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The Effects of Freestream Turbulence on a Galloping Square Tower

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SUMMARY Experiments show that freestream turbulence has profound effects on the galloping behaviour of a square tower. It has been suggested that increase in freestream turbulence increases the turbulent mixing in the separated shear layers and the rate of entrainment from the wake, and decreases the radius of curvature of the shear layers. These effects significantly alter the transverse force characteristic and hence the galloping behaviour of the tower. It is also shown that fine scale turbulence produced by a thin rod upstream of the stagnation streamline of the tower is sufficient to cause these effects.

1 INTRODUCTION

Galloping is the term used to describe large amplitude single degree of freedom motions associated with a sectional aerodynamic force characteristic which produces a force in the direction of and in phase with the cross-wind motion. Preliminary tests were carried out on a slender square tower in turbulent boundary layer flow and with flow normal to one face, galloping was evident at high reduced velocities.

Further tests were conducted on the square tower under similar conditions in smooth flow and no galloping was observed. No immediate explanation could be found for such observations. Therefore, a more detailed investigation into the effects of freestream turbulence on the galloping behaviour of a slender square tower was carried out and the results are presented in this paper.

2 THEORY

If a square cross-sectioned body with sides b moves with a velocity dy/dt in a flow with a mean velocity $\overline{U}$ normal to one face, as shown in Figure 1, the aerodynamic force acting on the body in the direction of motion is

$$F_y = F_L \cos\alpha + F_D \sin\alpha \qquad (1)$$

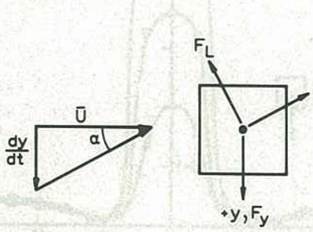

Figure 1 A square cross-section in flow

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

$$C_{Fy} = C_L \cos\alpha + C_D \sin\alpha \qquad (2)$$

in which C_{Fy} is defined as the transverse force coefficient. The term "transverse" is preferred in this context instead of "cross-wind" which is the direction normal to the mean wind. At zero angle of incidence, transverse is equivalent to cross-wind. The transverse force coefficient may be approximated by a polynominal as follows, (after Parkinson and Brook, 1961)

$$C_{Fy} = \sum_{i=1}^{n} A_i \alpha^i = \sum_{i=1}^{n} A_i \left(\frac{dy/dt}{\overline{U}}\right)^i \qquad (3)$$

A_i is the ith coefficient of the polynominal approximation. When the coefficient

$$A_1 = \left.\frac{dC_{Fy}}{d\alpha}\right|_{\alpha = 0^o} > 0 \qquad (4)$$

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 ζ_a.

For a vertical structure with a height h and constant cross-section, and is exposed to a turbulent boundary layer flow, as a first approximation in which nonlinearity is neglected, the equivalent aerodynamic damping for the complete structure is (after Vickery, 1975)

$$\zeta_a = -\frac{3\rho}{8\pi\rho_s(3+\gamma)} \cdot \frac{\overline{U}(h)}{n_o b} \cdot \frac{dC_{Fy}}{d\alpha} \qquad (5)$$

ρ is density of air. γ is the exponent of standard power law expression of longitudinal velocity profile. ρ_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 ζ_s, is zero or negative, the cross-wind response amplitude will grow until it reaches a steady magnitude governed by the nonlinearity of the aerodynamic damping. Even if the wind velocity and structural damping are such that the resultant damping is neither zero nor negative, the presence of a negative aerodynamic damping effectively reduces the total available damping of the structure. This results in an increase in response due to other excitations such as those associated with turbulence and the wake.

