

Simultaneous PIV/pressure measurements of the flow around elongated bluff bodies

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ABSTRACT: Synchronized pressure and Particle Image Velocimetry (PIV) data are presented from experiments on 6 elongated bluff bodies of varying leading edge geometry and constant chord-to-thickness ratio of 7. The experiments spanned a range of Reynolds numbers of order 10^4 , and the results show marked differences from previous results at lower Reynolds numbers. The surface pressure data show a gradual transition between two extremes. One extreme shows characteristics of being dominated by the separating-reattaching flow at the leading edge while the other shows that the trailing edge is dominant. The transition between these two extremes is observed to be continuous. The PIV data have been phase averaged, and a relationship is proposed to account for the observed shedding frequency variation which suggests that the leading edge geometry is a form of passive flow control.

KEYWORDS: Elongated bluff bodies, shedding frequency, vortex shedding, separation, reattachment, flow control

1 INTRODUCTION

Elongated bluff bodies contrast with shorter vortex shedding bluff bodies by the addition of leading edge separation-reattachment. The most common engineering application for these bodies is the case of suspension bridges. The geometry of the deck of a suspension bridge causes the flow to separate at the leading edge and reattach along the body before separating at the trailing edge, which initiates the vortex shedding process. Vortex shedding induced resonance is an issue for long-span suspension bridges whose design and construction makes them relatively flexible. A recent high profile example of vortex-induced vibrations on a full scale bridge structure was the Great East Belt Bridge in Denmark (Larsen et al., 2000).

Previous studies on elongated bluff bodies are few and typically limited to lower Reynolds numbers ($Re < 2000$); however, these works place the studies at higher Reynolds numbers in better context. The first indication that elongated bluff bodies are distinct from shorter bluff bodies was found in the splitter plate experiments of Nakamura and Nakashima (1986). In these experiments, a vortex street-like arrangement of vortices was observed even with the presence of a splitter plate in the wake. This result was surprising because the splitter plate negated the reliance on shear layer interaction in the recirculation region suggested by Gerrard (1966) to be crucial to the development of the vortex street for a circular cylinder. Nakamura and Nakashima (1986) realized that the vortex street-like arrangement was the result of an instability of the leading edge flow. Naudascher and Wang (1993) referred to this instability as the Impinging Leading Edge Vortex (ILEV) instability realizing that it was the leading edge vortices passing the trailing edge corner which completed the feedback loop to the leading edge vortex shedding. Thus, the vortex street-like arrangement of Nakamura and Nakashima (1986) was the observation of staggered leading edge vortices not trailing edge vortices observed in the wake

of circular cylinders. Hourigan et al. (2001) have discussed the relative importance between leading edge vortex shedding and trailing edge vortex shedding for elongated bluff bodies at low Reynolds numbers. They show that the preferred shedding frequency of leading edge vortices is determined by the natural trailing edge vortex shedding. Likewise, Mills et al. (2002) use external forcing at higher Reynolds numbers, and they show that the strongest shedding occurs when the external forcing is close to the trailing edge vortex shedding frequency. Similarly, the majority of the previous studies at higher Reynolds numbers are focused on external forcing (e.g., Stokes and Welsh, 1986; Parker and Welsh, 1983).

One of the most important studies of elongated bluff bodies at higher Reynolds numbers is that of Parker and Welsh (1983). Although the focus of their study was on acoustic forcing of the wake, they performed experiments over an extensive range of elongation, or chord-to-thickness, ratios up to $c/t = 52$. Within the range of elongation ratios there was a broad range ($7.6 < c/t < 25$) where the hot-wire anemometer in the wake did not detect any periodicity. This result suggests that periodic vortex shedding in the wake is suppressed over this elongation ratio range – a surprising result due to the persistence of vortex shedding for shorter bluff bodies. Roshko (1993) has shown that vortex shedding occurs for Reynolds numbers over at least 6 orders of magnitude even though its nature changes substantially. Others (e.g., Pastoor et al., 2008) have attempted to destroy vortex shedding as a form of drag reduction. However, vortex shedding has proven to be a persistent aerodynamic phenomenon, which is why its suppression over a wide range of elongation ratios for rectangular cylinders demonstrates the distinction between shorter bluff bodies and elongated bluff bodies at higher Reynolds numbers.

