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Effects of leading edge geometry on the vortex shedding frequency of an elongated bluff body at high Reynolds numbers

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ABSTRACT

Measurements have been performed in a large scale wind tunnel on an elongated bluff body with a chord-to-thickness ratio of 7 over the Reynolds number range $Re=4.0–7.5\times10^4$. Six different leading edge separation angles were created by altering the leading edge geometry. Time-resolved, synchronized, surface pressure and Particle Image Velocimetry data allow for detailed characterization of the flow around the body and in the recirculation region. The results show a linear decrease in the shedding frequency of nearly 40% as the leading edge separation angle is increased from 0°–90°. The PIV data are phase averaged in the recirculation region and the convection speed of the vortices is characterized. From the phase averaged data, the velocity outside of the recirculation region is observed to decrease markedly as the leading edge separation angle is increased, which is suggested to be responsible for the observed changes in the shedding frequency.

1. Introduction

Long-span bridges have been susceptible to vortex-induced instabilities, with examples including Rio-Niteroi Bridge (Battista and Pfeil, 2000), Storebaelt Bridge (Larsen et al., 2000), and Tokyo Bay Bridge (Fujino and Yoshida, 2002). Understanding the factors that controlled vortex shedding for these particular bridges was of critical importance to the development of mitigation strategies. However, a complete understanding of vortex shedding from such elongated bluff bodies remains incomplete.

For an elongated bluff body, the flow separates at the leading edge and reattaches along the chord of the body before separating once again at the trailing edge. Thus, the decks of nearly all long-span suspension and cable-stayed bridges can be classified as elongated bluff bodies. The leading edge separating-reattaching flow adds complexity to the case of classical von Kármán vortex shedding in the wake of shorter bluff bodies (i.e., those with no reattachment along the body). With the susceptibility of long-span suspension and cable-stayed bridges to these aerodynamic instabilities, it is important to understand the characteristics that distinguish elongated bluff bodies from the well-known case of shorter bluff bodies. For a review of the mechanisms associated with shorter bluff bodies the reader is referred to Zdravkovich (1997).

In his study on circular cylinder wakes, Roshko (1954) anticipated the shedding frequency based on certain parameters including vortex convection speed and base pressure; however, we have previously shown that the role of pressure in the recirculation region is reduced for elongated bluff bodies (Taylor et al., 2011). It has also been shown that, for elongated bluff bodies, the mechanism governing shedding frequency is dependent on the Reynolds number, which is typically defined using the thickness, or the cross-stream dimension, of the body, t. At lower Reynolds numbers ($Re<2000$), Nakamura and Nakashima (1986) discovered that the vortex shedding frequency of some elongated bluff bodies is controlled by the separated shear layer impinging on the trailing edge corner. Naudascher and Wang (1993) extended the definition of this instability and renamed it the Impinging Leading Edge Vortex (ILEV) instability since they found that the shedding frequency of the leading edge vortices can be controlled by a feedback loop of leading edge vortices impinging on the trailing edge corner – not necessarily the impingement of the leading edge separated shear layer. As a vortex passes the sharp trailing edge corner, a pressure pulse is experienced by the leading edge separation-reattachment and another leading edge vortex is shed from this location. Hourigan et al. (2001) suggested that the shedding frequency of the leading edge vortices in the ILEV instability was strongly influenced by the 'preferred' trailing edge shedding frequency (i.e., that determined using a leading edge of elliptical cross-section). For elongated bluff bodies at $Re>2000$ there are comparably fewer studies and the factors governing vortex shedding frequency are unclear.

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At Re > 2000, the ILEV instability is known to be suppressed for rectangular cylinders (Mills et al., 2003). Parker and Welsh (1983) performed the benchmark study for rectangular cylinders at Reynolds numbers of order $O(10^4)$ over a wide range of elongation ratios up to $c/t = 52$. They found that, with the ILEV instability suppressed, there was a wide range of elongation ratios ($7.6 < c/t < 25$) for which they could not detect periodic vortex shedding in the wake. However, several different studies have shown that with acoustic resonance or external forcing, the leading edge separated shear layer can be forced to once again shed vortices periodically at high Reynolds numbers (e.g., Parker and Welsh, 1983; Welsh et al., 1984; Stokes and Welsh, 1986; Mills et al., 2002). While many of these studies were focused on the susceptibility of elongated bluff bodies to acoustic forcing, the results obtained in unforced flow suggest that the preferred vortex shedding mode is that created by the ILEV instability and that the feedback between the leading edge and trailing edge shedding is disrupted at higher Reynolds numbers. Therefore, it is unclear how the vortex shedding frequency is controlled at these Reynolds numbers.

