The Effect of Vibrating Leading Edge Flaps on the Lift on a Square Prism

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ABSTRACT

This paper presents and discusses the results of a rigid pressure model test of a square prism with leading edge vibrating flaps. The results showed that the fluctuating lift on a square prism decreases by up to 70% by vibrating the leading edge flaps. Frequency domain analysis showed that the flaps have 2 effects on the flow that account for the reduction in the cross wind force.

INTRODUCTION

Ever since the problem of dynamic response of buildings was recognised by structural engineers, numerous ways of tackling it have been proposed. Tuned mass dampers [1] and sloshing dampers [2] and their derivatives [1, 3, 4] are the more classic ways of vibration control and utilise only mechanical mechanisms. On the other hand building shapes [5], corner modifications [6], horizontal or vertical slots [6, 7], moving boundary layer control [8], and other aerodynamic appendages [9] are relatively new ways to counter the problem by means of excitation control.

This paper outlines an experimental study on the effects of vibrating leading edge flaps, similar to the ones described by Mizota and Okajima [10], on the cross-wind excitation of a rigid 2D square prism pressure model. Effects of flap frequency and amplitude angle are discussed.

EXPERIMENTAL STUDY

Rigid Pressure Model

In the wind tunnel experiments a rigid 2D square prism pressure model was used. The model had dimensions of 200mm x 200mm x 1000mm. A circular end-plate of diameter 2m was located at each end of the model in order to make the approaching flow two dimensional. The edge of the end-plate was rounded to minimise boundary layer growth on the end-plate due to initial separation. The size of end-plates, necessary for 2D bluff body model tests, was chosen by following the recommendations of Kubo[11]. Each of the side walls was populated with 20 pressure taps in 5 stream-wise locations with the four pressure taps at each stream-wise location manifolded together using a 4 to 1 pressure manifold. Pneumatically averaged pressures on the opposite faces of the model were connected to the opposite sides of pressure transducers, enabling the measurement of cross-wind differential pressures on the model. More detail can be found in [12]. The distribution of the pressure taps is shown in Fig. 1.

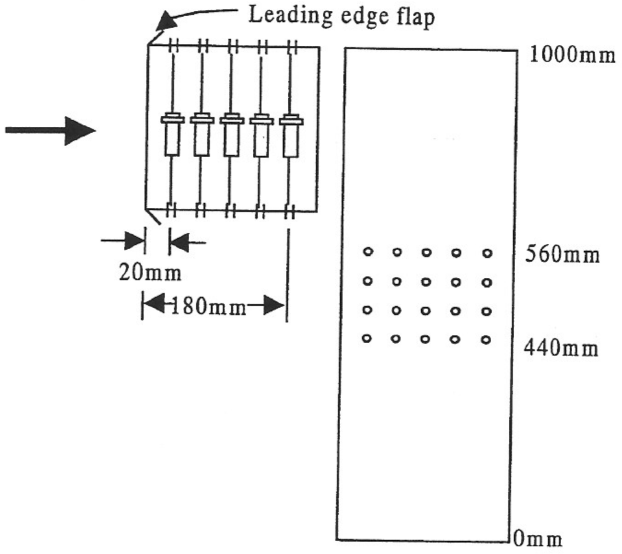

Figure 1 Distribution of pressure taps on the model

The flaps were designed to vibrate about the two leading edge corners of the model where flow separation occurs. They were hinged along these corners. The flapping motion was sinusoidal and was driven by two high frequency linear actuators for a range of frequencies, amplitudes and mean angles. The length of the flaps is believed to play an important role, and while a large chord is believed to have a more significant effect on cross-wind excitation, for practical reasons it is not desirable. The authors chose a flap length of 10% of the model width for this study, a size which was judged to be a good compromise between the two conflicting criteria.

Wind Tunnel Configuration

The pressure model was situated in the middle of a 3m x 6m open jet Twisted Flow Wind Tunnel at The University of Auckland. The twisting vanes were removed and inserts were used to reduce the jet to 3m x 3m during this study. The Reynolds number was kept constant at 1×10^5 throughout the study. Uniformity of the mean flow speed and turbulence intensity were checked using a hot-wire probe.

Data Collection

Pressure data were collected using 5 scanivalve pressure transducers via the manifolded tubing system described. Sixty-four blocks of 8192 pressure samples per channel were collected at 400 Hz. The gain of the overall tubing system was within 10% of unity up to 200Hz and the phase shift was linear up to 250Hz. Details of the response of the tubing system can be found in Li et al [12]. Electrical signals were amplified and low-pass filtered at 200Hz and then digitised using a 12-bit analogue-to-digital converter in a PC for later processing.

Wind Tunnel Tests

Wind tunnel tests were carried out to investigate the effect of flap vibrational parameters on the cross-wind forces developed on a 2D square prism. Details of each test are shown in Table 1 and the definitions of each parameter are illustrated in Fig. 2. These parameters were chosen as it covered the range of interest while within the limitation of the equipment. To limit the number of variables and to provide a base-case, the flow in the wind tunnel was smooth and angle of attack was kept at 0 degrees. Only the flap vibrational parameters such as flap reduced frequency, defined using the flap vibrational frequency, the model width, and the mean flow speed, and amplitude were varied in the study described herein. The flaps were worked in pairs throughout the experiment; when one flap swung outward, the other retracted, and vice versa, hence giving a 180 degree phase difference between the two flaps.

