Galloping Effects on Inclined Square Cylinder

K.M. Shum[1)], K.C.S. Kwok[1), 2),3)] and P.A. Hitchcock[1)]

[1)] *CLP Power Wind/Wave Tunnel Facility, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R. China*

[2)] *Department of Civil & Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R. China*

[3)] *School of Engineering, The University of Western Sydney, Sydney, New South Wales, Australia*

1. INTRODUCTION

Slender structures with inherently low damping can be prone to serious vibration excited by galloping effect. Galloping is a form of single-degree-freedom aerodynamic instability which affects structural cross-sections such as square, rectangular, crucifix and other sections with fixed separation points. Extensive wind tunnel studies on galloping of cantilevered structure, such as refs. [1-3], have been carried out to understand the excitation mechanism of galloping. Kwok and Melbourne [1] found that a slender square cylinder with an aspect ratio of 18:1 vibrated excessively under the combined effect of galloping and wake excitation when the reduced velocity was between 15 and 20. The effect of wake excitation diminished when the reduced velocity was above 20. Kawai [2] showed that galloping effect of a building model with an aspect ratio of 10:1 could not be observed when the angle of wind incidence was larger than 10°. Ziller and Ruscheweyh [3] presented two different methods of determining the onset velocity of galloping using the aerodynamic coefficients measured from wind tunnel tests. A review of the existing literatures indicated that there was no relevant research carried out to investigate the wind effects on inclined cantilever structures. Studies on the wind effects on inclined structures have mostly focused on stayed cables. However, structures are now designed with more complex and innovative architectural features. For instance, some bridge pylons are designed with an inclination mainly for aesthetic purposes. It is obvious that wind flow around an inclined structure can be significantly different from that around a vertical structure.

This paper presents the results from a program of wind tunnel study on the galloping effect of an inclined square cylinder. A single-degree-freedom model simulating the vibration of a slender structure in crosswind direction was designed and fabricated. A series of wind tunnel tests were conducted to study the galloping effect of the structure in terms of angle of wind incidence, inclination angle and structural damping ratio. The flow condition being considered in this study was a uniform smooth flow and the reduced wind velocity was 16. Different flow conditions and reduced wind velocities will be studied further in another series of wind tunnel tests.

2. EXPERIMENTAL SETUP

A series of wind tunnel tests were carried out in the upstream test section of the high speed section of the CLP Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology. The cross-section of the test section is 3 m wide and 1.6 m high. A slender square tower model was designed and fabricated with dimensions of 30 mm × 30 mm × 540 mm (W×B×H), resulting in a height to breadth ratio of 18:1. A 2 mm thick steel plate was installed at the base of the tower model. The natural frequency and the pivot point of the model were adjusted by the length of the 2 mm steel plate. The density and the natural frequency of the model were found to be about 223 kg/m^3 and 9.0 Hz.

A tailor-made mounting system was designed to be capable of changing the angle of inclination and the angle of wind incidence of the model. The mounting system consisted of two steel plates connected in an inverted T-shape and a 400 mm×400 mm steel plate fixed to the base of wind tunnel. There were a total of 53 pairs of precision-drilled holes in the base plate for altering the angle of wind incidence from -20° to +20° at an interval of 2.5° and a total of 19 pairs of precision-drilled holes at the vertical plate for altering the inclination angle of the model from -30° to +30° at an interval of 5.0°. The 2 mm steel plate together with the square tower model was fixed to the vertical plate of the inverted T-shape structure by four high strength tensile bolts. The inclination angle of the model was adjusted by fastening the bolts in different sets of holes on the vertical plate. The base plate of the T-shape structure was fixed to the 400 mm × 400 mm base plate and the wind incidence angle was adjusted by fastening the bolts in different sets of holes on the 400 mm×400 mm base plate. The model used was effectively pivoted at its base and had a straight line deflection mode. The crosswind displacement of the model (y) was measured by four strain gauges. The four strain gauges were attached to the surface of the 2 mm thick steel plate with two on each side forming a Wheatstone bridge circuit. The output signals from these strain gauges were amplified and filtered by a signal conditioner prior to data acquisition. A 100 Hz low pass filter was applied for data acquisition of crosswind displacement response of the model. The signals were sampled at a frequency of 1000 Hz for a duration of 180 s. The orientation of an inclined square tower model with respect to the mean wind direction was represented by an inclination angle α in the vertical plane and a yaw angle β in the horizontal plane, as shown in Figure 1. In this study, the tower model is defined as backward (forward) inclined when the inclination angle is positive (negative).