3 EXPERIMENTAL ARRANGEMENTS AND RESULTS

Experiments were carried out on a slender, very flexible square tower with a height to breadth ratio of 18 to 1 and an equivalent full scale height of about 200 m. The model used was pivoted at its base and being effectively rigid, had a straight line deflection mode. Strain gauge bridges were used to measure the overturning moment and transverse force on the model. The model was tested in the 2 m x 2 m working section of the Monash University, 400 kW Boundary Layer Wind Tunnel. Three types of flow were generated for these experiments, uniform smooth flow, turbulent boundary layer flow and rod-generated turbulent flow. In the latter case the background flow was similar to the uniform smooth flow but the turbulence near the stagnation streamline of the model was altered significantly by the placement of a thin rod upstream. The turbulence generated by the thin rod was relatively fine scale, with a longitudinal integral length scale of 0.016 m compared with an integral scale of turbulence of 0.27 m for the turbulent boundary layer flow.

Transverse response of the square tower at different angles of incidence of the mean wind in the uniform smooth flow, turbulent boundary layer flow and rod-generated turbulent flow are shown in Figures 2, 3 and 4 respectively. Transverse forces on the tower were also measured in the three types of flow and the transverse force coefficients are presented in Figure 5.

4 DISCUSSIONS

4.1 Galloping Response of a Slender Square Tower in Uniform Smooth Flow and Turbulent Boundary Layer Flow

For a square cross-sectioned body which is exposed to flow normal to one face, it has generally been concluded that the effect of increase in freestream turbulence is a progressive decrease in galloping response at a given wind speed (Novak and Davenport, 1970; Laneville and Parkinson, 1971; and others). However, measurements made in the present experiments at a reduced velocity of 48, as shown in Figures 2 and 3, show that while there was considerable galloping response in the turbulent boundary layer flow at zero angle of incidence, there was no galloping in the uniform smooth flow under similar conditions until the angle of incidence of the mean wind was about 9° from normal to one face.

It has been established earlier that aerodynamic force acting on the square tower is proportional to the slope of the transverse force coefficient versus angle of incidence of the mean wind. It is apparent in Figure 5 that at zero angle of incidence, the aerodynamic force resulting from the positive slope of the transverse force coefficient was sufficient to cause galloping in the turbulent boundary layer flow but not enough in the uniform smooth flow. It is not until the angle of incidence was about 9° that the positive slope of the transverse force coefficient was sufficient to cause galloping in the uniform smooth flow. The aerodynamic force can be quantified in the form of an equivalent aerodynamic damping, by using an approximated formula, equation 5, and these are listed in Figures 2 and 3. In the turbulent boundary layer flow, negative aerodynamic damping is the highest at zero angle of incidence at which considerable galloping response was observed when the resultant damping became negative. For similar conditions in the uniform smooth flow, the square tower was found to gallop readily at an angle of incidence of about 9° at which the negative aerodynamic damping is close to the maximum. It can be seen that at zero angle of incidence, the negative aerodynamic damping is significantly lower in the uniform smooth flow than for similar conditions in the turbulent boundary layer flow, and consequently, no galloping was observed in the uniform smooth flow.

