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# Bluff body aerodynamics in wind engineering

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**Abstract**

Most of the man made structures are bluff bodies. Therefore, the subject of this conference is central to the subject of wind engineering. One of the most obvious features of the flow around bluff bodies is the formation of strong large vortices in their wakes. These have a large impact on the wind loading of tall buildings and bridges, particularly the loading in the across-wind direction. Not only is the design for structural integrity affected but also the design for serviceability, since the motions induced by vortex shedding can easily reach objectionable levels from the point of view of human comfort. However, measures can be taken to reduce the effects of vortex shedding, including shape changes and supplemental damping devices. Wind turbulence is also a parameter that affects vortex shedding strongly and this can be sensitive to the terrain around the structure. Another feature of bluff body flows is that some of them are Reynolds number sensitive. The recent research on the oscillations of inclined cables on cable-stayed bridges reinforces the need always to be cognizant of the potential effects of Reynolds number and its interplay with turbulence and surface roughness.


*Keywords:* Wind loading; Tall buildings; Bridges; Dynamic response

## 1. Introduction

Buildings, bridges, stadiums and other structures must be able to withstand the forces of nature, at least to the extent that the probability of failure or loss of serviceability under natural forces is reduced to an acceptably low level. Wind is one of the principal forces of nature and, since most structures are bluff bodies, bluff body aerodynamics therefore becomes a critical subject area affecting structural design. Another important force of

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nature is the loading that occurs due to snow, including the effects of redistribution of snow under the action of wind as it blows around bluff structures. Wind also affects the performance of structures in a variety of other ways such as the dispersion of exhausts out of a building, the comfort and safety of people using pedestrian areas on and around buildings, the safety of traffic driving over bridges, the performance of signs over highways, to give a few examples. Therefore, bluff body aerodynamics has always lain at the heart of wind engineering. This paper will review a number of bluff body aerodynamic phenomena and their effect on structures and on people. One of the fascinations of wind engineering is the great variety of bluff body aerodynamic problems that are encountered. This is best seen through a series of examples.

### *1.1. Vortex shedding—buildings*

A principal feature of bluff bodies is that they create separated flow regions which become the source of vortex shedding. Vortex shedding excitation can create problems in a variety of contexts in wind engineering. A prime example is the across-wind excitation of very tall buildings by vortex excitation. Fig. 1 shows an example of base bending moment $M_y$ as a function of wind direction for a tall building. At around 180° wind direction, the mean moment is zero but the peak values in the negative and positive directions are at a maximum. It is quite often the case that the highest overall wind loading on a tall slender building results from across-wind vortex excitation which induces a large dynamic response. The resulting motions of the building may cause discomfort to the building occupants and it becomes a major concern of the structural designer and architect as to how they can keep these motions to within acceptable limits.

A good example of where motions were of major concern is the recently constructed Taipei 101 Tower in Taiwan, Fig. 2, which is currently the world's tallest building. The wind tunnel tests, Fig. 3, identified high across-wind loads, and building accelerations beyond the applicable comfort criteria. The solution was developed in the form of additional structure, modified shape and the installation of a large 740 ton tuned mass

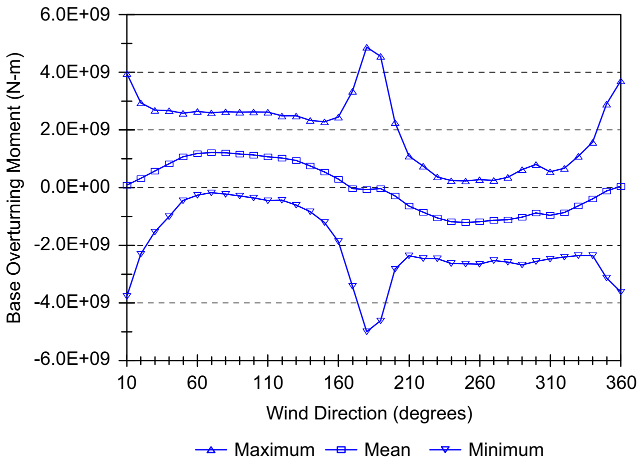


Fig. 1. Example of 50 year base bending moment of a tall slender building.

Fig. 2. Taipei 101 Tower.