Recently, in Taylor et al., (2011), we showed that several key trends related to shorter bluff bodies do not hold for elongated bluff bodies. The trends to which we refer were established primarily by Roshko (1954) who related base pressure, the scale of the recirculation region and the shedding frequency to each other. One of the reasons, which we offered in Taylor et al. (2011), to explain the departure from these established trends was a noticeable change in the dynamics of the formation process in the recirculation region using a force balance on the time-averaged recirculation region of three elongated bluff bodies of differing geometries. The force balance method allows for an assessment of three key forces in closing the recirculation region. These three forces are the surface integrals of the Reynolds shear stress, the streamwise Reynolds normal stress and the pressure, along the boundary of the recirculation region. As the scale of the leading edge separation-reattachment zone grew, it was observed that the dominance of the force due to the pressure decreased while the scale of the near wake recirculation region remained largely unaffected. Thus, it was suggested that the leading edge plays a critical role in the formation process of the near wake. However, it remains unclear the extent to which the leading edge geometry affects the wake shedding frequency at higher Reynolds numbers.

2 EXPERIMENTAL SETUP

2.1 *Wind tunnel tests*

The experiments were performed in Boundary Layer Wind Tunnel II at the University of Western Ontario. This wind tunnel is of closed circuit design consisting of a high-speed test section with a cross-section 3.35 m wide by 1.83 m high. In this case, we have utilized the smooth flow at the upstream end of the 39 m long test section which is measured to be uniform to within 1% away from the walls and to have turbulence intensity less than 1%.

2.2 Model details

The wind tunnel model was designed to accommodate different forebodies (i.e., attachments to the leading edge). The basic model was of rectangular cross-section with a chord (defined as the streamwise dimension) of 533.4 mm and a thickness of 76.2 mm giving an elongation ratio, or chord-to-thickness ratio, of $c/t = 7$. In this study, we used a combination of the base model and five forebodies which are shown in Figure 1. The leading edge separation angles are marked in Figure 1 and referred to in the text by θ . The leading edge separation angles have not been measured but are assumed to be tangent to the leading edge forebody at the fixed separation points. The validity of this assumption was confirmed in our previous study on elongated bluff bodies (Taylor et al., 2011). The shapes used in the current study allow us to capture both extremes at the leading edge: the case of no separation ($\theta = 0^\circ$), a blunt leading edge ($\theta = 90^\circ$), and a range in between.

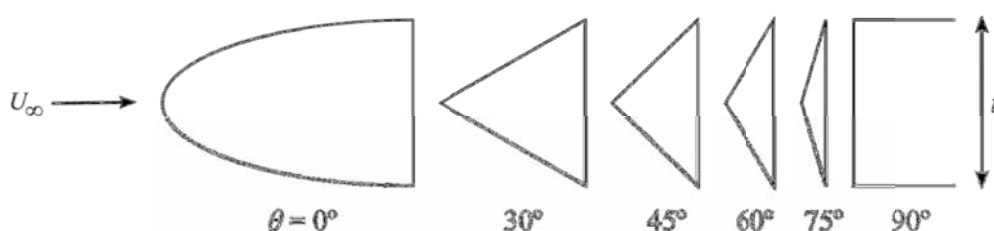


Figure 1. The five different forebodies and the leading edge of the base model (far right) are shown. Angles refer to the assumed leading edge separation angle, t is the thickness of the model and U_∞ the free stream speed.