Post Processing

This study focused mainly on the frequency domain analysis of the pressure fluctuations on the sidewalls of the model, although the pressure data were analysed in both the time and frequency domains.

Means and variances of the pressures were calculated and presented in dimensionless coefficient form. They were also combined across different channels to give unsteady cross-wind force coefficients. Results from testing different wind tunnel and vibration parameters were compared.

In the frequency domain analysis, individual power spectra of the 64 blocks of time series data were calculated using normal FFT procedures and then averaged together. Ensemble averaging with varying ensemble sizes was performed as described in a previous study [12]. The effects of vibrational parameters on force and pressure coefficients in different frequency bands were investigated.

Table 1 Flap parameters

Data set	Flap reduced frequency	Amplitude (deg)	Phase angle between flaps (deg)	Mean angle (deg)
1	No flap			
2	0	0	-	35
3	0.20	2.8	180	35
4	0.27	2.8	180	35
5	0.68	2.8	180	35
6	0.85	2.8	180	35
7	1.00	2.8	180	35
8	1.14	2.8	180	35
9	1.29	2.8	180	35
10	1.29	2.8	180	45
11	1.29	2.8	180	40
12	1.29	2.8	180	37.5
13	0.48	2.8	180	45
14	0.48	4.2	180	45
15	0.48	5.7	180	45
16	0.48	7.0	180	45
17	0	0	-	45

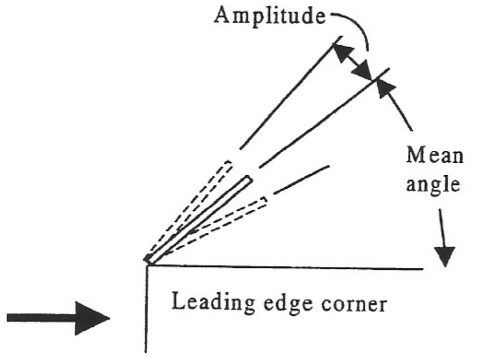

Figure 2 Definitions of vibrating flap parameters

RESULTS AND DISCUSSION

Time Domain Analysis

Fig. 3 contains the standard deviation of the side-force coefficient, C_{Lrms}, measured from data set 1-9. It shows the effect of flap vibrational frequency on the unsteady lift coefficient of the square prism at a mean flap angle of 35 degrees and with a relatively small flap amplitude. In this figure C_{Lrms} from data set 1 and 2 were both 1.26 and appear in the plot as 1 point. Data set 1 represents a plain square model while data set 2 corresponds to a square model with stationary flaps at 35 degrees. The value of 1.26 is within the range of other measured values [13, 14, 15]. As the reduced flap frequency increases from 0 to 1.29, the unsteady lift coefficient reduces by slightly more than 30% from 1.26 to 0.86.

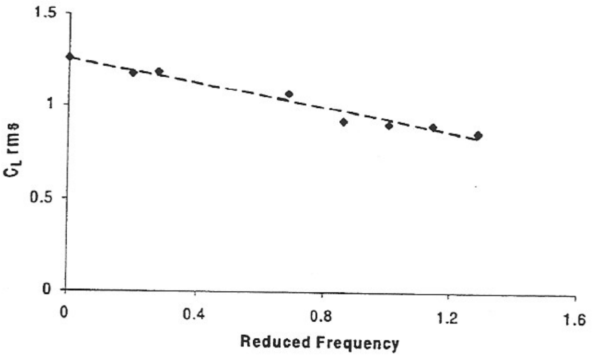

Figure 3 Variation of $C_{L\ rms}$ with flap frequency

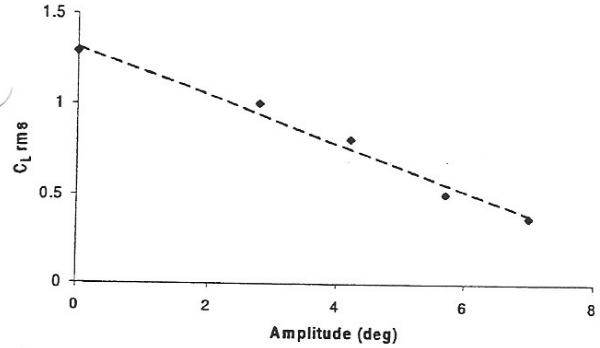

Figure 4 Variation of $C_{L\ rms}$ with flap amplitude

Fig. 4 shows C_{Lrms} for data sets 13-17 where the flap reduced frequency and mean angle were kept constant at 0.48 and 45° respectively. As the flap amplitude increases from 0 to 7 degrees, the unsteady lift on the model decreases almost linearly from 1.29 to 0.38.