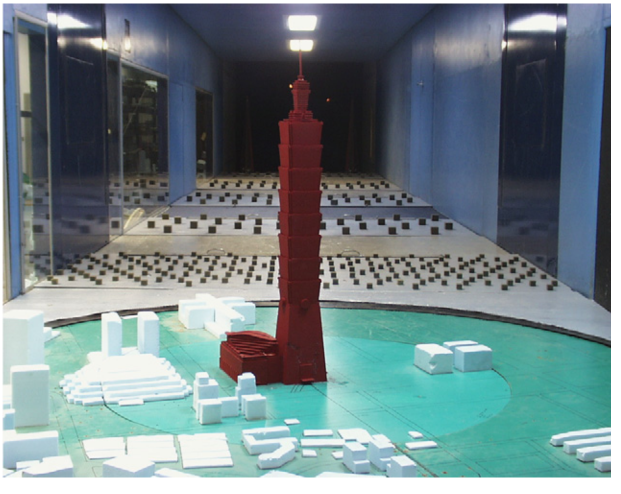

Fig. 3. Wind tunnel tests at RWDI of Taipei 101 Tower.

damper near the top of the tower. The shape modification was to soften the building corners as illustrated in Fig. 4. This reduced the base wind-induced base bending moments by approximately 25%, which solved some problematic foundation loads. The building

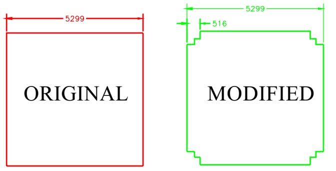


Fig. 4. Example of original and modified cross-section of Taipei 101.

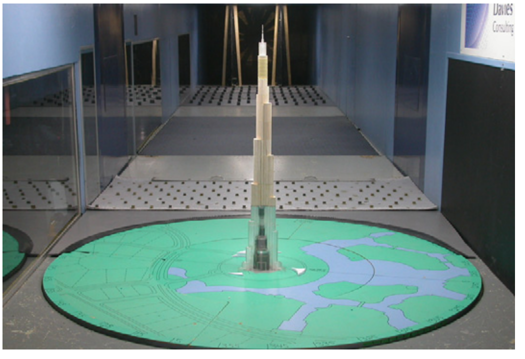

Fig. 5. Model of Burj Dubai Tower in RWDI's 2.4 m × 2.0 m wind tunnel.

motions were also reduced by the shape change but this was not enough on its own to bring the accelerations to within acceptable limits. Hence the need for a tuned mass damper which has been described by Irwin and Breukelman (2001). An important factor affecting the strength of vortex excitation is the turbulence intensity of the wind. In the example of Taipei 101 there is no structure of comparable size anywhere near it and the nearby terrain is largely flat. Therefore, the turbulence intensity in the top region is quite low. This accentuated vortex shedding. Towers in a location like downtown Manhattan see an entirely different type of approaching wind, full of turbulence from surrounding buildings. This tends to suppress vortex excitation from the building itself but can lead to strong buffeting effects coming from the wakes of other buildings. An example of where wake buffeting caused motion problems was the 67 storey Park Hyatt Tower in Chicago where the wake of the existing John Hancock Tower caused severe wake buffeting for northeasterly wind directions. This was solved through the installation of a 300 ton tuned mass damper in the Park Hyatt Tower.

A known solution to vortex excitation is to introduce set backs into the tower at various levels. The variations in cross-section with height confuse the vortices being shed by the tower. Not only is the across-wind width of the structure varying with height bu so also is the Strouhal number. Therefore, the shedding frequency varies with height and the aerodynamic excitation loses its coherence. Fig. 5 shows the wind tunnel model of the Burj Dubai Tower which will be substantially taller than even Taipei 101. It can be seen that the tower tapers with height. In addition the set backs are introduced in a spiral pattern that makes the cross-section highly non-uniform. This geometry, combined with a relatively mild wind climate has enabled the building motions to be maintained within acceptable limits even without a damping system. The Petronas Towers in Kuala Lumpur, Figs. 6 and 7, are another example

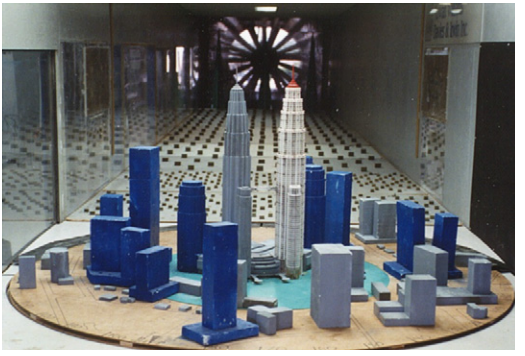

Fig. 6. Petronas Towers wind tunnel model.