2.3 Pressure measurements

Surface pressure measurements have been performed at 512 tap locations around the body (see Figure 2). The location of the taps yields three rings of sectional data in addition to five rows of spanwise data. The combination of tube length and restrictor size is one of the standard ones used at the BLWTL which has been repeatedly tested to ensure the frequency response is flat until approximately 200 Hz. We have sampled data from all 512 pressure taps near-simultaneously at a sampling frequency of 500 Hz and the data have been low pass filtered at 180 Hz to remove any effects of tube resonance. Multiplexed pressure scanners are used to sequentially scan up to 16 taps at each 0.002 s (corresponding to the 500 Hz sampling frequency). These measurements are interpolated in time to yield data which are essentially sampled simultaneously at all 512 pressure taps at 500 Hz. Phase lag tests have been performed to ensure that there are no errors from this procedure. The reader is referred to Ho et al. (1999) for more details on the pressure scanning system used in the current study.

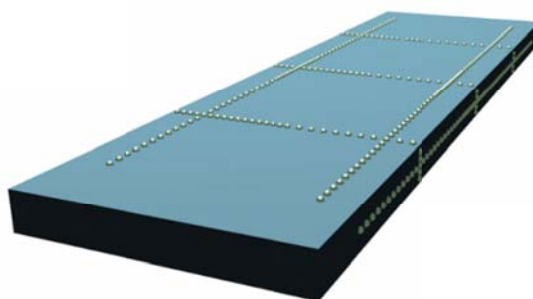


Figure 2. Gray markers represent the location of the surface pressure taps around the body. The camera in this figure is pointed at the trailing edge and top surfaces of the model.

2.4 Particle Image Velocimetry measurements

The Particle Image Velocimetry data were obtained using a custom long-duration time-resolved system developed at the University of Western Ontario. Development of the system is described in detail in Taylor et al. (2010). The camera has a 1024×1024 pixels² CMOS sensor with a 10-bit dynamic range. The innovation in the system comes from the streaming capability provided by IO Industries where the full resolution data can be streamed from the camera at 1000 frames per second for more than 20 minutes. In these experiments, the data are sampled simultaneously with the pressure data for 64 sec.

The large scale flow facility is seeded with atomized olive oil with a mean particle size of $1\ \mu\text{m}$ (Echols and Young, 1963). Illumination is provided by the Quantronix Darwin Duo laser which is a double-head Nd:YLF laser operating with a wavelength of 527 nm. Due to the repetition rate required by the cameras, the laser has to have substantial power and this laser can produce 80W of light power. Operating at 1000 Hz, the laser provides 22 mJ of light in each half of a PIV interrogation pair.

To limit the reflection that makes measurements near the body difficult, the camera was placed so that the center of the field of view coincided with the lower trailing edge corner of the body (Figure 3). Using this technique, the amount of reflected light from surface reflections entering the camera is significantly reduced without the use of expensive coatings. Because of the large scale nature of the wind tunnel, getting a sufficient combination of seeding and illumination proved to be the most challenging experimental aspect of the work. However, by focusing the available illumination power on the near wake, suitable signal-to-noise ratios were obtained over a region $1.6t \times 1.2t$ and velocity data were sampled encompassing the entire recirculation region (Figure 3).

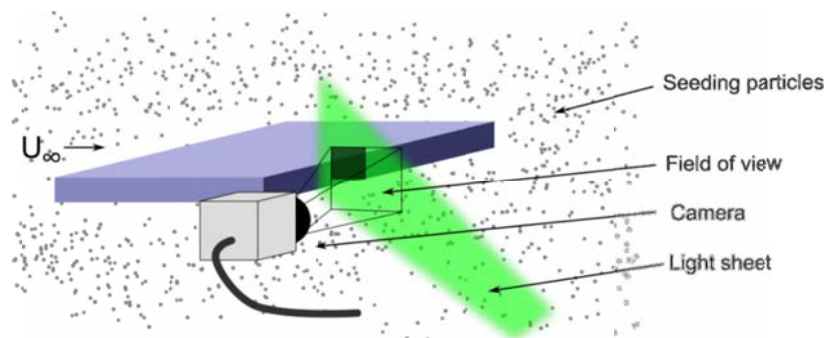


Figure 3. Schematic of the PIV setup.

