TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

15B-3

MEASUREMENTS OF COEFFICIENTS OF LIFT AND SPANWISE CORRELATION FOR A CIRCULAR CYLINDER OSCILLATING IN A TURBULENT FLOW

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ABSTRACT

For structures such as chimney stacks in the atmospheric boundary layer, measurements of cross-flow aerodynamic forces at high Reynolds Numbers and low response amplitudes are needed before more accurate models for structural response can be developed.

A prediction technique has been developed for the measurement of cross-flow forces acting on six short sections of a cylinder undergoing forced sinusoidal oscillations in a wind tunnel. Aerodynamic lift forces measured using this technique are decomposed into terms corresponding to aerodynamic damping, added mass and a residual random component. These measurements can then be used in the prediction of structural response.

Measurements of lift forces from a cylinder oscillating in a turbulent flow of 4% intensity at a Reynolds Number of 1.7×10^5 are presented. Oscillation amplitudes vary up to 3% of diameter and Reduced Velocity between 4 and 6. The results indicate that varying the oscillation amplitude and Reduced Velocity in this range has an effect on aerodynamic damping but that the residual forces are unaffected by the motion, both locally at each measurement position and in spanwise correlation.

INTRODUCTION

The prediction of cross-flow response of slender circular cylindrical structures to vortex shedding is still a relatively inaccurate process. This is due partly to a lack of understanding of the vortex shedding process itself and in particular the interaction of structural and fluid oscillations and also a lack of measurements of critical aerodynamic data.

When the amplitude of structural oscillation is very small the structural response is of a narrow banded random nature and prediction of response amplitudes may be carried out using random vibration techniques such as those presented by Vickery and Clark (1972). As the oscillations of the structure increase in amplitude, particularly when the structural frequencies and vortex shedding frequencies coincide, there is an interaction between the structural and fluid oscillations and the aerodynamic forces can increase dramatically. Data presented by Jones (1968) and Sarpkaya (1978), have shown that this interaction can occur in smooth flows at amplitudes of a few percent of diameter.

If the relative mass and structural damping of the structure are very low the cross-flow amplitudes can become of the same order as the cylinder diameter and the response timeseries becomes very narrow-banded, approaching a sinusoidal waveform. In this case Sarpkaya (1978) suggested that the response parameter Sg may be used to derive an estimate of the response amplitude.

In the middle ground where the response amplitudes are small and the fluid forces and structural response are still of a random nature but there is significant interaction between the flow and structural oscillations, comparatively few engineering models exist that enable the prediction of response amplitudes. One significant model for this regime is that provided by Vickery and Basu (1983), which is essentially that of Vickery and Clark (1972) but altered to include an aerodynamic damping term which depends non-linearly on response amplitude, however at low amplitudes the effect is predominantly linear. Inherent in this model is the assumption that the interaction between the structural and fluid motion is entirely incorporated in the aerodynamic damping term, which implies motion-dependent forces which are fully correlated in the spanwise direction. The remaining aerodynamic forces producing random structural vibration are supposed to be unaffected by the structural response amplitude.

In order to investigate the influence of cross-flow oscillation on aerodynamic forces due to vortex shedding, a wind-tunnel model was manufactured which enables forces to be measured simultaneously at several sections of a circular cylinder while the cylinder is forced to oscillate in a cross-flow direction. From the recorded timeseries of forces estimates of aerodynamic damping and mass can be extracted by correlating aerodynamic forces with the velocity and acceleration of the structure, leaving forces which are uncorrelated with cylinder motion.

In this paper experimental results are presented which demonstrate negative aerodynamic damping at vibration amplitudes of 3% of diameter and below at a Reynolds Number just at the start of the critical regime in a turbulent flow of 4% streamwise intensity. The parts of aerodynamic force which are uncorrelated with the motion of the cylinder are shown to be unaffected by the motion, both locally and in spanwise correlation.

EXPERIMENTAL TECHNIQUE

A sketch showing the general arrangement of the wind tunnel model is presented in Figure 1. The cylinder is 200mm diameter with an aspect ratio of 4.5. There are six force measurement transducers each supporting a section of cylinder 0.1 diameter long, spaced equally along the cylinder axis with a spacing of 0.75 diameter. Narrow air-gaps between the sections of cylinder are sealed with thin polyurethane elastomer. To mount the cylinder sections each transducer contains four beam springs with bonded semi-conductor strain gauges. The beams are aligned so that cross-flow forces induce bending stresses in the springs. An accelerometer which measures cross-flow acceleration is also contained at each transducer station. The cylinder can be forced to oscillate in a direction normal to the flow by an electromagnetic shaker at a maximum amplitude of 3% of diameter (6% peak-to-peak).