Fig. 7. Petronas Towers.

where a tapered shape, combined with a mild wind climate helped to keep the adverse effects of vortex excitation at bay without the need for a damping system. However, vortex excitation did cause the potential for vibration problems in the slender cylindrical struts supporting the sky-bridge between the towers about midway up their height, and in the spire at the top of each tower. As a result tuned mass dampers were installed in the struts and a chain impact damper was incorporated into each of the spires.

### 1.2. Vortex shedding—bridges

Many modern cable-stayed bridges have a cross-section consisting of a concrete slab deck mounted on steel longitudinal stiffening girders near the edges. The girders are supported by the stay cables. This configuration is economical and easily constructed but can be susceptible to vortex shedding oscillations. The strength of the vortex excitation is sensitive to the ratio of girder depth to deck width, details of the deck edges and the amount of turbulence in the wind. A further parameter affecting the amplitude of oscillations is the bridge damping.

In the 1990s RWDI undertook wind tunnel tests on the Second Severn Bridge in Western England. This 456 m span cable-stayed bridge, completed in the mid-1990s, is unusual in that it has a 3 m high, 50% porous wind screen along both edges of the deck for its entire length. The site has frequent strong winds and the existing Severn suspension bridge, which crosses the Severn River a few kilometers upstream has traffic restrictions imposed fairly frequently due to driver handling problems in strong winds. The screens on the new cable-stayed bridge are very effective and traffic restrictions have never had to be imposed. They are shown on the sectional model in Fig. 8. While the screens helped the traffic, they complicated the task of making the bridge behave well aerodynamically and the wind tunnel program was very extensive. A section that worked well for flutter seemed to be prone to vortex shedding oscillations, while aerodynamic modifications aimed at suppressing vortex shedding oscillations invariably seemed to have an adverse effect on flutter. In the end a section was selected that did exhibit limited amplitude vortex shedding oscillations but they were sensitive to damping and turbulence and, with the expected full-scale damping, and the estimated turbulence levels at the site, the amplitude of oscillation was expected to be within the criteria being used. Also, it was shown that vertical baffle plates under the deck could be used to suppress the oscillations.When the

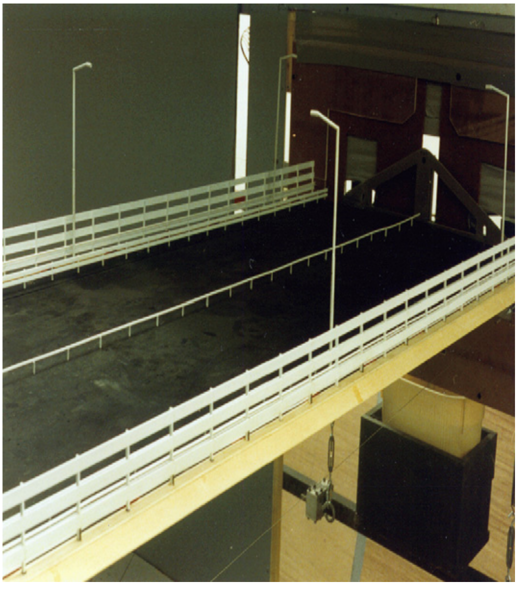

Fig. 8. Sectional model of Second Severn Bridge showing wind screens.

bridge was constructed, vortex oscillations were indeed observed, but with larger amplitude than expected. John Macdonald of the University of Bristol, had instrumentation on the bridge as part of his research and was able to record in detail the bridge response, the wind speed, the wind direction and the turbulence properties. This provided not only the opportunity to identify why the oscillations were larger than expected but also to compare wind tunnel test results with full scale, with some interesting conclusions with respect to turbulence effects and sectional model methodology. Full details have been published recently by Macdonald et al. (2002). Here, only the main results will be summarized.

