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Experiments on the aerodynamic behaviour of square cylinders with rounded corners at Reynolds numbers up to 12 million

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ABSTRACT

The influence of the angle of incidence and corner radius on the aerodynamics of square-section cylinders is studied by means of wind tunnel experiments. Two different corner radii ($r/D = 0.16$ and 0.29) were investigated at three angles of incidence ($\alpha = 0°$, $-22.5°$ and $-45°$). Steady and unsteady global forces and local surface pressures were measured in the high-pressure wind tunnel in Göttingen. The Reynolds number was varied up to values as high as 12×10^6, thereby spanning the known flow state regimes up to high transcritical. The results demonstrated that a decrease of the cylinder's bluffness induced lower maximum drag coefficients and r.m.s. values, as well as higher Strouhal numbers in all flow state regimes. Furthermore, the critical Reynolds numbers shifted to significantly lower values. For the cylinder configurations at $\alpha = 0°$ no upper transition or transcritical flow state was present up to $Re_D = 12$ million. A decrease in the angle of incidence resulted in a significant reduction of the length of the supercritical flow state, a shift of the drag force, Strouhal number and base pressure to higher values and an increase of the critical Reynolds numbers. The cylinders at non-zero angles of incidence all displayed a clear critical flow state, at which two discontinuous transitions were observed, accompanied by jumps in the C_D and C_L values and the Strouhal number. Only three out of six studied configurations experienced hysteresis, where for the high corner radius configuration at $\alpha = 0°$ a particularly broad hysteresis effect was measured.

1. Introduction

The flow around cylindrical structures with bluff cross-section (e.g. tall buildings, transmission lines, landing gear systems and support columns of offshore floating structures) has received considerable attention, motivated by the complex flow phenomena involved, such as shear-layer instability, flow separation and possible reattachment. The formation of Karman vortices in the wake of the structure leads to unsteady aero- and hydrodynamic loads on the body, which can result in flow-induced vibrations and possible structural damage. Understanding of the wake-flow topology, the behaviour of the vortex shedding process and the time-dependent net lift and drag forces in relation to the object shape and flow conditions is therefore a major research topic in the field of wind and marine engineering.

It is generally known that the flow topology and the vortex shedding process are strongly dependent on the cross-section of the investigated body. For circular cylinders the dependency on the Reynolds number, defined as $Re_D = \rho U_\infty D/\mu$, plays

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a dominant role, as the location of the separation points varies due to the rounded and continuous shape of the circular surface (Roshko, 1961; Achenbach, 1968; Bearman, 1969; James et al., 1980; Schewe, 1983; Zdravkovich, 1997). In contrast to the circular cylinder flow, the flow around a square-section cylinder with sharp edges is often viewed as an example for which the resultant aerodynamic forces are only partly sensitive to a variation of the Reynolds number, since the location of the first separation is fixed at the sharp leading edges (Delany and Sorensen, 1953; 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., 2005, 2007; Huang et al., 2010; Huang and Lin, 2011). These cylinders are strongly sensitive to variations of the angle of the incident flow though, since for increasing angles the flow around the cylinder becomes more and more asymmetric (Vickery, 1966; Bearman and Obasaju, 1982; van Oudheusden et al., 2005; Carassale et al., 2014).