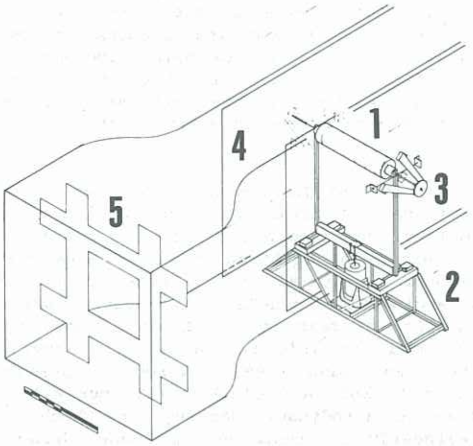

Figure 1 Sketch of cylinder installed in wind tunnel. **1**: Cylinder with 6 force transducers; **2**: Support truss, yoke, electromagnetic shaker, beam springs; **3**: Wire support harness; **4**: End plates; **5**: Turbulence grid.

When the cylinder is oscillating, the force measured by each transducer contains a component due to aerodynamic force and a component due to the mass and acceleration of the section of cylinder supported by the transducer. DFT-based techniques are used to extract the aerodynamic portion of the measured forces, using simultaneous records of force transducer and accelerometer outputs together with experimentally-determined estimates of the frequency response functions of the transducers to acceleration. Details of the experimental apparatus and data processing have been presented by Blackburn and Melbourne (1989).

The aerodynamic forces computed to act at each measurement station can be further processed by extracting components which are correlated with cylinder cross-flow velocity and acceleration on a least-squares basis. Since velocity and acceleration are uncorrelated in harmonic motion, the components thus extracted are also mutually uncorrelated. These components of motion-correlated force correspond to aerodynamic damping and added mass forces.

RESULTS

The aerodynamic force data presented here were collected in a turbulent flow at a blockage-corrected Reynolds Number of 1.7×10^5. The turbulence of 4% longitudinal intensity and an integral length scale of 1.5 diameters was produced by a turbulence grid located 50 cylinder diameters upstream of the model.

A comparison of cross-flow force autospectra at a Reynolds Number of 1.7×10^5 is shown in Figure 2.

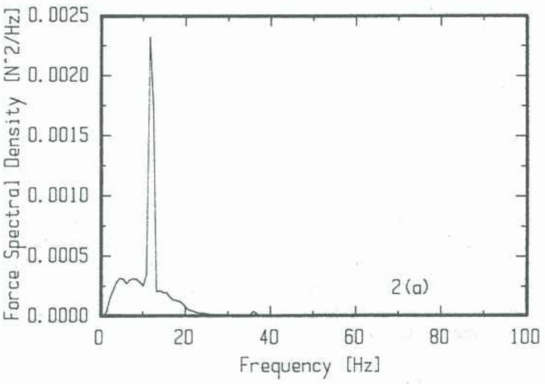

Figure 2(a) Autospectrum of cross-flow aerodynamic forces measured at one force transducer with the cylinder in forced oscillation at 3% of diameter amplitude.

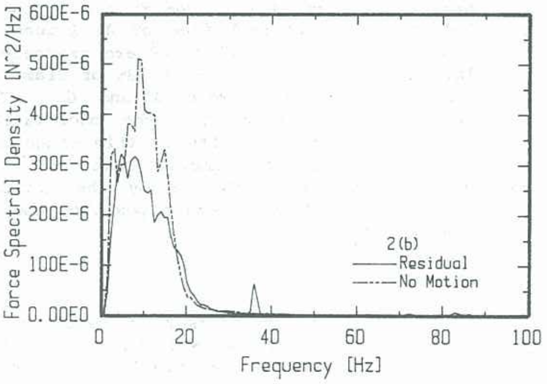

Figure 2(b) Comparison of spectra of residual cross-flow forces after removal of motion-correlated forces and forces recorded in the absence of shaking.

In Figure 2(a) the cylinder is driven by the shaker to an amplitude of 3% of diameter at a frequency of 12 Hz; the presence of aerodynamic forces at the shaking frequency can be clearly seen. Figure 2(b) shows the spectrum of the same data used to generate Figure 2(a) but after removal of terms correlated with motion, together with a spectrum recorded at the same Reynolds Number with the cylinder held fixed. In the spectrum of residual forces, the sharp peak at the shaking frequency has been removed but there is still some energy there. Also of interest is the presence of components at the third harmonic of the shaking frequency. Higher harmonics are not removed by the correlation process since they are orthogonal to the first harmonic and hence uncorrelated with it. When the cylinder is held stationary the other spectrum of Figure 2(b) shows that the vortex shedding process is quite wide-banded at Reynolds Number 1.7 x 10^5, but with a distinct spectral peak at 9 Hz (Strouhal Number = 0.14). Comparing the two spectra of Figure 2(b), introduction of shaking causes the distinct peak at 9 Hz to disappear and the residual R.M.S. lift to forces drop slightly. However raising the Reynolds Number to 1.8 x 10^5 in the absence of shaking also caused the distinct peak at 9 Hz to disappear, indicating that boundary layer effects are just bringing on the transition to critical flow, making the lift forces sensitive to small variations in Reynolds Number.