Mean wind speeds and turbulence intensities were measured at the cross-section where the model was positioned. Three different vertical lines of measurement were taken in accordance with seven designated height levels ranging from 75 mm to 540 mm above the ground. The positions of the three vertical lines were selected at the centre of model, 100 mm to the left of the model, and 100 mm to the right of the model. The maximum turbulence intensity was found to be less than 1% and the standard deviation of the mean wind speeds was found to be less than 1% of the average value of the mean wind speeds. Hence, the uniformity of the wind was reasonably good for the test.

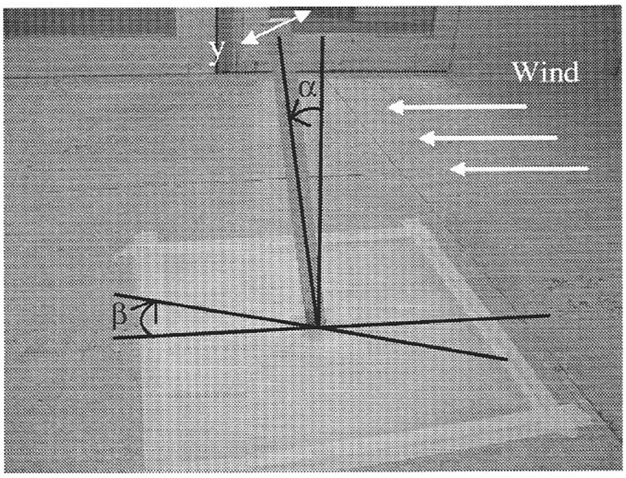


Fig. 1 Orientation of square tower model

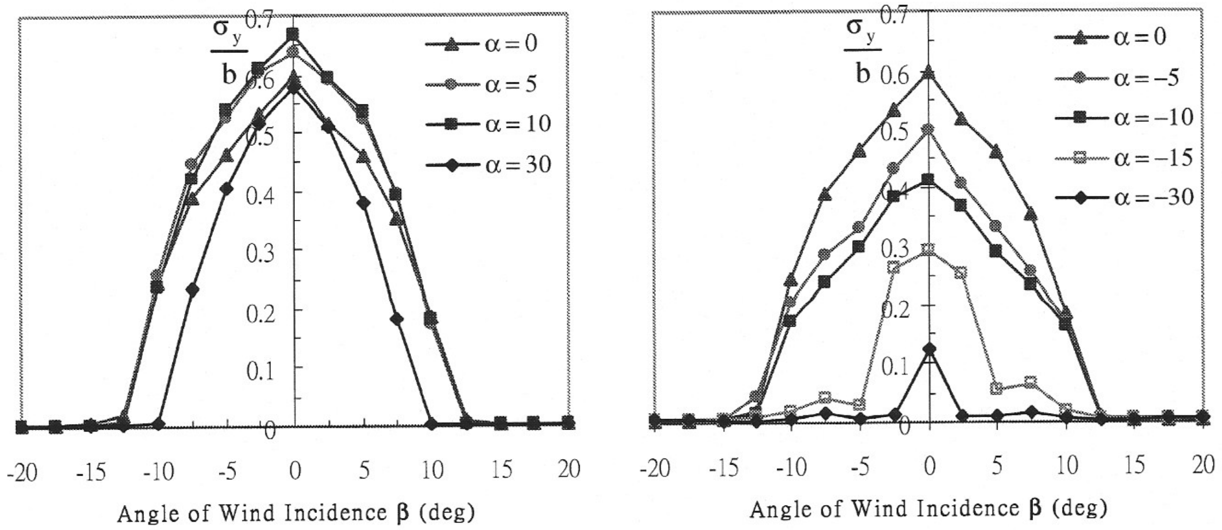


Fig. 2 Normalized transverse response of square tower model as a function of angle of incidence of mean wind for various angles of inclination angle

