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The Reynolds number dependency of the steady and unsteady loading on a slightly rough circular cylinder: From subcritical up to high transcritical flow state

Nils Paul van Hinsberg*

Institute of Aeroelasticity, German Aerospace Center, Bunsenstraße 10, D-37073, Göttingen, Germany

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ABSTRACT

Simultaneous measurements of the spanwise-integrated unsteady aerodynamic forces and time-averaged local surface pressures on a 2D slightly rough circular cylinder were carried out over a wide range of Reynolds numbers in the high-pressure wind tunnel in Göttingen. The Reynolds numbers of $15 \times 10^3 \le \mathrm{Re} \le 12 \times 10^6$ spanned the known flow state regimes from subcritical up to high transcritical. The surface of the cylinder had a mean relative roughness of $k_s/D = 1.2 \times 10^{-3}$. The results demonstrated that especially in the critical flow regime the spanwise flow was strongly three-dimensional. In this regime two discontinuities at two closely spaced Reynolds numbers were observed, coupled with critical fluctuations in the lift force and the formation of a separation bubble at each side of the cylinder. The narrowing of the wake led to a sharp decrease of the drag coefficient and a steep increase of the values for the minimum pressure coefficients and the base pressure coefficient. In the upper transition state the boundary layer separation wandered upstream, resulting in an increase of the drag coefficient and a decrease of the base pressure coefficient and the Strouhal number. All measured flow field properties reached intermediate steady plateaus in the transcritical state for $\mathrm{Re} \ge 1.3 \times 10^6$. It was also shown that the surface roughness had a strong effect on the cylinder flow; in particular the disappearance of the supercritical regime and the subsequent strong recovery of the drag coefficient in the upper transition.

1. Introduction

The flow around objects with circular cross section has received considerable attention, motivated by the fundamental flow phenomena involved as well as for its relevance to engineering applications, such as the flow around transmission lines, landing gear systems, high-speed trains, buildings and (semi-)submerged oil platform columns. One of the general characteristic features of bluff body geometries is the appearance of fluctuating aerodynamic loads. These can lead to flow-induced aeroelastic vibrations and, if low damped, to possible structure damage. Understanding of the wake-flow topology and the time-dependent behaviour of the vortex shedding process in relation to the object shape and flow conditions is therefore a major research topic in the field of bluff body aero- and hydrodynamics.

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* Tel.: +49 551 709 2989.
E-mail address: nils.vanhinsberg@dlr.de

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It is well known that for the flow phenomena of circular cylinders the Reynolds number plays a dominant role, as the location of the flow separation on the cylinder wall is Reynolds number dependent. Flow measurements on smooth circular cylinders and isolated surface pressure measurements on rough cylinders for flow conditions up to the supercritical regime have been subject of numerous investigations (Fage and Warsap, 1929; Güven et al., 1980; Achenbach and Heinecke, 1981; Zdravkovich, 1990; Shih et al., 1993; Zan and Matsuda, 2002; Norberg, 2003). By contrast, investigations at very high Reynolds numbers, hence within the transcritical regime at incompressible flow, are relatively rare (Roshko, 1961; Achenbach, 1968, 1971; Jones et al., 1969; James et al., 1980; Achenbach and Heinecke, 1981; Schewe, 1983, 1986; Adachi, 1997; Gölling, 2001; Zan, 2008). Because it is difficult to establish the necessary flow conditions for the transcritical Reynolds number regime inside a wind tunnel, in most of these studies either the cylinder diameter was too large – leading to non-negligible blockage ratio effects – the cylinder length-to-diameter ratio too small or the flow velocities too high – hence, compressibility effects were introduced (Jones et al., 1969). This resulted in a large scatter in the measured data like Strouhal number, drag coefficients and wall pressure coefficients.

