Background and Resonant Response of a Canopy due to Wind Action

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Abstract

The response of a cantilevered canopy to wind action can be seen as a combination of a low frequency background response onto which a beam resonant component is superimposed. The low frequency response is primarily driven in a quasi-steady manner by the fluctuating pressure distribution under the reattaching shear layer shed from the leading edge. The high frequency response from the resonant component is due to the inertial load distribution of the cantilever. This paper examines the relative contributions of the background and resonant response components to the total wind induced response of a canopy of different first mode frequencies.

Reference has also been made to the implications given by the Australian Wind Loading Code for crosswind design loads for canopies. The present data have been reduced to 1% damping and presented in terms of an equivalent triangular load distribution as a function of reduced velocity for various canopy frequencies.

1. Introduction

As the design for a cantilevered canopy such as a grandstand roof has been developed for increasing span, the structural frequency decreases and the structure becomes more sensitive to wind action. Although the Australian Wind Loading Code [1] speculates the dynamic interaction of the wind and structure having a first mode frequency of vibration of less than 1Hz, the effect of the structural frequency to the total response of the structure to the wind energy spectrum is very complicated. A description of the wind loading process on cantilevered roofs is given by Melbourne and Cheung [2] as the combined effects of the pressure driven low frequency response and the high frequency resonant response. The total response due to various configuration changes has been reviewed by Melbourne [3] for many large roof systems. But the relative contribution of these two responses as structural frequency changes has rarely been studied in detail. A Mechanical Engineering Final Year Project [4] has been set up in 1999 to investigate the magnitude of these contributions and its implications to the design loads given by the Australian Wind Loading Code. However, the study was carried out in the 30kW wind tunnel in a low turbulence wind model with turbulence intensity of 0.12 at the top of the model. Also due to the short time allocation for the project, very limited amount of data has been available to define the significance of the frequency changes to the response. Subsequently the model was modified and used in the present study in a suburban terrain wind model in the 450 kW wind tunnel at Monash University.

2. The experimental set-up

The canopy model consists of a base cantilever aluminum plate 1mm thick, 240mm wide and 30mm long in span fixed with araldite and bolted onto the top of a box 240mm by 170mm by 100mm high. Five additional plates were used to extend the canopy to various cantilever spans. For some plate configurations, additional mass was added to the plate to further vary the structural frequency for the study. Strain gauges were installed in the middle at the base of the cantilever and calibrated against moments applied to the canopy. The strain gauge outputs were low-pass and high-pass filtered 10% below the structural frequency to separate the background and the resonant response. The whole box and canopy set-up was installed in the centre of the 4m diameter turntable in the 2m working section of the wind tunnel. The structural frequency of the canopy model for various configurations in cantilever span length is given as follows:

Canopy	span ℓ (mm)	frequency n (Hz)	damping	Canopy	span ℓ (mm)	frequency n (Hz)	damping
× A	30	700	0.0103	○ Fd0	100	78	0.0180
+ B	32.5	388	0.0188	● Fd1	100	78	0.0220
□ C	40	341	0.0215	× Fd2	100	78	0.0310
■ C1	40	282	0.0190	△ F1	100	40.3	0.0110
◇ D	55	227	0.0170	◇ F2	100	29.3	0.0170
◆ D1	55	178	0.0140	□ F3d0	100	17.2	0.0200
△ E	75	139	0.0150	■ F3d1	100	17.2	0.0440
▲ E1	75	108	0.0170	× F3d2	100	17.2	0.0710

The canopy model was tested in a boundary layer flow developed with floor roughness elements and vorticity generators in the wind tunnel. The mean wind speed varied with height in terms of power law with an exponent of 0.18 and the longitudinal turbulence intensity was 0.22 at 100mm, the height of the canopy model. This wind model simulates a 1/150 scale model of the natural wind flow over suburban terrain. Mean, standard deviation, minimum and maximum moments were recorded for a sampling period of 40 seconds as a function of wind speed for the different canopy configurations. The experimental data are expressed in coefficient form in terms of the peak design triangular load distribution defined by the pressure Q at the leading edge of the canopy.

$$C_Q = \frac{Q}{\frac{1}{2}\rho \overline{V}_h^2}$$

where h is the height of the leading edge of the canopy
ρ is the air density and
$\overline{V}_h$ is the mean wind speed at the top of the canopy.