2.5 Phase averaging procedure

All of the data have been phase averaged based on the time signal of a pressure tap in the recirculation region. Two examples of the pressure time series at this location are shown in Figure 4. Figure 4(a) shows the data for $\theta = 0^\circ$ where the signal is distinctly periodic even though the amplitude of the signal changes continuously in time. In contrast, Figure 4(b) shows the data for $\theta = 90^\circ$ where the signal is noticeably noisier, yet a distinct periodicity is still observed. The fitted data in Figure 4 is computed using the coefficients of the dominant frequencies from a FFT performed on 2 sec. long windows. The fitted data were used to perform the phase average.

Phase averaging of the data is performed following the approach of Reynolds and Hussain (1972). In this approach the data are decomposed as follows (note that in our example we decompose the pressure, but the same is done for each component of velocity as well),

$$p = \langle p \rangle + \tilde{p} + p' \quad (1)$$

In Eq. 1, p is the instantaneous value of pressure, $\langle p \rangle$ is the global time averaged pressure, $\tilde{p}$ is the periodic component and p' is the fluctuation from the global time average and the periodic component. This fluctuating term is often referred to as the ‘incoherent’ part of the flow associated with turbulent motion whereas the periodic component is responsible for fluctuations from the global time average, but is a ‘coherent’, or organized, fluctuation.

Taking the reconstructed time signal, as described above, and dividing each cycle into 16 bins we obtain an expression for each bin n ,

$$\tilde{p}_n = \frac{1}{N_n} \sum_{i=1}^{N_n} p(\tau_i) \times M \quad \text{where, } M = \begin{cases} 1, & \text{for } \frac{(n-1)}{16f_s} \leq \tau_i < \frac{n}{16f_s} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where τ_i is the time (starting from $\tau = 0$) of a discrete sample and f_s is the vortex shedding frequency of the wake for each body.

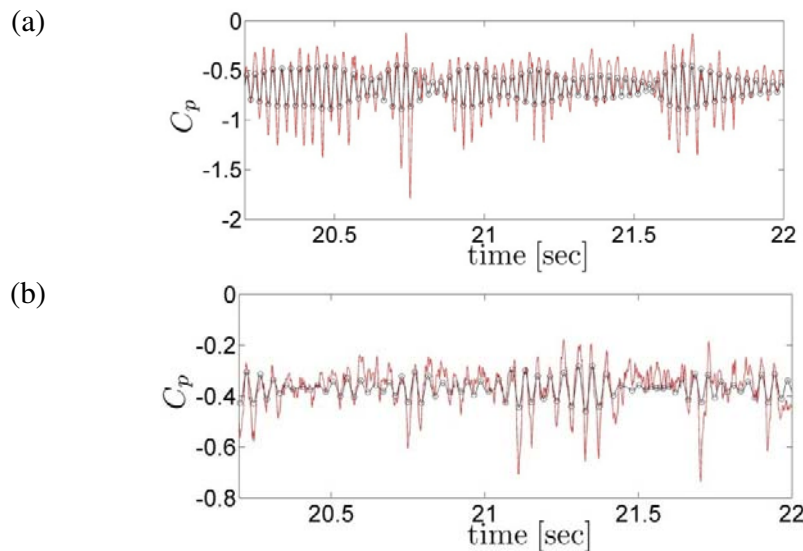


Figure 4. Example of the time signals from which the phase averages are constructed. (a) $\theta = 0^\circ$, (b) $\theta = 90^\circ$.