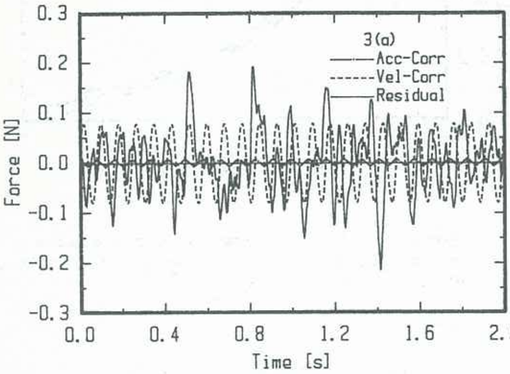

Figure 3(a) Plot of force components decomposed into those correlated with motion, and residual.

Typical force timeseries from which spectra and Coefficients of Lift are prepared are illustrated in Figures 3(a) and (b). Figure 3(a) indicates the relative sizes of the acceleration-correlated, velocity-correlated and residual force terms at 3% of diameter amplitude. Figure 3(b) shows timeseries of force before and after removal of motion-correlated terms.

Coefficients of Lift can be prepared from the force timeseries decomposed as previously described. Figure 4 shows the Coefficients of Lift of the residual forces from one of the force measurement rings at amplitudes of 1%, 2% and 3% of diameter as functions of Reduced Velocity.

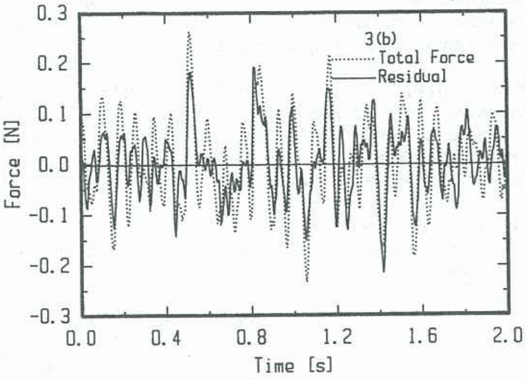

Figure 3(b) Comparison of aerodynamic forces before and after removal of motion-correlated terms.

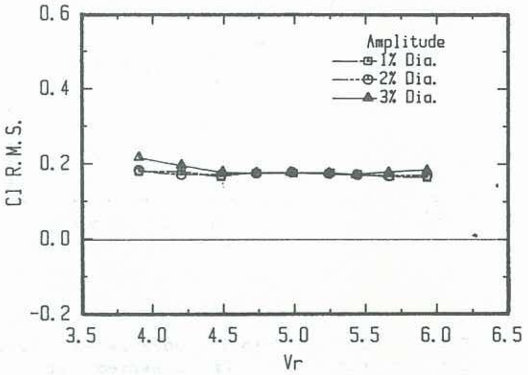

Figure 4. R.M.S. Coefficients of Lift from forces uncorrelated with motion as functions of Reduced Velocity and amplitude. The R.M.S. C_1 at the same Reynolds Number for no motion is 0.21.

Magnitudes of Coefficient of Lift of uncorrelated forces for the four most central transducers are all of a similar magnitude although there is some variation from ring to ring, as shown in Figure 5. All the Coefficients of Lift of residual forces display the same relative independence of Reduced Velocity.

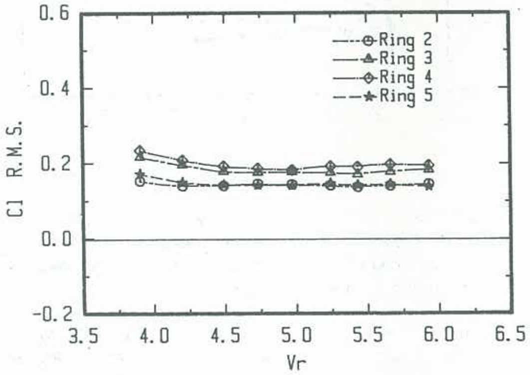

Figure 5 R.M.S. Coefficients of Lift from forces uncorrelated with motion at 3% of diameter amplitude. Comparison of results from four most central transducers.