3. Results and discussions

Measurements from the damping runs have shown that the standard deviation coefficient varies with damping to a power of –0.1 and –0.5 for the background and the resonant component of the response respectively. All data presented are corrected for damping to 1%. Mean, maximum (downward acting) and minimum (upward acting) coefficients C_Q are plotted as a function of reduced velocity $V_h/n\ell$ in Figure 1 and for the lower velocity range, in Figure 2. The equations given in AS1170 Clause 4.4.4 are also shown graphically for comparison. As the Code equations are given for full scale structures typically with damping 1.5 to 2%, the equations corrected to 1% damping are also plotted as shown dotted. The Code equations are generally in good agreement with the present measurements except that at low reduced velocities below 1, the experimental data are seen to be higher.

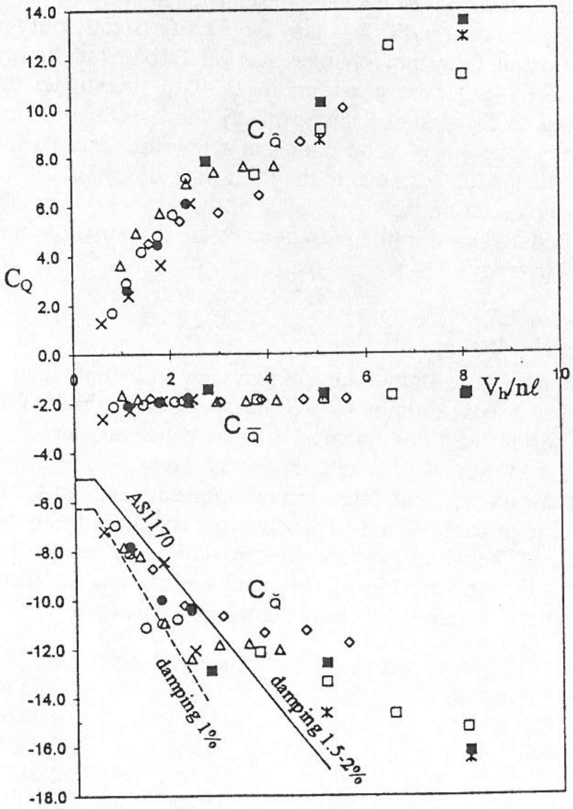

Fig. 1 Mean, maximum (downward acting) and minimum (upward acting) coefficients C_Q for the high reduced velocity range

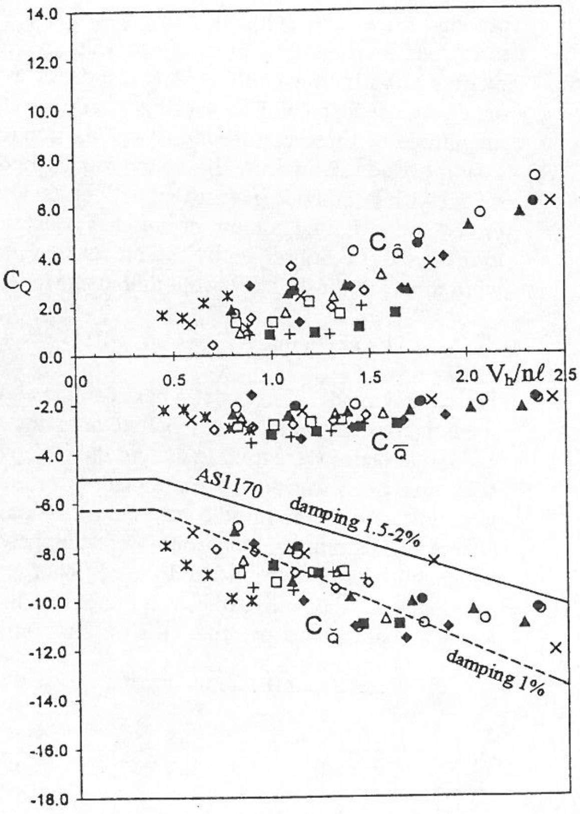

Fig. 2 Mean, maximum (downward acting) and minimum (upward acting) coefficients C_Q for the low reduced velocity range

The low-pass and high-pass filtered standard deviation coefficients for the background and the resonant components respectively are plotted in Figures 3 and 4. The background component increases but the resonant component decreases as the structural frequency increases. It can be seen from the wind energy spectrum that at the high frequency end the wind energy to excite the structure is relatively lower and thus the resonant component of the response spectrum would become smaller. For the background component, however, the excitation mechanism is quite different. For the stiffer structure with higher structural frequency, the vortex shedding process at the leading edge of the canopy is more enhanced and thus more energy would be available under the reattaching shear layer. Hence the background component primarily driven by this fluctuating pressure distribution is seen to increase.

