Galloping of an inclined square cylinder

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Keywords: galloping, wake excitation, inclination, wind incidence, structural damping.

ABSTRACT

Slender structures with inherently low damping can be prone to serious vibration excited by galloping effect. Extensive wind tunnel studies on galloping of vertical cantilevered structure existed in the literature but none of it concerned about the structure with an inclination to wind. 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. To better quantify the effects of aerodynamic damping and wake excitation, transverse force coefficients of the square tower model were measured in uniform smooth flow condition. The flow condition being considered in this study was uniform smooth flow and turbulence flow conditions and the reduced wind velocity was 16.

1. INTRODUCTION

Slender structures with inherently low damping can be prone to serious vibration excited by galloping. 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 structures, such as Kwok & Melbourne (1980) and Kawai (1995), have been carried out to understand the excitation mechanism of galloping. Kwok & Melbourne (1980) 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 (1995) showed that galloping 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 & Ruscheweyh (1997) 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 stay-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 studies on the galloping of an inclined square cylinder. A single-degree-freedom model simulating the vibration of a slender structure in its crosswind direction was designed and fabricated. A series of wind tunnel tests were conducted to study the galloping of the structure in terms of angle of wind incidence, inclination angle and structural damping ratio. The flow conditions being considered in this study were a uniform smooth flow and a turbulent flow. The aerodynamic damping effect, mainly governed by the cross-sectional shape of structures, is believed to be the most influencing factor affecting the galloping response. By using the quasi-steady assumption, Parkinson and Smith (1964) measured the transverse force coefficients of a square cylinder and indicated that the galloping instability occurs when the slope of the transverse force coefficient is positive at zero angle of wind incidence. To better quantify the effect of aerodynamic damping of an inclined square cylinder, a stationary model with its dimensions exactly same as that of the aeroelastic model was fabricated and tested under smooth flow condition. Some preliminary measurement results of the mean wind force acting on the stationary square cylinder model were presented. The reduced wind velocity was 16.

2. THEORY

If a square cross-sectioned body with side b moves with a velocity in a flow with a velocity \( \dot{y} \) in a flow with a mean wind velocity \( \bar{U} \) normal to one face as shown in Figure 1, the aerodynamic force acting on the body in the direction of motion is

\[
F_y = -(F_L \cos \alpha + F_D \sin \alpha)
\]  

(1)

A quasi-steady approach assumes that at every instant during the oscillation, the aerodynamic force acting on the body is the same as for a static test on the same rigid body at the same angle of incidence.
of the mean wind. (1) can be rewritten as

\[ C_{Fy} = -(C_L \cos \alpha + C_D \sin \alpha) \]  

(2)

in which \( C_{Fy} \) is defined as the transverse force coefficient. At zero angle of incidence, transverse is equivalent to cross-wind. The transverse force coefficient may be approximated by a polynomial as proposed by Parkinson and Brook (1961).

\[ C_{Fy} = \sum_{i=1}^{n} A_i \alpha^i = \sum_{i=1}^{n} A_i \left( \frac{y}{U} \right)^i \]  

(3)

\( A_i \) is the \( i \)th coefficient of the polynomial approximation. When the coefficient

\[ A_i = \frac{dC_{Fy}}{d\alpha} \bigg|_{\alpha=0^\circ} > 0 \]  

(4)

That is when the slope of the transverse force coefficient at zero angle of incidence is positive, the aerodynamic force acting on the body is in the direction of the motion and the body is theoretically susceptible to galloping. (4) is well-known as Den Hartog’s criterion for galloping instability. This aerodynamic force can be conveniently expressed as an equivalent aerodynamic damping \( \xi_a \).

For an inclined structure with constant cross section and is exposed to a smooth flow condition, as a first approximation in which nonlinearity is ignored, the equivalent aerodynamic damping for the complete structure is (Vickery et al. 1975)

\[ \xi_a = -\frac{\rho_a}{8\pi \rho_s n_o b} \frac{U}{dC_{Fy}} \frac{dC_{Fy}}{d\alpha} \]  

(5)

\( \rho_a \) is density of air. \( \rho_s \) and \( n_o \) are the structural density and natural frequency of the structure respectively. If the equivalent aerodynamic damping is negative so that the resultant damping, that is aerodynamic damping plus structural damping, is zero or negative, the transverse response amplitude will grow until it reaches a steady magnitude governed by the nonlinearity of aerodynamic damping.

