders with $r/D = 0.16$ and 0.29 (r being the corner radius) for Reynolds numbers up to 12×10^6. We showed that the critical Reynolds numbers, the maximum drag coefficients and the fluctuating lift shifted to lower values with increasing corner radius, whereas simultaneously higher vortex shedding frequencies were obtained. An increase in the angle of incidence was found to derive in higher drag forces and Strouhal numbers, as well as in a significant reduction of the Reynolds-number length of the supercritical flow state.

1.2. *Influence of surface roughness on circular cylinders*

In cold regions, precipitation roughens the relatively smooth surface of, for example, bridge hangers, stay cables and overland transmission lines. This can lead to modifications in the cross-sectional shape of the cables, thereby making them aerodynamically unstable and thus prone to galloping (Gjelstrup et al. (2012), Demartino et al. (2015), Demartino and Ricciardelli (2015)). The pillars of offshore floating platforms and offshore wind turbines undergo a continuous increase of their local surface roughness due to rust and marine growth. The influences of the texture, relative height and location of the surface roughness on their hydro- and aerodynamic behaviour of circular cylinders in particular, have been examined in numerous experimental and numerical investigations. However, in many of these studies the surface roughness was solely applied to force a transition of the boundary layer at low Reynolds numbers in order to simulate flow phenomena that physically occur at much higher Reynolds numbers. Batham (1973), Szechenyi (1975), Güven et al. (1980) and Nakamura and Tomonari (1982), for example, uniformly covered the cylinder surface with solid particles, like glass beads or sand paper, to simulate higher Reynolds numbers in their experiments. To study the flow phenomena in the transcritical Reynolds regime Ribeiro (1991) applied spanwise roughness stripes at a single and multiple angular positions, whereas Achenbach (1971), Achenbach and Heinecke (1981), Bearman and Harvey (1993), Adachi (1997) and Yamagishi and Oki (2004) used uniformly distributed dimples and grooves to investigate their influence on the flow behaviour up to the supercritical and upper transition regime.

Within the critical and supercritical Reynolds numbers ranges, the forces and pressures on the cylinder are sensitive to even the smallest disturbances in the flow conditions and in the local model surface topology and roughness (Niemann and Hölscher (1990), Zdravkovich (1990)). Measurements of the unsteady aerodynamic forces and time-averaged local surface pressures on a slightly rough ($k/D = 1 \times 10^{-3}$ with k the (mean) absolute height of the uniformly distributed roughness) circular cylinder were performed by van Hinsberg (2015) up to $\mathrm{Re}_D = 12 \times 10^6$. This study showed that an increase of the surface roughness led to an earlier onset of the critical flow state, in which the spanwise flow was found to be strongly three-dimensional and exhibited just like for the smooth circular cylinder an asymmetric bistable state with one-sided reattachment of the boundary layer, as well as hysteresis effects. The surface roughness furthermore induced a reduction of the supercritical flow state to a single point and a strong recovery of the drag coefficient in the upper transition.

1.3. *Objective of the present study*

Whereas the aerodynamic behaviour of (slightly) rough circular cylinders has been subject of extensive research, until now no attention has been paid to the flow behaviour of rough, sharp-edged, and rounded square-section cylinders. No information is available on the effects of surface roughness alone, or on the combined influence of surface roughness and corner radius on the aerodynamic forces and vortex shedding of square-section cylinders with rounded edges. This is actually quite surprising, as it is a problem of considerable relevance to, for example, marine and civil engineering, where marine growth and rust significantly increase the surface roughness of the structures during their lifetime.

Owing to the lack of both experimental and numerical data in this area, an experimental study was performed to investigate the aerodynamics of two-dimensional, slightly rough, square-section cylinders with rounded corners. This publication focuses on the effects of surface roughness and corner radius on the instantaneous and time-averaged aerodynamic forces and the vortex shedding frequency in the Reynolds-number range of $\mathrm{Re}_D = 6 \times 10^4$ up to 12×10^6. The research was carried out using rigid, two-dimensional cylindrical models with two different corner radii, namely $r/D = 0.16$ and $r/D = 0.29$. Both cylinders had a non-dimensional surface roughness of $k/D = 1 \times 10^{-3}$ this value being typical for support columns of large offshore floating structures after a few years of operation. Two angles of incidence, $\alpha = 0^\circ$ and -45°, were investigated. The results are part of an experimental database that is currently being filled for future validations of CFD codes, in particular for simulations at very high Reynolds numbers up to $O(10^7)$.

2. Experimental investigation

2.1. *Flow facility*

The experiments were conducted in the closed-circuit High-Pressure Wind tunnel Göttingen (DNW-HDG) of the German-Dutch Wind Tunnels. The closed test section has a cross-section of $0.6 \times 0.6\ \mathrm{m}^2$ and measures 1 m in length. The maximum free stream velocity is 35 m/s and the pressure inside the wind tunnel can be varied in the range from atmospheric to 10 MPa the latter inducing a density change of the fluid in the range of 1.225 kg/m^3 up to about 112.36 kg/m^3. The combined change of both flow parameters allows simulations for Reynolds numbers up to the order of 10^7 at low-subsonic free stream velocities. The free stream