Frequency Domain Analysis

Fig. 5 shows the power spectra of data set 2 and 9. The reduced frequency on the horizontal axis is defined using the frequency from spectral analysis, model width, and mean flow speed. The Strouhal number of both data sets was 0.126. Despite of differences in $C_{L\ rms}$, both spectra showed 95% of the total energy between reduced frequencies of 0.11 and 0.14. Hence in small amplitude conditions, flap frequency seems to have similar effect on all frequency components.

Fig. 6 shows the power spectra of data sets 13-16. The Strouhal number of these data varied from 0.120 to 0.124. For a reduced flap frequency of 0.48, increasing the vibrational amplitude from 2.8 to 7 degrees gradually decreases the energy in the reduced frequency band between 0.11 and 0.14, from 89% to 57%. Hence in contrast to the effect of flap frequency, flap amplitude tends to affect the vortex shedding process more than other frequency bands.

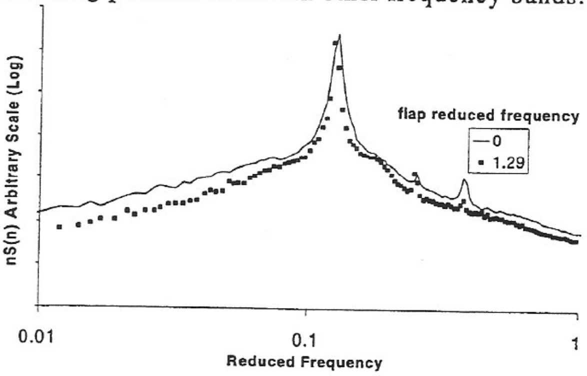

Figure 5 Effect of flap reduced frequency on cross wind force spectra

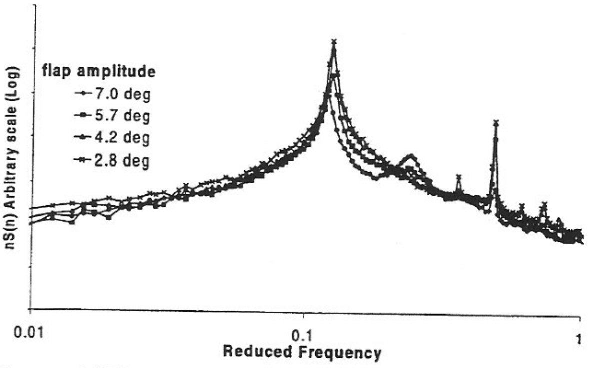

Figure 6 Effect of flap amplitude on cross wind force spectra

DISCUSSION

The above observations suggested that the vibrating leading edge flaps had two effects on the fluctuating lift force on a square prism. First the vibrating flaps introduce a pressure/force fluctuation at the flap operating frequency. This effect was first discussed by Mizota and Okajima[10]. They described the effect of the flaps as if the model itself is vibrating in a heaving mode. This effect was later explored by Gupta et al[16] for vibration control. A series of peaks corresponding to the flapping motion can be clearly seen in fig 6. The size of the peaks in Fig 6 increased as the flapping amplitude increased.

The first effect alone would not lead to the decrease in fluctuating lift as shown in Fig 3 and 4. A normalised co-spectra plot (not shown herein due to space constraint) of individual pressures showed distinct similarities in the low frequency region between high amplitude flapping results and the moderately turbulent flow results from the previous study[12], showing a tendency of early reattachment when the flaps are active.

It is suggested that the second effect of the vibrating flaps are to make the pressure fluctuation as if it is in a more turbulent environment. The velocity fluctuations introduced at the flap tips work as small-scale turbulence and change the characteristics of the shear layers. It decreases the radius of curvature of the shear layers, hence promoting earlier reattachment of shear layers as suggested in the normalized co-spectra results, and decreasing excitation forces in Fig 3 and 4.

Gartshore[17] explained the galloping of rectangular sections qualitatively and demonstrated the effect of small-scale turbulence on their stability. Using only 1 vibrating flap, this idea can be extended to verify the ability of the flap to change the shear layer characteristics. Preliminary tests with only one flap active showed a mean lift coefficient of magnitude 0.5-0.7 at zero incidence. The sign of the mean lift coefficient in all the tests indicated a lower pressure on the side with the active flap, which is consistent with the theory above.

CONCLUSIONS

For a square prism with vibrating leading edge flaps:

1. Increasing the reduced frequency of the vibrating flaps from 0 to 1.29 reduced C_{Lrms}, by more than 30%.
2. Increasing the vibrational amplitudes from 0 to 7 degrees reduced C_{Lrms}, by up to 70%
3. Reduction in unsteady cross-wind force with increase in flapping frequency was achieved by weakening the pressure fluctuations over a broad frequency band. Increasing flap frequency seems to have a similar effect for pressure fluctuations at all frequencies.
4. Reduction in unsteady cross-wind force with increase in flap amplitude was caused mainly by weakening of the pressure fluctuations around the shedding frequency. Hence it is believed that large flap amplitudes disrupt the vortex shedding process.

The results suggest that the vibrating flaps introduce a pressure fluctuation at the flapping frequency, and change the characteristics of the shear layer as if the oncoming flow is more turbulent.

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