3. EXPERIMENTAL SETUP

A series of wind tunnel tests were carried out at the high speed section of the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology. For smooth flow condition, the tests were carried in the upstream test section of the high speed section. Mean wind speeds and turbulence intensities were measured at the cross-section where the model was positioned. The fluctuating wind velocity was measured at various heights at the centre of the working sections using a hot-wire anemometer. Measured mean wind speeds at the centre of model were normalized with respect to the value at building height and are presented in Figure 2(a) together with the measured turbulence intensities. The maximum turbulence intensity was found to be less than 0.5% 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 satisfactory for the test. For turbulent flow condition, the tests were carried out in the downstream test section of the high speed section at which a boundary layer wind model corresponding to an open terrain (Category 2) in the AS/NZS 1170.2:2002 (Australian/New Zealand Standard 2002) was simulated using a combination of solid wooden fences and roughness elements over a 21 m fetch length at WWTF. Measured and target gust wind speed profiles were normalized with respect to the value at building height and are presented in
Figure 2(b) together with the measured turbulence intensity profiles. The measurement results are reasonably consistent with the profiles suggested by the AS/NZS 1170.2:2002, with the difference generally not exceeding 5%.

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. The natural frequency and the pivot point of the 1-D aeroelastic model were adjusted by the length of a 2 mm thick steel plate that was installed at the base of the tower model. The density and the natural frequency of the model were found to be about 223 kg/m³ and 9.0 Hz. The model was effectively pivoted at its base and had a straight line deflection mode. The crosswind displacement (y) of the model was measured by four strain gauges. Two strain gauges were installed on each side of the 2 mm thick steel plate forming a Wheatstone bridge circuit. The output signals from these strain gauges were amplified and low-pass filtered at a frequency of 100 Hz by a solid-state signal conditioner prior to data acquisition. To quantify the effect of aerodynamic damping, a rigid and light weighted model was fabricated with its dimensions exactly same as that of the 1-D aeroelastic model. The stiffness of the model was adjusted by the length of a stainless steel bar and the natural frequency of the rigid model was found to be about 32.0 Hz. The aerodynamic forces were measured by four strain gauges. Two strain gauges were installed on each side of a 8 mm thick steel bar forming a Wheatstone bridge circuit. The output signals from these strain gauges were amplified and low-pass filtered at a frequency of 100 Hz by a solid-state signal conditioner prior to data acquisition. The orientation of the inclined square tower model with respect to the mean wind direction was represented by an inclination angle $\alpha$ in the vertical plane and a yaw angle $\beta$ in the horizontal plane, as shown in Figure 3. In this study, the tower model is defined as backward (forward) inclined when the inclination angle is positive (negative).

Figure 2: Simulated wind characteristics
4. RESULTS AND DISCUSSION

4.1 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 Figures 4 and 5 for the smooth and turbulent flow conditions. 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 angles of inclinations and was found to be about 0.30% of critical damping. Similar to the case of a vertical square cross-sectioned body reported by Novak and Davenport (1970), the effect of increase in free-stream turbulence decreases the galloping response of an inclined square sectioned structure. Evidently, the maximum normalized transverse response of the tower model increases when the inclination angle of the model is increased from -30° to +10° in both smooth and turbulent flow, as shown in Figure 6. When the model is inclined at an inclination angle of +30°, the maximum normalized transverse response is smaller than that at an inclination angle of 0°. For wind incidence angle within ±7.5°, considerable normalized transverse response can always be observed for the case where the model is backward inclined to smooth wind condition, up to the tested maximum angle of +30°. However, when the model is forward inclined to the smooth wind condition, not only does the normalized transverse response of the tower decrease with the decreasing inclination angle, but so too does the range of wind incidence angles that can excite the tower to vibrate significantly. For the model backward inclined to turbulent wind condition, considerable normalized transverse response can be observed at wind incidence angle within ±5°. When the model is forward inclined to the turbulent wind, the normalized transverse response of the tower also decreases with the decreasing inclination angle but the range of wind incidence angles that can excite the tower to vibrate is almost unaffected. 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 in smooth flow condition at a wind incidence angle of 0°. The effect of inclination is thus considered to be an influencing factor affecting the transverse response of square-sectioned tower structures. The effect of turbulent will be further studied in another series of wind tunnel tests at higher reduced velocity.
Figure 4: Normalized transverse response of square tower model as a function of angle of incidence of mean wind for various angles of inclination angle in uniform smooth flow

