Particle Image Velocimetry Measurements of Wake Flows of Various Bridge Sections

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1 INTRODUCTION

Deck geometry is one of the crucial factors that influence the flow characteristics and aeroelastic response of long-span bridges. The wake flow patterns of bridge sections become increasingly important when exploring the interaction between the wind and the structure, as designs are becoming longer and lighter. Since the flow field and the vortex shedding activity produced by simple wind-structure interaction are often complex in nature, the ambiguous effects of bridge deck geometry cause the level of complexity to increase significantly.

Mills, Sheridan and Hourigan [1] have investigated, through the use of PIV, the flow around elongated flat plates of various elongation ratios to describe the impact of the leading edge vortices on the trailing edge shedding activity and the interaction found to occur between them. However, the effects of body geometry on the flow structure and shedding activity have yet to be established, causing such study to be considered as a necessary addition to further research within the field of bridge aerodynamics. Here, the resulting trailing edge and wake flow fields from four differing model geometries are discussed and compared, emphasizing the significance and direct engineering implications of bridge deck design. The ensemble averaging technique [2] to identify the turbulent structure in the near wake of a normal plate was applied here to characterize the organized coherent concentrations of large scale vorticity [3] unique to the body from which they are shed. In doing this, measured characteristics of each vortex street topology, such as vortex spacing, size, strength, convective speed and shedding frequency are examined.

2 PARTICLE IMAGE VELOCIMETRY MEASUREMENTS

Particle Image Velocimetry (PIV) is a reliable non-intrusive method to measuring complex flow fields through experimental investigations [4]. The PIV system used for the current experiments makes use of a double pulse Nd:YAG laser that produces a sheet of light, which illuminates seeded particles in the flow. The particles scatter light into a photographic lens located at 90 degrees to the sheet. Images are formed then subsequently transferred to a computer for completion of a two frame cross-correlation analysis.

The PIV measurements in this study are sampled at approximately 15 Hz, as the tunnel speed is set to 17.8 m/s yielding a moderately high Reynolds number of 3×10^5. The time delay between the double pulse, set to be within the range of 10 – 20 μs, changes with regard to how much of the flow is measured, as it is dependent on the size of the field of view captured by the photographic lens.

3 WIND TUNNEL TESTS

Tests involving flow around elongated cylinders, of various geometries, have been carried out in a 0.5m x 0.5m x 2m open return wind tunnel at the Boundary Layer Wind Tunnel Laboratory at The University of Western Ontario. The purpose of each test is to measure the wake structure resulting from the specific bluff body geometry, as well as the flow field exhibited at the trailing edge through the use of PIV. The cylinders tested have an elongation ratio of 7 and are symmetric in cross-section with leading and trailing edges of distinct rectangular, triangular and circular geometry. The cross-section of the fourth cylinder is one which resembles the design of the existing Storebælt Bridge, found in Denmark, which experienced significant vortex-induced response just prior opening and the subsequent installation of turning vanes [5]. Figure 1 shows a sketch of the four shapes.

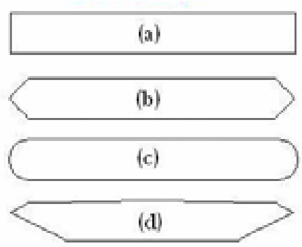

Figure 1. Sketches of the four model cross-sectional geometries (a) Rectangular edge (b) Triangular edge (c) Circular edge (d) Storebælt

4 WAKE COMPARISON AND ANALYSIS

The overall objective of the present study is to provide a quantitative interpretation of the wake topology characterized by the existence of a geometry-dependent vortex street. Vortex street comparisons amongst body are accomplished on the basis of the mean vortex spacing ratios, vortex size, circulation strengths, convective speeds and Strouhal number.

The PIV measurements suggest that the more streamlined cylinders, essentially the triangular and circular edge models as well the Storebælt model, exhibit structured wakes which resemble a Karman street, whereas the bluff rectangular edge geometry generates a relatively disorganized wake, where no periodic shedding is found, at least for this particular elongation ratio and Reynolds number. A comparison of the mean velocity profiles measured 2h downstream of each trailing edge shown in Figure 2, suggests that the rectangular model produces the widest wake while the width of the other models follow in an order that corresponds well with the vortex street spacing illustrated in Figures 3-5. Because the rectangular model has been singled out as the geometry which doesn’t produce a vortex street, an additional study was prompted involving the Reynold Stress distributions produced in the wakes of the four cylinder geometries to investigate the relationship that exists between the presence of a vortex street and its influence on surrounding turbulent activity.