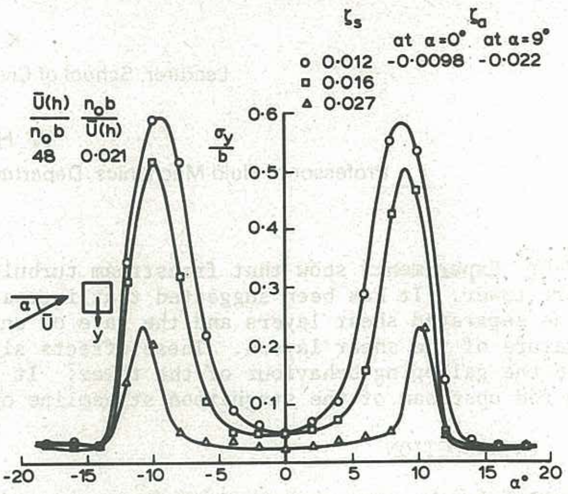

Figure 2 Transverse response of a square tower in uniform smooth flow

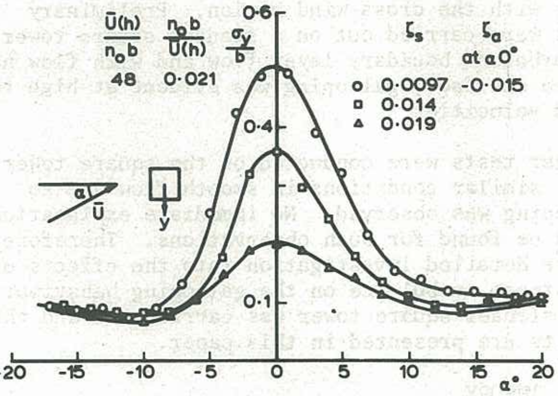

Figure 3 Transverse response of a square tower in turbulent boundary layer flow

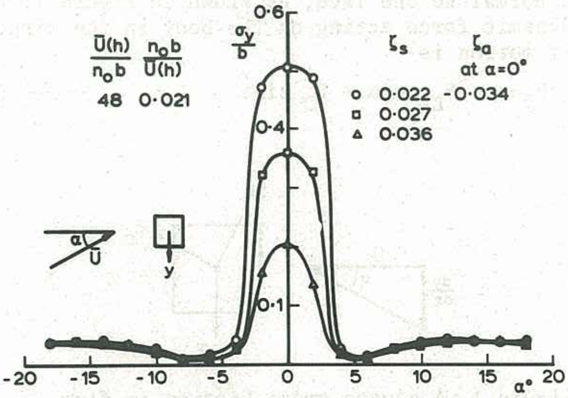

Figure 4 Transverse response of a square tower in rod-generated turbulent flow

It is interesting to examine the response of the square tower in the uniform smooth flow at a reduced velocity of 16, as shown in Figure 6. It is evident that the large galloping response at zero angle of incidence is consistent with the estimated negative aerodynamic damping which at -0.33% is higher than the structural damping at 0.22%. However, the considerable response observed at a structural damping of 0.48% is contrary to the criterion that the resultant damping equals or is less than zero for galloping to occur. It is believed that this large response was initiated by wake excitation. For a square tower, wake excitation has been shown to be most intense at a critical reduced velocity of about 10 and is still significant at a reduced velocity of 16. The presence of a negative aerodynamic damping reduces significantly the total damping of the square tower. Consequently, the response due to wake excitation was increased to a significantly larger magnitude. Assuming the motion of the tower is sinusoidal, the maximum effective angle of incidence due to the motion was estimated to be about 12° and 19° at a structural damping of 0.48% and 0.22% respectively. These angles of incidence are well into the range in which the maximum positive slope of the transverse force coefficient is contained, as shown in Figure 5. It is therefore concluded that at a damping of 0.48%, the tower was assisted by a more substantial aerodynamic force associated with galloping during part of the cyclic motion and was able to maintain a relatively large response which would not have been possible otherwise. The large galloping response at a damping of 0.22% is also believed to be partly due to this effect.