Figure 5: Normalized transverse response of square tower model as a function of angle of incidence of mean wind for various angles of inclination angle in turbulence flow
Figure 6: Normalized transverse response of square tower model as a function of angle of incidence of mean wind for various angles of inclination angle in smooth and turbulence flows

The galloping response of a vertical square cylinder measured by Kwok and Melbourne (1980) are re-plotted in Figure 7 together with the current test results. It can be seen that the variation patterns of the galloping response with the wind incidence angle are remarkably similar. Some discrepancies between the two test results may be attributed to different surfaces and material of the models used in the tests as well as wind tunnel conditions.

Figure 7: Comparison to galloping response reported by Kwok & Melbourne (1980)

4.2 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 and various levels of structural damping are shown in Figures 8 and 9 for the smooth and turbulent flow conditions. 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 the occurrence of 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. To better quantify the effects of aerodynamic damping and wake excitation, the transverse force coefficients of an inclined cantilever structure were measured and the results are presented in Figure 10. The Reynolds number was about 36,200. It can be seen that for the case where the model is forward inclined at 10° in smooth wind condition, the estimated aerodynamic damping at a wind incidence angle of 0° is positive, which is about 0.10% of critical damping. At this angle of inclination, the combined aerodynamic damping and structural damping always results into a positive total damping but considerable normalized transverse response of the tower model can still be observed as shown in Figure 8(c). It is believed that this large transverse response is due to lock-in effect triggered by wake excitation. Similar observation was made by Kwok and Melbourne (1981). Another interesting phenomenon to note from Figure 10 is that the equivalent aerodynamic damping of the square tower model is significantly affected by the inclination angle to wind. The estimated aerodynamic damping decreases from 0.10% to -0.08% of critical damping when the inclination angle of the model is increased from -10° to +0° in smooth flow condition. The estimated aerodynamic damping is about -0.23% of critical damping when the inclination angle of the model is increased to +10° in smooth flow condition. The presence of a negative aerodynamic damping reduces significantly the total damping of the tower model and consequently the response due to the wake excitation is increased to a larger magnitude. The overall damping of the tower model is positive for the cases considered in Figure 8. Hence, under the influence of negative aerodynamic damping, the transverse response of the tower model backward inclined at 10° is generally larger than the other two cases for the same level of structural damping.

![Figure 8: Normalized transverse response of the square tower model as a function of angle of incidence of mean wind for various levels of structural damping](image-url)
SUMMARY

A wind tunnel investigation on the transverse response of a slender square tower model in a uniform smooth wind and turbulent flow conditions has been carried out. The test results indicate that the maximum normalized transverse response of tower model that is backward inclined to the approaching wind is much larger than that for a forward inclined model with the same magnitude of inclination. This is mainly attributed to the presence of negative aerodynamic damping for a
backward inclined model. For wind incidence angles within ±7.5°, considerable galloping response can always be observed for the case where the model is backward inclined to smooth flow condition. When the model was forward inclined to smooth flow condition, not only does the galloping response of the tower decrease with the decreasing inclination angle but so too does the range of wind incidence angle that can excite the tower to gallop. The effect of increase in free-stream turbulence decreases the galloping response of an inclined square sectioned structure. However, for the model backward inclined to turbulent wind condition, considerable normalized transverse response can be observed at wind incidence angle within ±5°. When the model is forward inclined to the turbulent wind, the normalized transverse response of the tower also decreases with the decreasing inclination angle but the range of wind incidence angles that can excite the tower to vibrate is almost unaffected. 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 galloping at zero angle of incidence. For the case where the model is forward inclined at 10° in smooth wind condition, the estimated aerodynamic damping at a wind incidence angle of 0° is positive, which is about 0.10% of critical damping and hence the total damping is always positive for the model forward inclined at 10° to smooth wind condition. At this particular angle of inclination, considerable normalized transverse response of the tower model can still be observed. This suggests that the response is due to lock-in effect and the effect of wake excitation is dominant even at a reduced velocity of 16.

ACKNOWLEDGEMENT

The financial support from The Hong Kong University of Science and Technology (HKUST) and CLP Power Wind/Wave Tunnel Facility of HKUST through a Postdoctoral Fellowship to the first author is sincerely acknowledged.

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