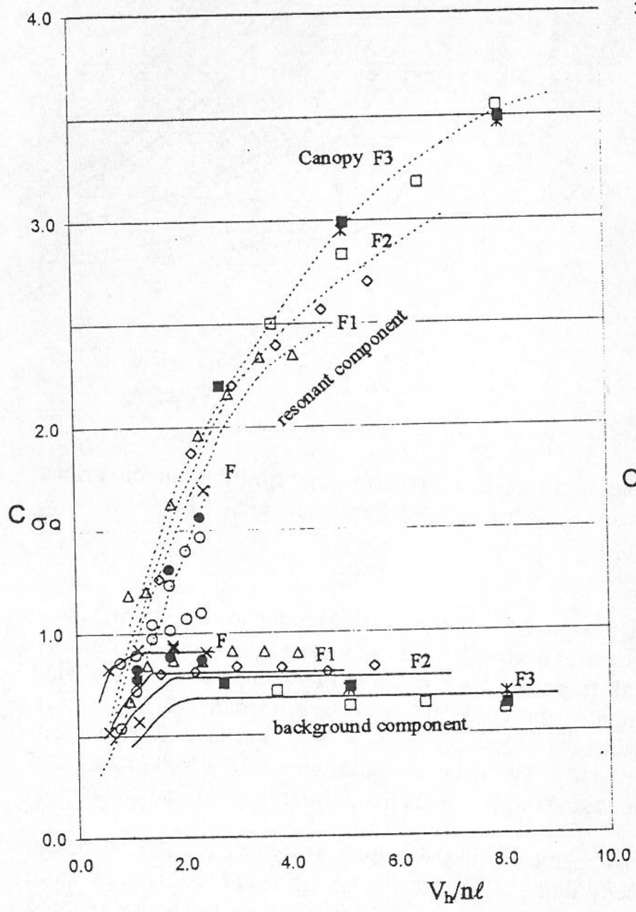

Fig. 3 Low-pass and high-pass standard deviation coefficients C_Q for the high reduced velocity range

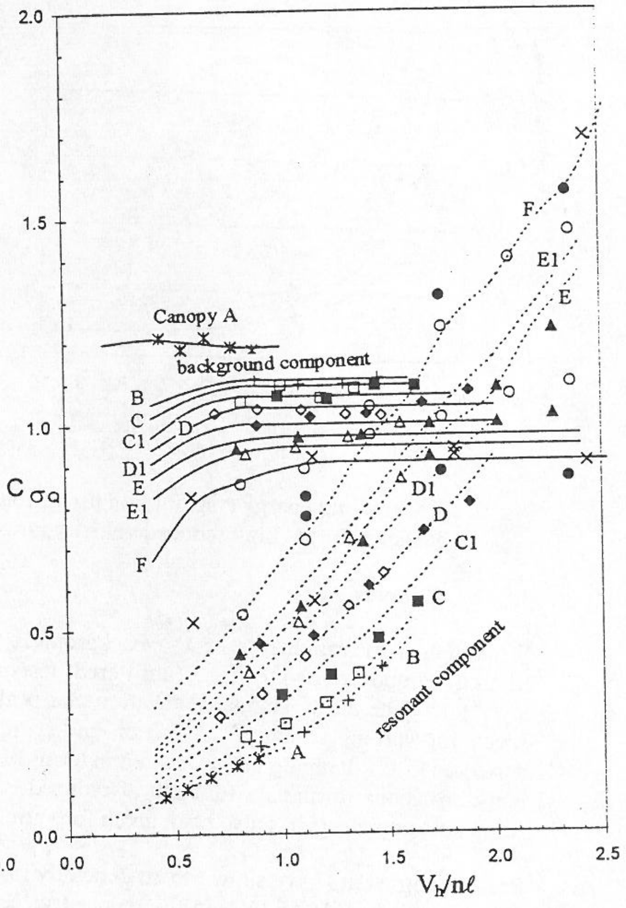

Fig. 4 Low-pass and high-pass standard deviation coefficients C_Q for the low reduced velocity range

The relative contribution of the background and resonant energy to the total response energy can be seen in the plot of the squared ratio of the background to total standard deviation coefficient as a function of reduced velocity for various structural frequencies. As shown in Figure 5, the background contribution decreases as the structural frequency decreases, at a faster rate than inversely proportional. Since most full-scale structures are designed for the lower reduced velocity range, the background contribution curves are expanded for reduced velocities below 2.5 as shown in Figure 6. The velocity ratio used in the present study is approximately between 1:3 to 1:2 in general. For the length scale of 1/150, the frequency scale thus becomes approximately 60:1. Hence, graphs can be drawn in Figure 6 to indicate the approximate full-scale structural frequency range. For reduced velocities below 2.5 and full-scale frequencies above 5Hz, the background energy contribution is always over 50%. For full-scale frequencies below 1Hz at a reduced velocity of 2.5, the background energy contribution is just below 0.25, i.e. the background component coefficient would be less than half of the standard deviation coefficient of the total response. AS1170 currently requires the dynamic analysis procedure to be used in the design of structures having a first mode frequency of less than 1 Hz.

