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# Wake dynamics of a cantilevered circular cylinder of aspect ratio 4

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ABSTRACT

Near-wake characteristics of a low aspect ratio ($h/d = 4$) cantilevered circular cylinder protruding a thin laminar boundary layer were investigated both numerically ($Re = 300$) and experimentally ($Re = 10,400$). Despite the substantial differences in the investigated $Re$, the wake dynamics show striking similarities and appear governed by similar instability mechanisms: (i) a Kármán-like vortex shedding instability, and (ii) a low-frequency instability related to the flow over the free end and near the cylinder-wall junction. Attention is drawn to the low-frequency instability, which comprises a significant portion of the kinetic energy content in the wake, and has not been reported in previous experimental or numerical investigations. It appears to be characteristic of intermediate aspect ratio cantilevered circular geometries and the boundary layer state, since the phenomenon is not observed for turbulent boundary layers of similar thickness.

## 1. Introduction

The flow across cantilevered bluff bodies is ubiquitous in the natural environment and in industrial applications, *e.g.*: wind loadings on trees, buildings, and chimney stacks. Hence, it is not surprising that such geometries have been the subject of a multitude of experimental and numerical studies over the last century; *e.g.*: Sakamoto and Arie (1983), Okamoto and Sunabashiri (1992), Fox and Apelt (1993), Rodi (1997), Martinuzzi and Havel (2004), Wang et al. (2010), Sumner (2013) and Hosseini et al. (2013). Previous experimental studies on cantilevered bluff bodies have shown that the flow development and related structural loading characteristics strongly depend on the shape of the body, oncoming boundary layer characteristics, the body aspect ratio and the Reynolds number $Re$ of the flow based on the characteristic length scale of the body (*e.g.*, Okamoto and Sunabashiri, 1992 and others).

Notwithstanding some differences in the wake dynamics and loading characteristics, cantilevered prismatic and circular cylinder geometries share several features. Sakamoto and Arie (1983) provide a useful classification for finite aspect ratio cantilevered cylinders. For a cylinder of height $h$ and frontal width $d$, the diameter for circular cylinders, protruding an on-coming boundary layer of thickness $\delta$, a critical aspect ratio $h/d$ exists. The critical aspect ratio is a function of both the obstacle geometry and the relative boundary layer thickness $\delta/h$. An overview of the literature for Reynolds numbers, based on $d$, $1000 < Re < 70,000$, suggests that for thin boundary layers ($\delta/h < \sim 0.3$), the critical aspect ratio for circular cylinders is in the range $3 < h/d < 4$ and depends little on the state of the on-coming boundary layer (Sakamoto and Arie, 1983; Okamoto and Sunabashiri, 1992; Agui and Andreopoulos, 1992). For circular cylinders of aspect ratio less than critical, antisymmetric vortex shedding in the wake is generally not reported. For thin boundary layers, irregular symmetric shedding of vortex pairs from opposing sides of the cylinder (sometimes reported as arch vortex shedding) have been reported for $0.5 < h/d \leq 3$, giving rise to broad energy concentrations in the spectra of the wake velocity fluctuations (Okamoto and Sunabashiri, 1992; Zhu et al., 2017).

For larger aspect ratio circular cylinders protruding a thin boundary layer, such as the one in this study, a generic sketch of the main flow features is illustrated in Fig. 1. For these aspect ratios, a dominant feature is the existence of a periodic process involving counter-rotating vortices alternately shed from opposing faces of the cylinder resulting in an antisymmetric, staggered von Kármán street. The periodic shedding process gives rise to sharp, energetic spectral peaks for the wake velocity fluctuations. The associated frequency, in terms of the non-dimensional Strouhal number based on $d$, $St$, depends on $h/d$ and weakly on $Re$. $St$ ranges from approximately 0.14 at $h/d = 4$ and increases as $h/d$ increases, asymptotically approaching the value for the 2D cylinder with large $h/d$. Strong narrow-banded concentrations of fluctuating energy, *i.e.*, spectral peaks, are generally observed in velocity spectra at locations from the ground plate to heights of $\sim 0.6 - 0.7h$ (Farivar, 1981; Krajnović, 2011).

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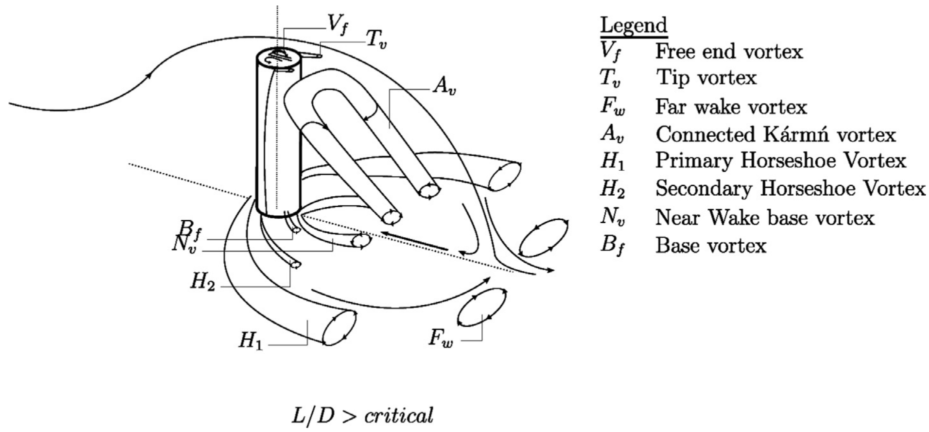


**Fig. 1.** Schematic representation of the main flow structures for the flow around a finite cantilevered cylinder adopted from Porteous et al. (2014) based on the study by Krajnović (2011).