3. RESULTS AND DISCUSSION

3.1 Effect of Inclination Angle

For aesthetic reasons, it is inevitable that structures or their slender parts may be designed to have certain inclination which can affect the wind flow around it. The effect of inclination angle on the transverse wind response of a slender structure was thus investigated by a series of wind tunnel tests. The measured normalized transverse responses of the square tower at different angles of incidence of the mean wind with various inclination angles are shown in Fig. 2. The normalized transverse response of the structure is defined as the ratio of the standard deviation of transverse displacement response of the tower model to the width of the square tower model. The inherent damping ratio of the model was essentially the same at different angle of inclinations and was found to be about 0.33% of critical damping. Evidently, the maximum normalized transverse response of the tower model increases when the inclination angle of the model is increased from -30° to $+10^\circ$. When the model is inclined at an inclination angle of $+30^\circ$, the maximum normalized transverse response is smaller than that at an inclination angle of 0°. For wind incidence angle within $\pm 7.5^\circ$, considerable normalized transverse response can always be observed for the case where the model is backward inclined to wind, up to the tested maximum angle of $+30^\circ$. However, when the model is forward inclined to the wind, not only the normalized transverse response of the tower decreases with the decreasing inclination angle but also the range of wind incidence angle that can excite the tower to vibrate. For the case where the model is inclined to the wind at -30°, a notable normalized transverse response of the tower model can only be observed at a wind incidence angle of 0°.

The effect of inclination angle on the normalized transverse response of the tower model can be further studied by examining the normalized transverse response at different inclination angles and the results are shown in Fig. 3. The figure indicated that the maximum transverse response increases with increasing inclination angle from -30° to $+10^\circ$ and then remains at almost the same level of amplitude until the inclination angle is increased to $+20^\circ$. It can be seen that the maximum normalized transverse response of the tower model at an inclination angle of $+25^\circ$ and $+30^\circ$ are smaller than that at an inclination angle of $+20^\circ$. Fig. 3 also portrays that the maximum normalized transverse response of the tower model being backward inclined to the wind is much larger than that being forward inclined to the wind under the same level of inclination. Therefore, the effect of inclination is considered to be an influencing factor affecting the transverse response of square-sectioned tower structures.

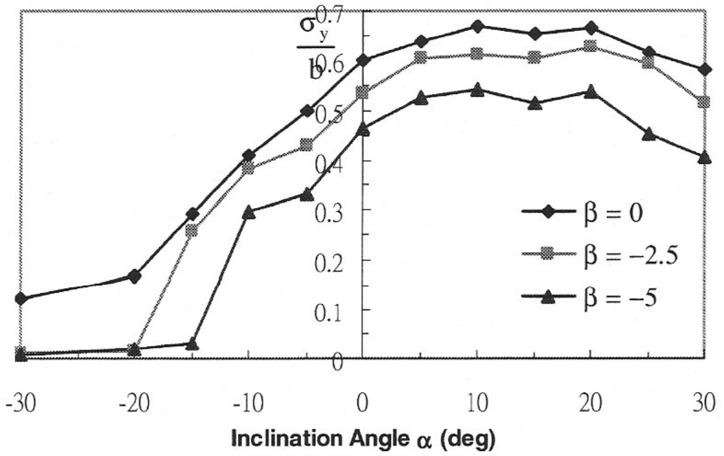
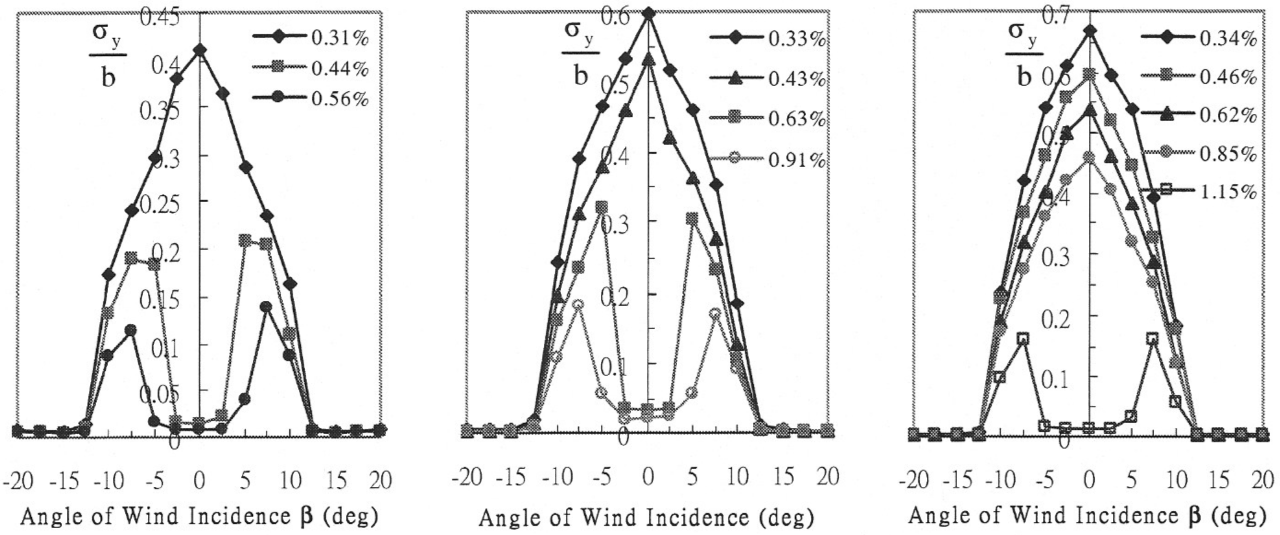