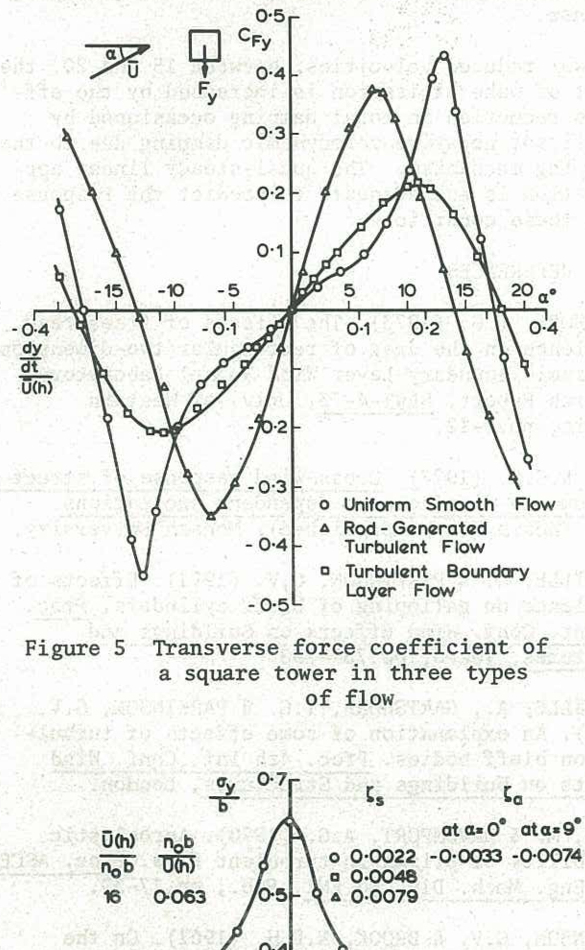

Figure 5 Transverse force coefficient of a square tower in three types of flow

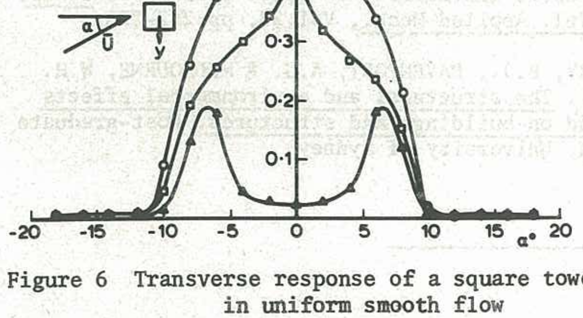

Figure 6 Transverse response of a square tower in uniform smooth flow

Observation made here supports the general belief that quasi-steady approach to galloping is valid only at very high reduced velocities. In operating conditions where other excitations, such as wake excitation, are present, galloping behaviour of a structure can be significantly altered and a quasi-steady approach becomes unacceptable (Kwok, 1977).

4.2 Effects of Freestream Turbulence on the Transverse Force Coefficient Characteristic of a Square Tower

Gartshore (1973) suggested that the effect of increasing freestream turbulence is to increase the turbulent mixing in the shear layers and hence to increase the rate of entrainment of fluid for the wake and decrease the radius of curvature of the shear layers. It was suggested that the decrease in the radius of curvature of the separated shear layers induces earlier reattachment of the shear layers, and this was employed to explain the effects of freestream turbulence on the drag and base pressure coefficient of bluff bodies. Using this physical mechanism, Gartshore (1973) and later Laneville, Gartshore and Parkinson (1975) suggested that the effects of freestream turbulence on galloping are also caused by the earlier reattachment of the separated shear layers to the windward face of the bluff body.

It was further suggested by Gartshore (1973) that fine scale turbulence upstream of a bluff body's stagnation streamline is particularly important in the entrainment process described above. Experiments conducted on square and rectangular prisms showed that only the fine scale turbulence along the stagnation streamline of the body, produced by the placement of a thin rod upstream of the body, was required to produce all the major effects of freestream turbulence on the drag and base pressure coefficient.

It is possible to explain the effects of freestream turbulence on the transverse force coefficient characteristic shown in Figure 5 and the subsequent galloping behaviour of the square tower in terms of the increase in entrainment described above. Sketches of expected streamlines around the square tower in low freestream turbulent flow and in high freestream turbulent flow are shown in Figure 7. Only the mean streamlines are used in these sketches. At small angles of incidence, as sketched in Figure 7b, positive transverse force occurs when there is a partial reattachment of the shear layer on the windward face of the tower, although vortex shedding does make reattachment intermittent. Since increase in freestream turbulence increases the rate of entrainment from the wake and decreases the radius of curvature of the shear layers, more substantial reattachment and hence higher transverse force are expected in high freestream turbulence flow than in low freestream turbulence flow. This is believed to cause a higher transverse force coefficient in the turbulent boundary layer flow than in the uniform smooth flow at small angles of incidence. Maximum transverse force is expected to occur when reattachment at the trailing edge of the windward face becomes permanent. Therefore by using the same argument as before, maximum transverse force is expected to occur at an angle of incidence which is smaller in the high freestream turbulence flow than in low freestream turbulence flow, as shown in Figures 7c and 7d. Although earlier permanent reattachment is evident in the turbulent boundary layer flow, the corresponding maximum transverse force coefficient is, as shown in Figure 5, significantly smaller than in the uniform smooth flow. This appears to be largely due to the presence of both a velocity profile and a turbulence intensity profile in the turbulent boundary layer flow.