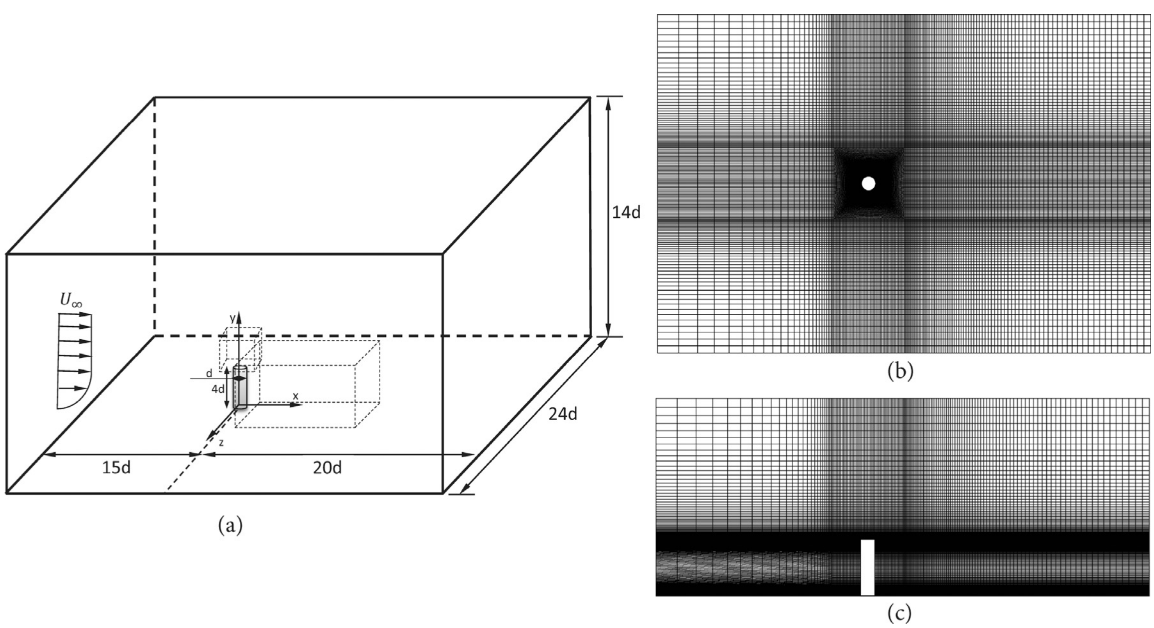


**Fig. 2.** Computational domain details: (a) cylinder sketch with domain boundaries and respective dimensions, (b) and (c) computational O-grid mesh topology.

**Table 1**
Comparison of Strouhal number and drag coefficient at $Re = 300$.

| | $Re_d = 300$ | |
|---|---|---|
| | $C_d$ | $St$ |
| Present study | 1.347 | 0.207 |
| Experimental study[a] | – | 0.203 |
| Experimental study[b] | 1.21 | – |
| Numerical studies[c] | 1.28–1.37 | 0.206–0.212 |

[a] Norberg (2003).
[b] Weiselsberger (1921).
[c] Zhang et al. (1995), Henderson (1995, 1997), Persillon and Braza (1998) and Morton and Yarusevych (2010).

Spectra of surface pressure fluctuations on the sides for the cylinder, within 1$d$–2$d$ from the cylinders height, and on the cylinder tip show low-frequency spectral energy accumulations. The energy is much more broadly distributed when compared to the periodic shedding signatures. Farivar (1981) also observed similar broadband spectral energy concentrations in the velocity fluctuations immediately downstream of the cylinder for $Re = 70,000$ and associated these spectral signatures with the motion of vortices generated at the tip. He reported that the spectral peaks were centered around 0.4$St$. However, the influence of the boundary layer state (laminar *vs.* turbulent) and Reynolds number was not investigated.

Generally, a counter-rotating pair of vortices extending streamwise from the cylinder-wall junction are observed in the base region. Unfortunately, the dynamics of pressure or velocity fluctuations in the junction region remain poorly investigated. Agui and Andreopoulos (1992) studied the spectra of the surface pressure fluctuations in the junction region for a sub-critical aspect ratio of $h/d = 2$ for a thin, turbulent boundary layer ($\delta/h \approx 0.05$). Low-frequency broadband energy concentrations were observed and related to the bimodal behavior of the turbulent horseshoe vortex observed for taller wing-body junction flows (Devenport and Simpson, 1990). For laminar boundary layers, Baker (1991) investigated the dynamics of the laminar horseshoe vortex system upstream of tall cylinders and reported an instability resulting in a broad spectral energy accumulation for the fluctuating surface pressure in the upstream separation region occurring in a non-dimensional frequency ($f(\delta^\star D)^{1/2}/U_\infty$) in the range of 0.07–0.09.

Many of the aforementioned studies focused on the influence of $\delta/h$, but more recent results suggest that $\delta/d$ may also be important.