Fig. 3 Maximum normalized transverse response of square tower model at different inclination angles

3.2 Effect of Structural Damping

Galloping usually occurs when the negative aerodynamic damping due to structural motion is larger than the structural damping. The effect of structural damping is thus an important factor affecting the onset velocity of galloping. The effect of structural damping on the transverse response of the tower model was investigated in this study. The normalized transverse responses of the square tower at different angles of incidence of the mean wind with various levels of structural damping are shown in Fig. 4. It can be seen that the transverse response of the tower model decreases as the structural damping is increased, as expected. A larger damping value is required for the structure with a larger inclination angle to prevent from galloping at zero angle of incidence. Large galloping response of tower model with different inclination angles can be observed at zero angle of incidence when the structural damping is below a certain value. This normally suggests that the structure starts to gallop when the structural damping is below a certain value. However, it was pointed out by Kwok and Melbourne [1] that the effect of wake excitation can be significant for a square vertical tower at a reduced velocity of 16. Hence, large transverse response of tower model may be observed even if the structural damping was larger than the negative aerodynamic damping. The transverse response of the tower model when forward inclined at -10° decreased significantly due to a slight increase in damping from 0.31% to 0.44%. When the tower model is backward inclined at +10°, considerable galloping response continued to be observed for structural damping values ranging from 0.34% to 0.85%. This suggests that the effect of wake excitation was less dominant for the case where the model was forward inclined. However, to accurately account for the effect of wake excitation, a further wind tunnel study will be carried out to determine the transverse force coefficient of an inclined cantilever structure.



(a) α = -10°   (b) α = 0°   (c) α = +10°

Fig. 4 Normalized transverse response of the square tower model as a function of angle of incidence of mean wind for various levels of structural damping

4. CONCLUSIONS

A wind tunnel investigation on the transverse response of a slender square tower model in a uniform smooth wind has been carried out. The test results indicate that the maximum normalized transverse response of tower model being backward inclined to wind is much larger than that being forward inclined to wind under the same level of inclination. For wind incidence angle within ±7.5°, considerable galloping response can always be observed for the case where the model is backward inclined to wind. When the model was forward inclined to wind, not only the galloping response of the tower decreased with the decreasing inclination angle but also the range of wind incidence angle that can excite the tower to gallop. It was also found that the transverse response of the tower model decreased as the structural damping value was increased. A larger damping value is generally required for the structure with larger inclination angle to prevent from galloping at zero angle of incidence. This suggests that the effect of wake excitation may be less dominant for the case where the model is forward inclined.

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