The Coefficients of Lift of the velocity-correlated forces at 3% of diameter amplitude are shown in Figure 6. These forces correspond to aerodynamic damping: a positive value of Coefficient of Lift indicates negative aerodynamic damping, that is the flow is transferring energy to the structure. Coefficients measured at lower amplitudes show the same trends.

The Coefficients of Lift of the acceleration-correlated forces at the same amplitude are shown in Figure 7. These forces correspond to Added Mass of fluid: a positive value of Coefficient of Lift indicates a negative added mass.

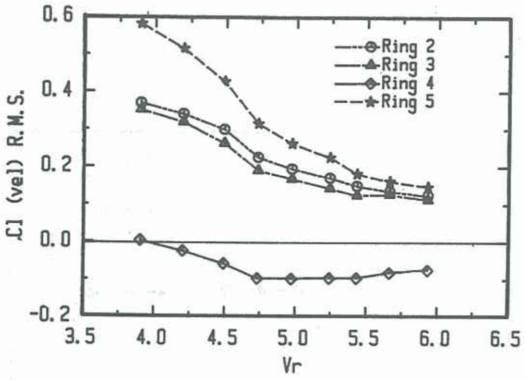

Figure 6. Velocity-correlated R.M.S. Coefficients of Lift measured at four transducers as functions of Reduced Velocity at 3% of diameter amplitude.

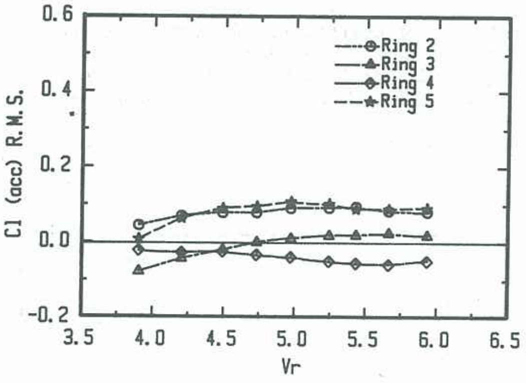

Figure 7. Acceleration-correlated R.M.S. Coefficients of Lift measured at four transducers as functions of Reduced Velocity at 3% of diameter amplitude.

The signs of the motion-correlated Coefficients of Lift and their trends with Reduced Velocity correspond broadly with those found by other workers, for example Sarpkaya (1978) who conducted forced oscillation experiments in subcritical flow. It seems from an inspection of Figures 6 and 7 that there is an offset in mean value between the Coefficients of Lift found at each of the four central force measurement stations, but a similar trend with Reduced Velocity for each. At this stage it is uncertain if this effect is due to experimental error or aerodynamic effects caused perhaps by spanwise variation in boundary layer flows at the onset of the critical Reynolds Number regime.

While motion-dependent forces are by definition perfectly correlated in a spanwise direction although perhaps with a variation in sign, the residual forces show a reducing degree of coherence in the spanwise direction as the measurement stations become further apart, as has been known for some time. From cross-correlations computed between the aerodynamic forces at the various locations plots have been prepared. Although of limited spanwise resolution, they can still be used to compare the spanwise correlation of residual aerodynamic force as a function of oscillation amplitude. Figure 8 indicates that there was no observable change in spanwise correlation with increase of oscillation amplitude.

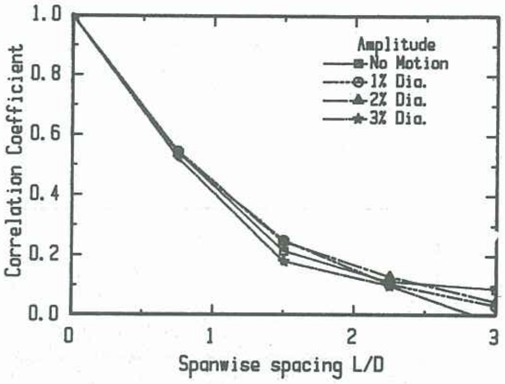

Figure 8. Plot of spanwise correlation of residual force as a function of amplitude at Reduced Velocity of 5.25.

CONCLUSION

The experimental results indicate that in the flow regime investigated, cross-flow oscillation has little influence on the portion of the aerodynamic forces which are not correlated with the motion of the structure, both locally and in spanwise correlation.

Analysis of motion correlated forces suggests that a negative aerodynamic damping exists and varies with Reduced Velocity in a manner broadly similar to studies conducted both in subcritical [Sarpkaya (1978)] and postcritical [Jones (1980)] smooth flows.

There is agreement between experimental results and Vickery and Basu's (1983) model in that there was no observed interaction between motion and uncorrelated local forces and spanwise correlation.

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