1.1. Influence of surface roughness

On one hand, perfectly smooth cylinders with a relative surface roughness of less than $k_s/D{\sim}10^{-5}$ represent one end of a spectrum and have been thoroughly investigated because of their unique flow phenomena; on the other hand, however, they will almost never be found outside the laboratory surroundings. Here k_s is the (mean) absolute height of the roughness elements and D the diameter of the cylinder. Rain and snow for example roughen the relatively smooth surface of bridge cables and transmission lines; the same holds for impacts of bugs on landing gear systems and antennas. In order to prevent submerged support elements of large offshore structures from erosion these elements are painted before assembly, thereby thus directly increasing their surface roughness by a few orders of magnitudes. For the latter case the surface roughness will continuously further increase due to sea shells and underwater plants that stick to the submerged parts. One can therefore imagine that besides global parameters, like Reynolds number, Mach number and free stream turbulence, the cylinder's surface roughness, as a local parameter, may also have a substantial effect on the flow–structure interaction described above. The possible influences of rough surfaces on the flow phenomena and on the surface pressures and forces acting on a circular cylinder have been investigated in many aspects already. Papers on this topic include (Fage and Warsap, 1929; Batham, 1973; Szechenyi, 1975; Achenbach, 1977; Güven et al., 1980; Achenbach and Heinecke, 1981; Nakamura and Tomonari, 1982; Niemann and Hölscher, 1990; Zdravkovich, 1990; Ribeiro, 1991; Bearman and Harvey, 1993; Adachi, 1997; Yamagishi and Oki, 2004, 2005, 2007).

Many of the aforementioned authors applied surface roughness only as an instrument to provoke an artificial transition of the boundary layer in order to simulate high-Reynolds number flow phenomena at physically low Reynolds numbers. The influence of uniformly distributed dimples and grooves at the cylinder surface on the drag coefficient and Strouhal number up to the supercritical/upper transition range was for example studied by Achenbach (1977), Achenbach and Heinecke (1981), Bearman and Harvey (1993), Adachi (1997) and Yamagishi and Oki (2004, 2005, 2007). Ribeiro (1991) applied spanwise roughness stripes at a single angular position or at multiple circumferential angles to simulate the flow phenomena in the transcritical Reynolds regime. The same principle was applied in the numerical study by Behara and Mittal (2011), in which they used a roughness element to promote early transition of the boundary layer on the upper half of a smooth cylinder. Note, however, that the three-dimensional flow domain in their simulations only covered one cylinder diameter in spanwise direction and was built up by 11 uniformly spaced sections of the two-dimensional mesh. To reach higher Reynolds numbers in their experiments, Batham (1973), Szechenyi (1975) and Güven et al. (1980) covered the cylinder surface uniformly with solid particles, like glass beads or sand paper.

The interchangeability in effect between Reynolds number and surface roughness, which is often given as a justification for examining high-Reynolds number flow phenomena, is questionable though. Particularly in the critical and supercritical Reynolds number ranges the outcome of the measurements is sensitive to even the smallest disturbances in the flow conditions and in the local model surface topology. This is for example the case for the transition and separation positions of the boundary layer, the surface pressure distribution, the three-dimensionality of the flow along the span of the cylinder and the vortex shedding in the wake, hence the overall induced aerodynamic forces. An increase of the surface roughness influences the boundary layer for example in several ways: the position of the transition from laminar to turbulent is shifted towards lower circumferential angles and the onset to critical Reynolds number shifts towards lower values (Niemann and Hölscher, 1990; Zdravkovich, 1990).

1.2. Objectives of the present study

The main objective of this study is to investigate the effects of the Reynolds number on the flow of a slightly rough circular cylinder in terms of instantaneous aerodynamic forces, time-averaged surface pressure distributions and the Strouhal number. A cylinder with a distributed slight roughness of $k_s/D{\sim}10^{-3}$ was chosen, as this case can often be found in the civil and marine engineering community, where smooth circular cylinders naturally become slightly rougher during their lifetime (e.g. towers of wind turbines and (semi-)submerged oil platform columns). Detailed flow investigations around a smooth circular cylinder were performed by Schewe (1983) in the high-pressure wind tunnel in Göttingen (DNW-HDG). As these results are taken as reference, the current measurements were conducted inside the same wind tunnel. The tunnel can be pressurised up to