Ensemble-averaged wake topology produced by the triangular edge, circular edge, and Storebælt geometries can be seen in Figures 3-5. At comparable convection speeds of approximately 85% of the freestream flow, visual differences in the vortex spacing and size amongst the wake flows are apparent. More specifically, it is the triangular edge model which sheds a vortex street with the largest spacing ratio; the circular edge model which produces the smallest vortices in the wake; and the Storebælt model which experiences differences in the strengths of the vortices shed from the top and bottom separated shear layers. In an early attempt to link the strength of the vortex street produced by the three shedding bodies and the aerodynamic forcing experienced in each case, Table 1 reveals that the triangular edge model sheds the strongest vortices, while being subject to the largest lift fluctuations. In the case of the Storebælt model, the vortices shed from the top separated shear layer are approximately 1.5 times stronger then those of the bottom; the lift fluctuations are shown to be the least of the three shedding models. As previously stated, the rectangular model does not produce a vortex street in the classical sense, and as such a relatively smaller value of the rms lift coefficient was found.

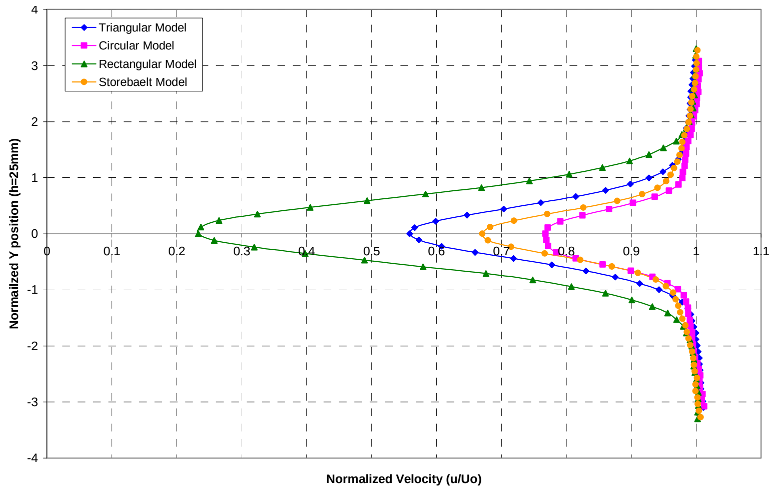

Figure 2. Comparison of mean velocity profiles measured 2h downstream of the trailing edge at Re = $3x10^5$.

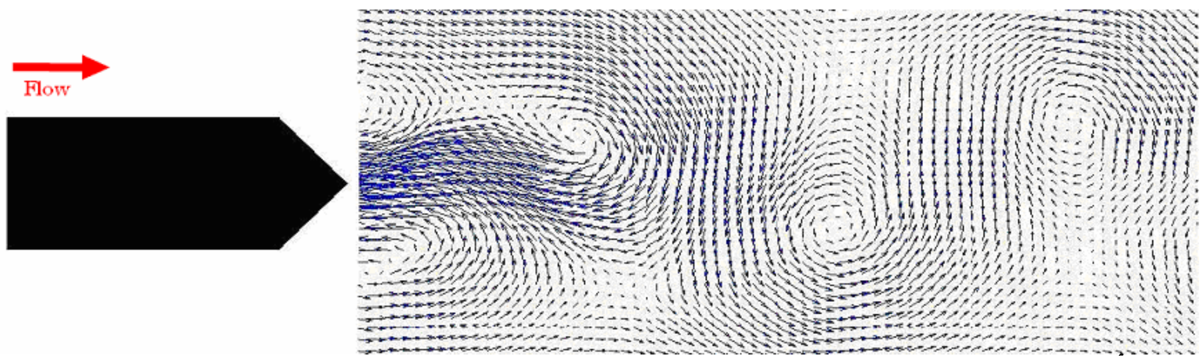

Figure 3. Ensemble averaged wake flow at $U_{conv} = 0.853U_\infty$ behind the Triangular edge model at Re = $3x10^5$.

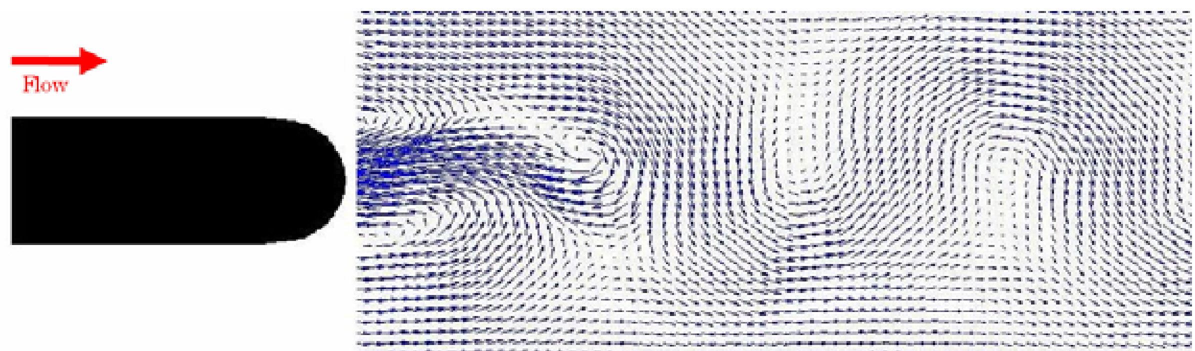

Figure 4. Ensemble averaged wake flow at $U_{conv} = 0.847U_\infty$ behind the Circular edge model at Re = $3x10^5$.

