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Review article

Aerodynamics of nominally circular cylinders: *A review of experimental results for Civil Engineering applications*

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A B S T R A C T

Fluid-dynamic loads have a great influence on the design of many Civil Engineering structures. In particular, circular sections are widely used in constructions, yet when it comes to aero- or hydro-dynamics simple geometry brings a complex behavior, as the features of flow separation strongly depend on Reynolds number. This has triggered a remarkable research effort towards the understanding of the aerodynamic behavior of circular cylinders. Indeed, circular cylinders used in Engineering applications are seldom perfect ones. In many cases, it has been observed that imperfections affect aerodynamics to a large extent. For this reason, a considerable effort has also been devoted to the understanding of how aerodynamics is modified by imperfections. This paper contains a review of existing literature on experimental results of interest for Civil Engineering applications on the aerodynamics of cylinders, whose geometry deviates from that of a perfect circular cylinder. Such deviations are classified into cylinder and flow irregularities, and the former are further subdivided into surface, section and spanwise irregularities. The need for further research is pointed out at the end of the paper.

Contents

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1. Introduction

Fluid-dynamic loads have a great influence on the design of many Civil Engineering structures. These loads mainly depend on structural geometry, and their characteristics can be measured by means of experiments or using Computational Fluid Dynamics simulations. In particular, in Wind Engineering the role of aerodynamics is pointed out in the Alan Garnett Davenport wind loading chain, through the definition of an aerodynamic shape factor describing the effects of geometry and the leakage on the local pressures [1].

Because of its simple geometry, the circular cross-section is widely used in many fields of Engineering; in particular, in Civil Engineering circular cross-sections are commonly used for chimneys, towers, bridge cables, bridge piers and towers, offshore piles and so on. On the other hand, when it comes to aero- or hydrodynamics (for brevity in the following we shall simply refer to aerodynamics), simple geometry brings a complex behavior, as the features of flow separation strongly depend on Reynolds number.

The diameter-based Reynolds number, *Re*, has been singled out as the governing parameter for the aerodynamics of perfectly smooth, infinitely long, straight circular cylinders placed in a uniform cross flow; this is the case that we shall call *perfect circular cylinder*. In practical applications, *Re* ranges from less than one up to a hundred for tiny fibers in liquids, up to hundreds of million for cooling towers and interplanetary rockets. However, practical situations deviate more or less from this theoretical case and it can be defined *irregularity* (or *disturbance*) any feature causing deviation from the perfect circular cylinder case. We shall call *nominally circular cylinder* a cylinder featuring small irregularities.

The aerodynamics of nominally circular cylinders has been the subject of numerous investigations. However, most of them, while having scientific and practical importance, do not seem to be contained in a general framework. With the aim of understanding the aerodynamic characteristics, the conceptual division of the parameters into *governing* and *influencing* is useful [2]. In the case of nominally circular cylinders, all transition states can be defined by *Re*, which turns out to be the only governing parameter, and by an appropriate set of influencing parameters which describe the disturbances. When an influencing parameter exceeds a certain magnitude, it can become a governing parameter in some transition states (i.e. it defines different aerodynamic regimes). However, it is not trivial to establish precisely when this happens. In general, an influencing parameter for a given set of governing parameters can be a governing parameter in other circumstances [2]. Detailed experimental and/or simulated data are required for a correct classification of these parameters.

In this review, we consider only experimental results. Cylinders are always considered as stationary, and accordingly, no aeroelastic effects are dealt with. Cylinders are also considered as isolated, therefore aerodynamic interference due to the presence of neighboring objects is not dealt with. Moreover, the case of porous cylinders is not dealt with; in this context, porous meant as a cylinder having holes visible to the unaided eye that allow air or liquid to pass through. Only steady flow condition are considered, therefore oscillatory flows are not dealt with. With an eye to Civil Engineering applications, the fastest wind ever recorded (with the exclusion of tornado winds) was during the passage of Tropical Cyclone Olivia on 10 April 1996, with a maximum gust speed of 113 m/s [3]. This value corresponds to a Mach number of $M = 0.32$. Accordingly, in this review, only the subsonic regime (valid for $M \leq 0.3$) is examined. The minimum wind speed of interest for the aerodynamics of Civil Engineering structures is related to the assessment of vortex- and buffeting-induced response; it is assumed that values of *Re* lower than 300 are of no practical interest (see Table 1). Finally, to improve readability, an attempt has been made to make the symbols used in this review homogeneous, so they do not necessarily reflect the original choices made by the authors.

1.1. Parameters describing nominally circular cylinders irregularities and their classification

An irregularity can be a geometric feature (*cylinder irregularity*) or a flow feature (*flow irregularity*), and the former is further subdivided into *surface irregularities*, *section irregularities* and *spanwise irregularities* (Fig. 1).

Agreement in the definitions adopted by different authors of the different class of bodies in which one dimension dominates on the remaining two seems not to exist; moreover, these definitions are frequently incorrect. However, the term cylinder is the most adopted and can be considered justified when considering the relatively common use of the term within fluid mechanics. In the following, the term *cylinder* will be used to indicate an infinite-length, constant-section body with a straight axis, which is, therefore, completely defined by the cross-sectional shape (Fig. 2). The term *prism* will be used to indicate a finite-length, constant-section body with a straight axis which is, therefore, completely defined by the cross-sectional shape and by the length (Fig. 2). The term *elongated body* will be used to indicate any body in which one dimension dominates on the remaining two (Fig. 2).

The parameters defining the geometry and used to describe the cylinder disturbances are (Fig. 2):

- *Local radius*, $R(\theta, z, t)$: the distance from the center of the section, *C*, to a point on the surface, which is a function of the angle θ in the body cross-section, of the position *z* along the cylinder axis and of time *t*; the variability with time is meant to account for sectional shape variations associated with the presence of water rivulets or ice;