The full-scale data showed clearly that the damping ratio of the bridge was lower by about a factor of two than was assumed during design, which in turn had been based on recognized standards. Also the data showed that low turbulence intensities were quite common at the site even at wind speeds up to 20 m/s. Frequently the intensity was in the range 4–7%. The sectional model tests were done in both smooth and turbulent flow. However, testing of a sectional model in turbulence entails some assumptions, because typically the larger scales of turbulence present at full scale cannot be simulated on the model due to the limited size of the wind tunnel working section. Therefore, only the high-frequency part of the power spectrum can be simulated and it is of interest to know how test results in such a "partial simulation" compare with full scale. The Second Severn Bridge provided an opportunity to make such a comparison. The partial simulation approach, described in more detail by Irwin (1998), is illustrated in Fig. 9. The vertical scale is the turbulence power spectrum normalized using the mean velocity, $U$, rather than the more typical root-mean-square turbulence velocity. With this normalization the wind tunnel spectrum curve should match the full-scale curve at least in the high-frequency part of the spectrum. As described by Irwin (1998) this requires low turbulence intensities on

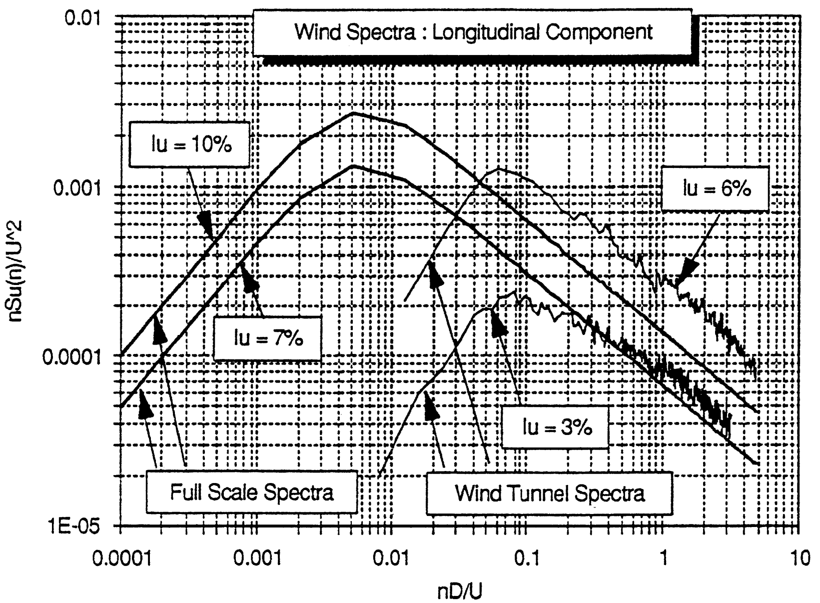


Fig. 9. Partial simulation of turbulence on a sectional model.

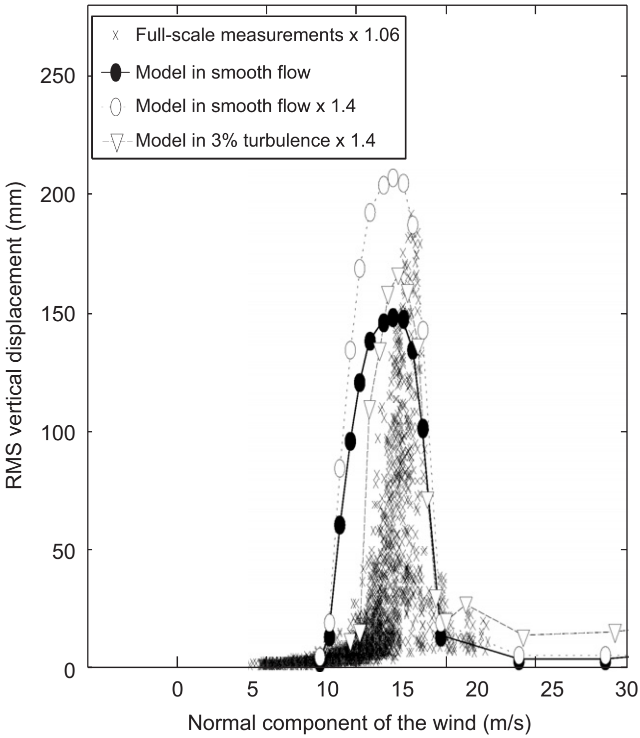


Fig. 10. Comparison of sectional model with full-scale data. Model damping ratio = 0.35%; full-scale damping ratio = 0.29%.