3 RESULTS

3.1 Shedding frequency

The most important aerodynamic feature in application to bridge structures is the shedding frequency since it is the shedding frequency which dictates when vortex-induced resonance will begin. We have measured the shedding frequency by calculating the time series of the sectional lift force, which is computed at each time step by integrating the surface pressures around each streamwise loop of pressure taps. The shedding frequency is normalized using the Strouhal number based on the model thickness as $St = ft/U_\infty$, where f is the shedding frequency in Hz, t is the model thickness and U_∞ the free stream speed.

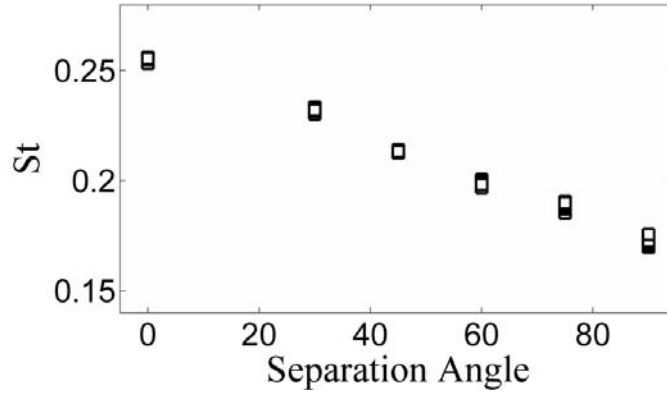


Figure 5. Thickness-based Strouhal number variation with leading edge separation angle. Each square marker represents a separate Reynolds number between $4-7.5 \times 10^4$.

3.2 Leading edge separation bubble

The size of the mean leading edge separation bubble is x_r and is estimated by the fluctuating pressures along the surface. Roshko and Lau (1965) showed that the mean pressures underneath separation bubbles collapse when the streamwise dimension is scaled by x_r . Their observation was true for a wide variety of leading edge geometries. Additionally, Ram and Arakeri (1990) observed that the maximum fluctuating pressures occur at the same streamwise location when scaled by x_r and that these maxima occur at approximately $0.95x_r$. Thus, we define the leading edge reattachment length by $x_r = x|_{\max(C_p)}/0.95$ and mark the potential errors due to the spatial resolution of the pressure taps in Figure 6.

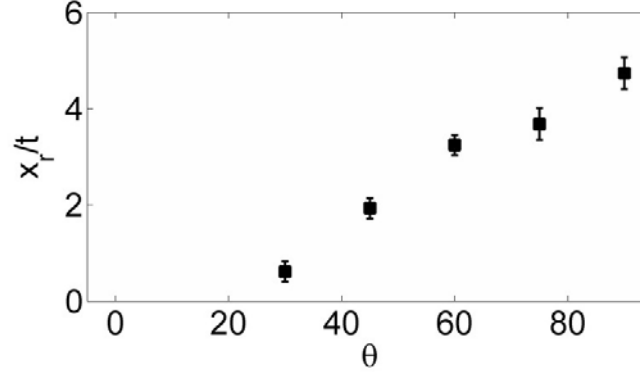


Figure 6. Leading edge mean reattachment length x_r is normalized by the thickness, t , and plotted against the leading edge separation angle, θ . Error bars mark uncertainty in the estimate arising from the spatial resolution of the pressure taps.

Another method to quantify the leading edge separation bubble is to study the vortices which are shed from this location. It should be noted that there is no periodicity to the shedding of vortices from the leading edge at the Reynolds numbers of the present study. This result is anticipated from Cherry et al. (1984) who also characterize leading edge vortices shed from a blunt-nosed semi-infinite plate using autocorrelations. In Figure 7, we present contours of the autocorrelation coefficient defined as,

$$R(\Delta x, T) = \frac{\langle p'_1(x_0, \tau) p'_2(x_0 + \Delta x, \tau + T) \rangle}{\sigma_{p_1} \sigma_{p_2}} \quad (3)$$