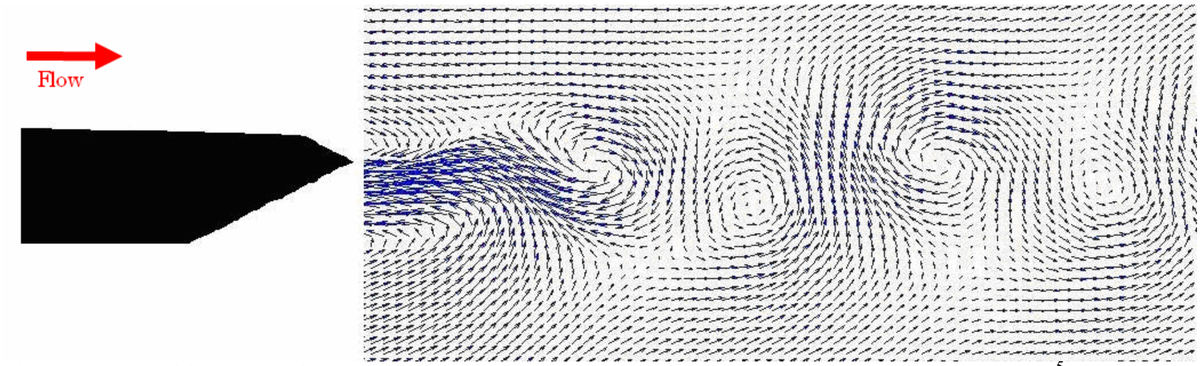

Figure 5. Ensemble averaged wake flow at $U_{conv} = 0.862U_\infty$ behind the Storebælt model at Re = $3x10^5$.

Table 1. Vortex circulation (normalized by the weakest) and corresponding RMS lift coefficient for each model.

Model	Vortex Circulation		C_L RMS
Rectangular	n/a		0.037
Triangular Edge	1.73		0.055
Circular Edge	1.24		0.046
Storebælt	1.55 (top)	1(bottom)	0.030

5 CONCLUSIONS

Alternate shedding of vortices in the near wake, in the classical vortex street configuration, imposes large fluctuating pressures normal to the direction of flow and may cause structural vibrations, which can lead to failure [6]. Focusing on the unique features of the four resulting trailing edge and wake flows, primarily comparisons of mean wake flows; vortex street spacing ratios; vortex sizes and strengths; vortex convective speeds; shedding frequencies via Strouhal numbers; and trailing edge-vortex street circulation ratios, provide much needed insight as to how the variations in geometry can alter the aerodynamic behaviour of the body. Implications of such investigations become evident as the relationship between the aerodynamic forces and pressure fluctuations experienced in each case suggest that the body which produces the vortices of greatest strength also undergo the largest variable forcing. The corresponding flow field examination of the Storebælt design is a primary one, as it is seen as a vital means to answering cause-effect questions resulting from a study involving the vortex-induced response of the Storebælt Bridge previously examined at the BLWTL [5].

6 REFERENCES

1 R. Mills, J. Sheridan, and K. Hourigan, Particle image velocimetry and visualization of natural and forced flow around rectangular cylinders, Journal of Fluid Mechanics, 478 (2003) 299-323.

2 M. Kiya and M. Matsumura, Incoherent turbulence structure in the near wake of a normal plate, Journal of Fluid Mechanics, 190 (1988) 343-356.

3 B. Cantwell and D. Coles, An experimental study of entrainment and transport in the turbulent near wake of a circular cylinder. Journal of Fluid Mechanics. 136 (1983) 321-374.

4 R. J. Adrian, Particle-imaging techniques for experimental mechanics, Annual Review of Fluid Mechanics, 23 (1991) 261-304.

5 J. M. Terres-Nicoli, The torsional vortex-induced response of the Storebælt bridge, Master Thesis, Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, London, Ontario, Canada 2002.

6 C.H.K. Williamson, Vortex dynamics in the cylinder wake, Annual Review of Fluid Mechanics, 28 (1996) 477-539.