the model, typically less than half the full-scale value. In Fig. 9, it can be seen that the wind tunnel spectrum for 3% turbulence matches fairly well with that of 7% at full scale. Fig. 10 shows the comparison of the vortex excitation data from the sectional model with the full-scale measurements. The full-scale data points were obtained not quite at mid-span and so were increased by a factor of 1.06 to give the values at mid-span. The model data shown for smooth flow as solid points were the result of simply scaling the observed sectional model deflections up by the ratio of full-scale length to model length, in this case 50. This approach is frequently used in sectional model tests. It can be seen that while the peak in response occurs at close to the same wind speed as at full scale, the excitation occurs over a broader wind velocity range than at full scale and does not reach as high a peak value. There is an additional correction factor that can be introduced to account for the difference in modal deflection shape between model (uniform) and full scale (approximately sinusoidal), and for generalized mass differences. Using the approach described by Irwin (1998), for the case where the vortex excitation force is assumed to be perfectly correlated along the span, this "mode shape correction factor" was calculated to be 1.4. The open circle points in Fig. 10 show the smooth flow sectional model data with this factor applied. This causes the peak in model response to now exceed the full-scale value.The final set of model data in Fig. 10, shown as open triangular points, is that with 3% turbulence in the wind tunnel and with the mode shape correction applied. The turbulence was targeted to simulate the high-frequency portion of the spectrum of about 6% or 7% turbulence at full scale, which was the range of intensity where most of the vortex excitation episodes observed at full scale occurred. Above about 8% intensity the full-scale excitation was greatly reduced, Macdonald et al. (2002). It can be seen in Fig. 10 that the model results at 3% turbulence intensity are in better accord with the full-scale data.

The range of wind speeds for the excitation is considerably narrowed, coming much closer to full scale, and the peak value is only slightly lower. In fact, the difference in peak value can be partly attributed to a small residual difference between model damping and full-scale damping. The model damping ratio had been set to 0.35% based on early feedback from the full-scale measurements. When the full-scale data analysis was eventually completed the estimate of the full-scale damping was reduced to 0.29%. Correcting for this would bring the results into closer alignment. The model response is still somewhat broader than the full-scale response. This could be due to the lack of low-frequency turbulence fluctuations on the model. Intuitively these would be expected to narrow the response peak further, since they would resemble the effect of having the mean speed meander in an out of the vortex lock-in range. For speeds in the middle of the lock-in range these meanderings would be insufficient to go outside the range, but for speeds near the edge of the lock-in range the excitation would be intermittently "turned off", causing a reduction in response.The solution to the vortex excitation oscillations on the Second Severn Bridge was to install vertical baffle plates as illustrated in Fig. 11, similar to those developed during the design phase sectional model tests. These were refined through further testing after construction, before final installation over the central 252 m of the main span. Fig. 12 shows the full-scale response recorded after the baffle plates were installed, MacDonald et al. (2002), and it can be seen, in comparison to Fig. 10, that they were very effective in eliminating the peak response. These results indicate how important it is to fully account for the effects of wind turbulence and damping when assessing the effects of vortex shedding on bridges. Other types of aerodynamic solutions to oscillations of plate girder bridge decks are described by Irwin and Stone (1989).

### 1.3. Other interesting effects on tall buildings

It is known that the highest peak local loads on buildings are often caused by the flow separation and generation of vortices near building corners. Wind tunnel tests on buildings with balconies located at the corners have shown substantial reductions in these peak suctions. This is attributed to the breaking up of the strong corner vortices by the flow disturbances created by the balconies. Irwin et al. (1998) give an example where a

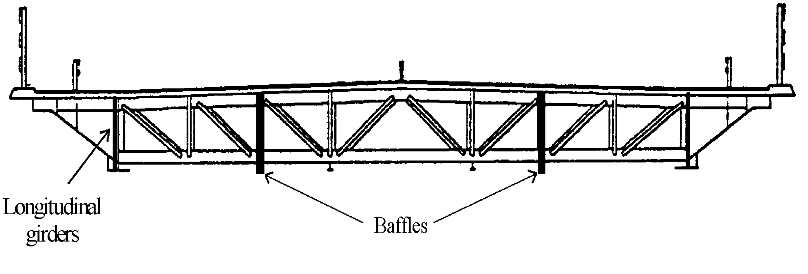


Fig. 11. Second Severn Deck cross-section with baffle plates.