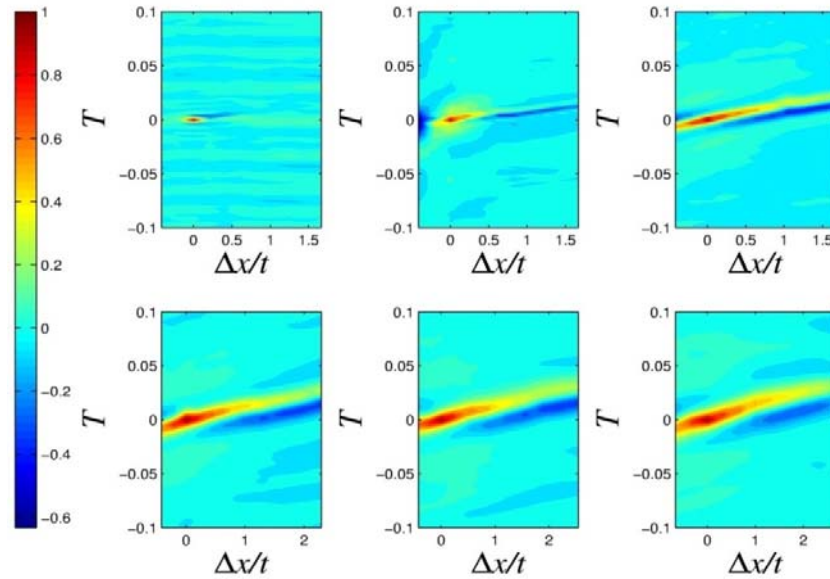


Figure 7. Contours of the correlation coefficient defined by Eq. 3 with $x_0 = x|_{\max(C_p)}$. From top left to bottom right: $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$. Color map applies to all θ .

where x_0 is a reference streamwise location; τ is time; Δx and T are the spatial and time lags, respectively; a prime marks a fluctuation from the mean; angle brackets represent the time-average of the entire time series; and, σ is the standard deviation. In Figure 7, we define the reference streamwise location, x_0 , as $x_0 = x|_{\max(C_p)}$ which is just upstream of the mean reattachment length.

The ridge of high correlation observed in Figure 7 was suggested by Cherry et al. (1984) to correspond to a 'footprint' of a leading edge vortex, and by calculating the slope of this ridge one obtains an approximation to the convection speed of a vortex traveling along the surface. For all cases with leading edge separation (i.e., all but $\theta = 0^\circ$) the range of estimated convection speeds is $0.5-0.55U_\infty$.

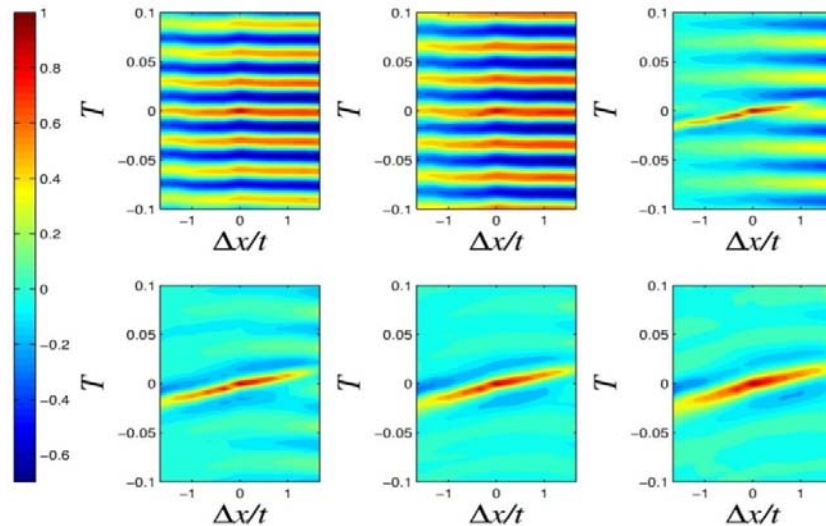


Figure 8. Contours of the correlation coefficient defined by Eq. 3 with $x_0 = 5.5t$. From top left to bottom right: $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$. Color map applies to all θ .