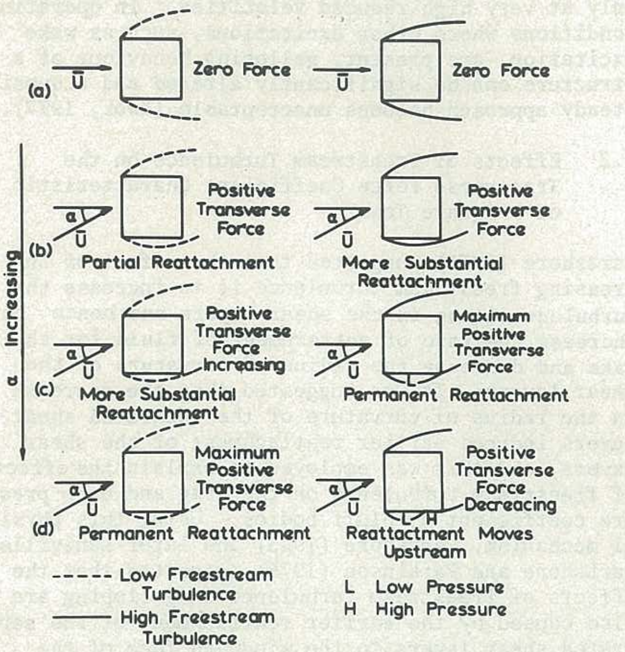

Figure 7 Sketches of expected effect of freestream turbulence on separated streamlines and transverse force of a square section

With the square tower in the rod-generated turbulent flow, maximum positive slope of transverse force coefficient and maximum galloping response were recorded at zero angle of incidence, as shown in Figures 4 and 5. In comparison with measurements made in the uniform smooth flow, the transverse force coefficient increases markedly at small angles of incidence and is at a maximum at a smaller angle of incidence. It is important to note that the placement of the thin rod upstream of the tower introduces fine scale turbulence only along the stagnation streamline of the tower and the background flow is identical to that in the uniform smooth flow. It can be seen that this is sufficient to alter significantly the transverse force coefficient characteristic and the galloping behaviour of the tower. The addition of fine scale turbulence near the stagnation streamline increases the rate of entrainment from the wake and decreases the radius of curvature of the shear layers. Therefore at small angles of incidence, more substantial reattachment and hence higher transverse force coefficient was recorded in the rod-generated turbulent flow than in the uniform smooth flow. Similarly, maximum transverse force coefficient associated with permanent reattachment at the trailing edge of the windward face of the tower occurred at an angle of incidence which is smaller in the rod-generated turbulent flow than in the uniform smooth flow. It is evident, at least qualitatively, that the fine scale turbulence along the stagnation streamline of the square tower has a similar effect on the transverse force coefficient characteristic and galloping behaviour as observed in the turbulent boundary layer flow.

Measurements made by Gartshore (1973) have already shown that only the fine scale turbulence approaching a bluff body along its front stagnation streamline is required to produce the major effects of freestream turbulence on the drag and the base pressure coefficient of square and rectangular prisms. Results of the present experiments indicate quite clearly that this is also significant in altering the galloping behaviour of a square tower. The existing data therefore suggests that only the the fine scale turbulence along the stagnation streamline of a bluff body is required to produce all the major effects of freestream turbulence on the flow around the body.

5 CONCLUSIONS

Increase in freestream turbulence increases the turbulent mixing in the separated shear layers and the rate of entrainment from the wake, and decreases the radius of curvature of the shear layers. These effects significantly alter the transverse force characteristic and hence the galloping behaviour of a square tower. Only the fine scale turbulence along the stagnation streamline of the tower is required to produce these effects.

At high reduced velocities, greater than 20, a quasi-steady linear approximation of the aerodynamic force associated with the transverse force characteristic is acceptable as an indication of possible galloping instability, although this generally leads to conservative estimations of the galloping response.

At lower reduced velocities, between 15 and 20, the effect of wake excitation is increased by the effective reduction in total damping occasioned by significant negative aerodynamic damping due to the galloping mechanism. The quasi-steady linear approximation is not adequate to predict the response under these conditions.

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