Another critical aspect of elongated bluff bodies to consider, which is particularly relevant to bridge aerodynamics, is how changes to geometry affect the vortex shedding frequency. For example, it remains unclear whether or not the ILEV instability is suppressed for geometries other than the rectangular cylinder at the higher Reynolds numbers that are the focus of the current study. In general, previous studies on elongated bluff bodies have concluded that changes in the leading edge geometry affect the shedding frequency more significantly than changes to the trailing edge geometry (Welsh et al., 1984; Stokes and Welsh, 1986; Nguyen and Naudascher, 1991). Likewise, changes in the leading edge separation-reattachment have been shown to create markedly different levels of turbulent kinetic energy and near wake structure (Taylor et al., 2013). A force balance analysis in the near wake (Taylor et al., 2011) showed that larger leading edge separation-reattachment increases the role of the turbulent stresses in the recirculation region. The current study focuses on how the size of the leading edge separation-reattachment affects the shedding frequency variation of elongated bluff bodies through changes in the leading edge geometry. Furthermore, departures from the parametric trends established by Roshko (1954) for shorter bluff bodies are discussed.

2. Details of the experiments

2.1. Model details

The model has been designed to accommodate different forebodies of constant cross-section that can be fit to the leading edge. Six different forebodies were used including the rectangular forebody, which is part of the base model, as shown in Fig. 1. The base model is of rectangular cross-section with a thickness, t, of 76.2 mm and a chord-to-thickness ratio of $c/t = 7$. The chord-to-thickness (elongation) ratio is kept constant across all tests; however, the length of the forebody is not considered in the measurement of the chord. The forebodies used in the current study include one of elliptical cross-section (3:1 axis ratio) and four of triangular cross-section with half interior angles, θ, ranging from 30° to 90° at 15° increments defined in Fig. 1. The streamlined forebody of semi-elliptical cross-section provides baseline behavior for when the wake is not influenced by the leading edge separation-reattachment. The streamwise location $x = 0$ corresponds with the fixed separation points for all of the geometric configurations except for the one of elliptical cross-section (which has no leading edge separation).

Roshko (1993) emphasized two extrinsic characteristics that alter the three-dimensionality of a given experiment: aspect ratio and end plates. In the present experiments, rectangular end plates are used which extend 0.3 m from the surface of the model, normal to the top and bottom surfaces, 0.41 m upstream from the leading edge and 0.57 m downstream into the wake from the trailing edge (Fig. 2). These dimensions ensure that they protrude into the wake for at least one complete vortex shedding wavelength. Cherry et al. (1984) review the aspect ratios (span-to-thickness) used in various studies involving leading edge separation showing that the range in previous experiments is 2–18. Thus, the aspect ratio in the current study is relatively high with a span-to-thickness ratio of 24 (span-to-chord ratio is 3.4). In the present study, the model is instrumented to assess the three-dimensional nature of the flow, and the surface pressures show that the average pressure distribution is constant across the span for each case.

2.2. Wind tunnel tests

The tests were performed in a large-scale wind tunnel in the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario. The tunnel is of closed-circuit design and includes a test section measuring 3.35 m wide by 1.83 m high giving a blockage ratio of 4.1%. The length of the test section is 39 m, and the testing was all performed approximately 2 m from the inlet. At this location, hot-wire anemometry data show the longitudinal turbulence intensity to be less than 1% with no dominant peaks in the spectrum to avoid forcing of the convectively unstable leading edge separated shear layers (e.g., Chaurasia and Thompson, 2011; Thompson, 2012). The vertical and horizontal velocity profiles are uniform to within 1%, away from the walls. The susceptibility to acoustic resonance of these phenomena has

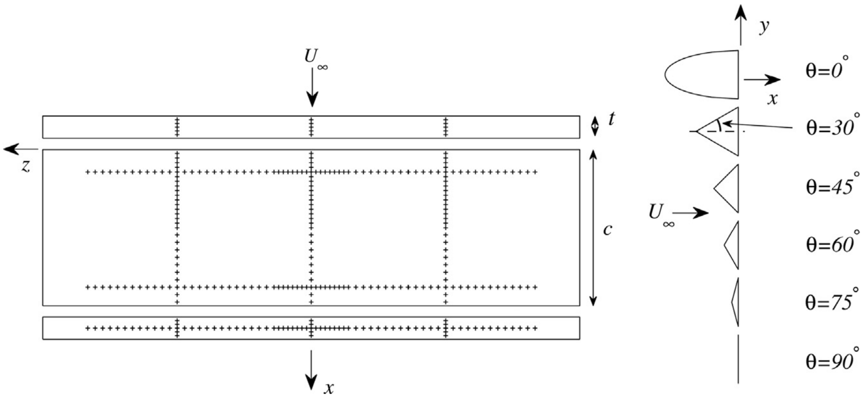

Fig. 1. Schematic of the model showing the pressure tap layout (+ symbols) and the different leading edge attachments used in the experiments.