Having used the autocorrelation in space and time to characterize the leading edge vortices, we perform a similar analysis near the trailing edge. This type of analysis allows us to explore the state of the leading edge vortices when they approach the trailing edge. In Figure 8 we once again show contours of the correlation coefficient defined by Eq. 3, but the reference streamwise value has changed to $x_0 = 5.5t$. It is observed from Figure 8 that for $\theta = 75^\circ$ and 90° little has changed between the autocorrelation map at this location and that shown near the leading edge in Figure 7. However, this is in contrast to the case of $\theta = 0^\circ$ and 30° where the autocorrelation map is dominated by a strong periodic feature in time whose wavelength matches that of the wake vortex shedding. Therefore, we have cases which can be labeled as ‘trailing edge dominated’ ($\theta = 0^\circ$ and 30°) and cases which can be labeled as ‘leading edge dominated’ ($\theta = 75^\circ$ and 90°), yet the most striking feature of Figure 8 is the apparent continual transition between these two extremes. The transition is apparent from the autocorrelation maps of $\theta = 45^\circ$ and 60° because characteristics of both leading and trailing edge features are observed.

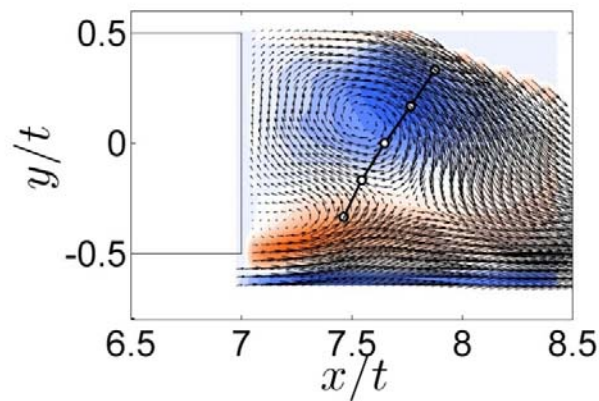


Figure 9. Phase averaged velocity vectors and vorticity contours (red: positive, blue: negative). Line is phase averaged pressure where distance from the surface is representative of suction at that location.

3.3 Results of the phase average

The phase averaging procedure is discussed in detail in §2.5 and an example of the result is shown in Figure 9. From Figure 9 it is observed that we can estimate features of the vortices in the near wake region with data that are spatially well resolved.

Although various features of the vortices in the near wake region can be computed, we focus on the convection speed. We suggest that the convection speed during the growth process and the shedding frequency are closely related. This notion is somewhat intuitive because if a vortex leaves the recirculation faster, then the next vortex can form sooner. Gerrard (1966) used a similar argument in his hypothesis regarding the effects of free stream turbulence on the shedding frequency of a circular cylinder. Using the phase averaged data in the recirculation region, we estimate the convection speed of a clockwise vortex (i.e., $y < 0$) through the vortex shedding cycle; these data are plotted in Figure 10. Agreeing with our hypothesis, it is observed that when the shedding frequency is higher the vortices have greater convection speeds through the recirculation region.

4 DISCUSSION & CONCLUSIONS

Based on the data presented, it is apparent that there is a gradual transition between bodies which are dominated by the leading edge flow and those which are dominated by the near wake. No-

where is this transition more evident than in Figure 8. As we have previously discussed, from this figure there are clear cases ($\theta = 75^\circ$ and 90°) that are ‘leading edge dominated’ and other cases ($\theta = 0^\circ$ and 30°) that are ‘trailing edge dominated’. The transition between these two extremes appears to be gradual suggesting a continuous, rather than discontinuous, influence of the leading edge separating-reattaching flow on the near wake vortex shedding.