To reduce the strong Reynolds number dependency and the high drag forces on structures built up from circular or square-section cylinders with sharp edges these cylindrical constructions are often seen with rounded or chamfered corners. Pioneering work in the field of rounded cylinder flow was performed by Delany and Sorensen (1953) and Polhamus (1958), who presented drag coefficients, lift coefficients and Strouhal numbers of bluff bodies having various shapes for a wide range of Reynolds numbers up to 2×10^6. Regarding the square-section cylinder they found that for a non-dimensional cross-sectional corner radius ratio of $r/D = 0.167$ – with r the cross-sectional corner radius of the cylinder with reference size D – there exists a drag crisis including hysteresis effect. Apart from the transcritical range the trend of the curve for $C_D(Re_D)$ was similar to the one found for a circular cylinder; the critical Reynolds number regime, however, was shifted to much higher values and the drag coefficients, especially in the critical and supercritical regime, were higher as well. Tamura et al. (1998) performed both experiments and CFD simulations to study the influence of the corner radius ($r/D = 0$ and $r/D = 0.167$) of a square-section cylinder at $Re_D = 10^4$ and 10^6. They observed a decrease in the drag coefficient and in the r.m.s. of the fluctuating lift coefficient by rounding the sharp-edged corners, as well as a narrowing of the wake behind the cylinder with increasing Reynolds number. Carassale et al. (2013) and Carassale et al. (2014) demonstrated that by increasing the corner radius of square-section cylinders the aerodynamic behaviour of these cylinders could be strongly modified as a result of the promoted flow reattachment on the lateral faces. They found that for increasing corner radius the Strouhal number increased over the complete investigated range of incident angles. An increase in Reynolds number in the supercritical flow regime ($Re_D \geq 1\times10^5$) resulted in a shrinkage of the separation bubbles at both side surfaces towards the leading edge and a recovery of the base pressure for $\alpha = 0°$.

The distinct differences in Strouhal number, drag and lift coefficients for rounded square cylinders at sub- and supercritical Reynolds number has recently also drawn attention in the offshore industry as one of the explanations for the drastically different flow-induced motion behaviour of offshore floating platforms against the predicted vortex-induced motion from scaled model tests (Irani et al., 2008; Ma et al., 2013). A numerical study by Wu et al. (2014) showed that the delayed flow separation at full-scale resulted in reduced vortex-induced motion response, consistent with the field observation of the vortex-induced motion. They, however, pointed out that the numerical simulation of the vortex-induced motion at such high Reynolds number must be validated against well-controlled test data, which has not yet been available, before final conclusions can be drawn.

1.1. Objective of the present study

With the current knowledge it is still unknown which flow phenomena are to be expected for rounded-corner structures beyond $Re_D = 2\times10^6$, the highest investigated Reynolds number until today (Delany and Sorensen, 1953). Up to which Reynolds number, for example, will the supercritical regime remain stable, as observed by Delany and Sorensen (1953) and Polhamus (1958) for square-section cylinders with corner radii of $r/D \geq 0.167$ at an angle of incidence of $\alpha = 0°$? Does there also exist an aerodynamic hysteresis within the critical flow state or a second upper transition state for rounded square-section cylinders, similar to the results of smooth and slightly rough circular cylinders by, respectively, Schewe (1983) and van Hinsberg (2015)? What will be the influences of a variation of the cylinder's angle of incidence or corner roundness on the Reynolds-number dependent flow behaviour around the two cylinders?

To find answers to these questions, a wind tunnel test campaign was performed, in which the focus lied on the influence of the Reynolds number on the steady-state performance of square-section cylinders with varying corner radius. For this purpose not only an overlap of the Reynolds number range with existing measurements was performed, but also an extension of the investigated Reynolds numbers to values as high as possible, for this particular study up to $Re_D = 12\cdot10^6$. The research was carried out in the High-Pressure Wind Tunnel in Göttingen (DNW-HDG) using rigid cylindrical models with two corner radii ($r/D = 0.16$ and $r/D = 0.29$) at three angles of incidence according to the angle definition in Fig. 1 ($\alpha = 0°$, -22. 5° and -45°). The global time-dependent forces, obtained by using piezoelectric balances, and two mean surface pressures were measured in the Reynolds number range of 8×10^3 up to 12×10^6. As the above-mentioned references illustrate, experimental studies at these high Reynolds numbers are non-existent until today, since it is difficult to achieve those Reynolds numbers at physically incompressible flow conditions ($M \leq 0.1$) in wind- or water tunnels. Moreover, numerical simulations of flow phenomena around bluff bodies at these high Reynolds numbers are still a challenge for CFD codes. The results presented herein can therefore also be used to build up an experimental database for numerical validation, in particular at transcritical Reynolds numbers up to and beyond $O(10^7)$.