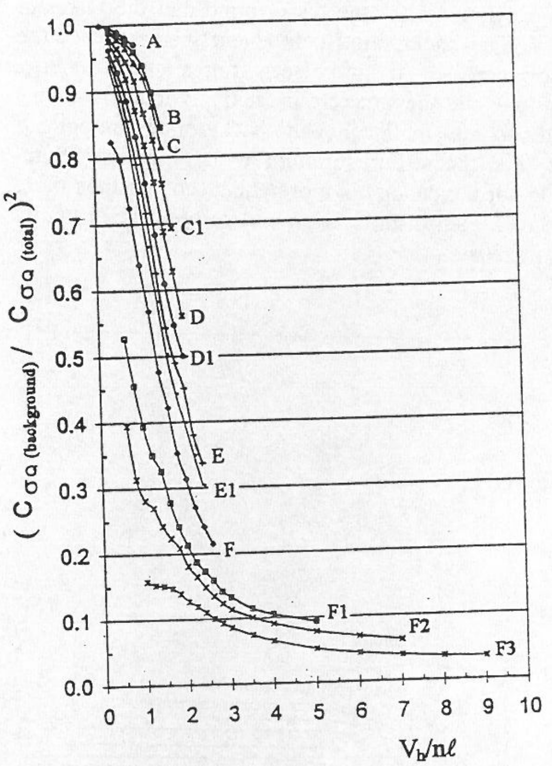

Fig. 5 Background energy contribution for various frequencies for the high reduced velocity range

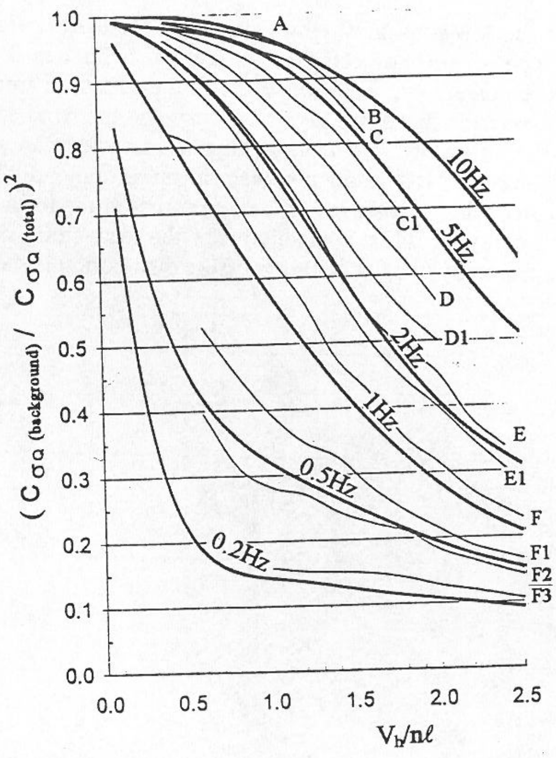

Fig. 6 Background energy contribution for various frequencies for the low reduced velocity range

4. Conclusions

Wind tunnel measurements of the background (low-pass filtered) component, the resonant (high-pass filtered) component and the total (unfiltered) response of a canopy have been made in a turbulent boundary layer flow. The mean, standard deviation and peak responses were measured as a function of mean wind speed for various structural frequency and damping configurations. The experimental data have been corrected to 1% damping and presented in terms of an equivalent peak design triangular load distribution in non-dimensional form as a function of reduced velocity. The relative contribution of the background and resonant components has also been given for various structural frequencies at different reduced velocities.

Peak response data have shown to be generally in agreement with the design values given in the Australian Wind Loading Code AS1170 in the reduced velocity range of 1 to 2. The experimental results are seen to be higher for reduced velocities below 1 and to be lower for reduced velocities above 1. The background component of the response decreases as the structural frequency decreases, but remains constant for the range of reduced velocity. The resonant component increases with reduced velocity as well as with structural frequency at constant reduced velocity. Results have shown that for reduced velocities below 2.5, the background energy contribution dominates when the structural frequency is above 5Hz.

References

[1] Australian Wind Loading Code, AS1170.2-1989, Published by Standards Australia.

[2] W.H. Melbourne and J.C.K. Cheung, Reducing the wind loading on large cantilevered roofs, J. Wind Eng. Ind. Aerodynamics. 28 (1988) 401-410.

[3] W.H. Melbourne, The response of large roofs to wind action, J. Wind Eng. Ind. Aerodynamics. 54/55 (1995) 325-335.

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