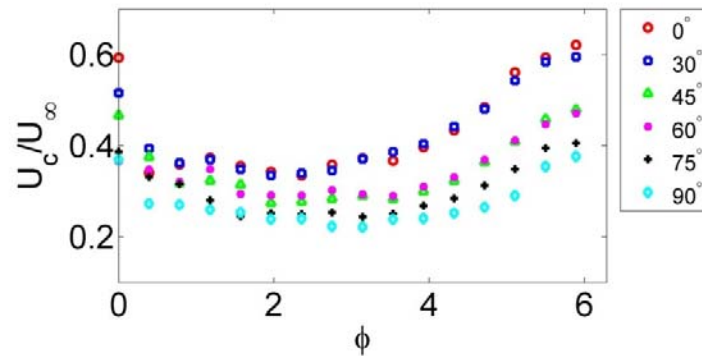


Figure 10. Phase averaged convection speed of a vortex ($y < 0$) through all phases $\phi \in [0, 2\pi]$. Values in the legend correspond to the leading edge separation angle, θ .

We have not shown the frequency content of the leading edge separation bubble, but we could not detect any peaks in the spectra of the surface pressure data near the leading edge which confirms the suppression of the ILEV instability for all of these bodies at Reynolds number $O(10^4)$. Therefore, the determination of the shedding frequency at these Reynolds numbers must be a different mechanism than the feedback instability at lower Reynolds numbers.

A larger leading edge reattachment length corresponds to stronger separation, and it is expected that turbulence of larger scale is also produced. Therefore, we suggest that the leading edge flow is still significant in the determination of the shedding frequency; however, at higher Reynolds numbers it is no longer through a feedback mechanism. Returning to the hypothesis that faster moving vortices in the recirculation region (Figure 10) accompany higher shedding frequency, the turbulence created at the leading edge is suggested to slow down the growing vortices, which lowers the shedding frequency.

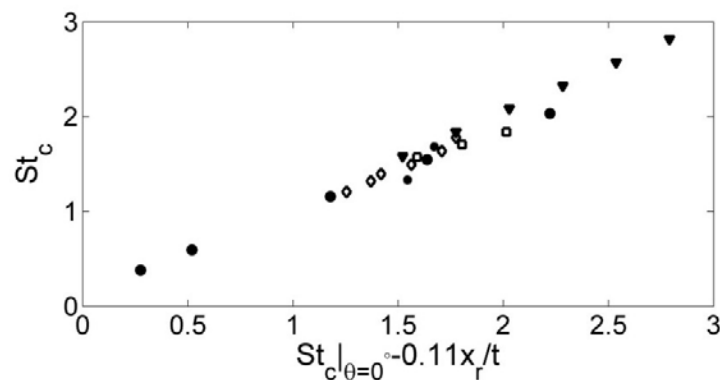


Figure 11. Plot of the modified chord-based Strouhal. Legend: Naudascher & Wang (1993): $\square$ – Rectangular cylinder, $\bullet$ – Semi-circular leading edge; $\blacktriangledown$ – Elliptical leading edge from Mills et al. (2005); $*$ – from Taylor et al. (2011); $\diamond$ – Present data.

Extending this hypothesis to other elongated bluff bodies, we propose that the chord-based Strouhal number be modified by,

$$St_c = St_c|_{\theta=0} - g(x_r) \quad (4)$$

where, $g(x_r)$ is some function based on the reattachment length. Combining the data from Figure 5 and Figure 6 we obtain,

$$St_c|_{c/t=7} = St_c|_{c/t=7, \theta=0^\circ} - 0.11x_r. \quad (5)$$

We extend this relationship established for $c/t = 7$ to other bodies using data available in the literature (Figure 11). From Figure 11 it appears that this relationship yields a reasonable collapse of the data. Therefore, it appears that the leading edge offers a type of flow control through the level of turbulence rather than synchronization through feedback as it does at lower Reynolds numbers. Further studies are underway to examine how the turbulence created at the leading edge is connected to the vortex convection speed in the recirculation region.

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