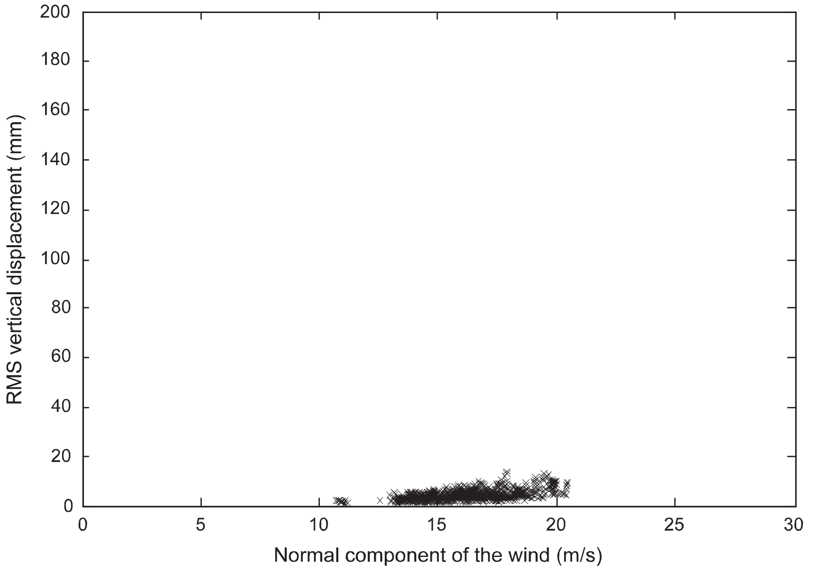


Fig. 12. Full-scale vertical response of Second Severn Bridge with baffle plates installed.

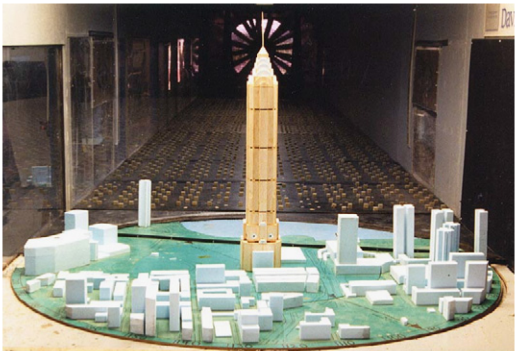

Fig. 13. Tower model with openings at various levels.

building was tested with and without balconies. Local peak pressure coefficients were reduced by 50%.

The high drag and across-wind forces on bluff bodies can be alleviated to some extent by allowing air to pass through holes in the body. Fig. 13 shows an example of a wind tunnel test on an extremely tall tower planned for Hong Kong. The model had openings at various levels to represent ‘‘refuge’’ floors where occupants could assemble outside in the event of fire. The openings reduced the negative pressure in the wake region enough to generate significant savings in the structure due to reduced wind loads both in drag and across-wind directions. Irwin et al. (1998) give another example of the use of openings to reduce building response to wind on a tall building planned for Chicago.Not to be forgotten are strong ground level winds that can be created by tall buildings due to their tendency to deflect strong upper level winds downwards. This has resulted in city bylaws requiring this type of effect to be examined during the planning stage. Recently the American Society of Civil Engineers has published a state of the art report on assessing and improving comfort in outdoor areas, with special emphasis on wind effects, edited by Irwin (2004).

### 1.4. Cable vibrations on bridges

A final topic that will be mentioned is the problem of cable vibrations on cable-stayed bridges. There has been extensive research into this topic over the last 20 years or so. The phenomenon of "rain–wind" vibrations has been the most commonly observed problem, where rivulets of rainwater running down inclined cable stays have, in combination with wind, caused fairly severe and frequent oscillations in the wind speed range of about 7–15 m/s. The problem can be largely avoided either by increasing the damping of cables so that the mass-damping parameter $m\zeta/\rho D^2 > 10$, where $m =$ mass per unit length, $\zeta =$ damping ratio, $\rho =$ air density and $D =$ cable diameter (Irwin, 1997). Another approach is adding a spiral fillet to the cable to throw off the rivulets. While these solutions are known to work the exact mechanism of the excitation could still do with further research. Another problem that has been occasionally seen is vibration of inclined cables even in dry conditions. Recently RWDI led some aerodynamic research into this problem for the US Federal Highway Administration. RWDI enlisted the help of the University of Ottawa and the National Research Council of Canada to complete this research and professor Tanaka was able to continue this research under NSERC funding. The results were interesting since it was concluded that within a narrow range of Reynolds number inclined cables can experience an instability similar to Den Hartog galloping. Some of the results have been published by Cheng et al. (2003) and they highlight the importance of Reynolds number, surface roughness and turbulence when examining cable vibration problems.

## 2. Conclusions

The variety of bluff body aerodynamic problems that occur in wind engineering is almost limitless. The present paper has touched on a few and illustrated how important these problems can sometimes be to the safety and economics of large buildings and bridges.

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