Chapter 7

Summary and Future Work

7.1 Summary

7.1.1 Fixed Cylinder

In smooth flow, transition from the subcritical to critical regimes was achieved through a reduction in local lift forces rather than a reduction in spanwise correlation; the Strouhal number and spanwise correlation remained almost constant until the end of the precritical regime.

The forces and pressures had greatest spanwise uniformity in smooth subcritical flow, with lower uniformity in the remaining flows. Values of sectional coefficients of lift in smooth subcritical flow were higher than previous observations for high aspect ratio cylinders in low blockage flows; it was thought that these observations and in addition the lack of Strouhal peaks in the smooth supercritical flows were attributable to the combination of moderate cylinder aspect ratio (4.5:1) and tunnel blockage (10%). By comparison with previous results, it was thought that the measured values of sectional σ_{C_l} in smooth subcritical flows were larger by a factor of approximately two than those for a high aspect ratio cylinder in low-blockage flow.

Addition of grid turbulence of low intensity (I_u up to 4.2%) promoted early critical transition, above which the results were similar to those for smooth supercritical flow. Increasing turbulence intensity (I_u up to 18%) brought about re-established vortex shedding, as shown by a rise in lift coefficients, appearance of a Strouhal peak centred at $St = 0.23$, and increased spanwise correlation of lift (but lower than in smooth subcritical flow).

Comparison with published observations of sectional lift forces from full scale flows at higher Reynolds numbers and similar turbulence intensities showed that coefficients of lift and spectral bandwidths measured in full scale were lower. This difference is thought to have been due to the comparatively small scale of turbulence used for the present experiments ($L_u^x/D \approx 0.5$). The influence of cylinder aspect ratio and blockage was thought to be smaller in the turbulent transcritical flows than in smooth subcritical flows. With a lack of comparable wind tunnel results, it is difficult to be more conclusive on this aspect, however, comparison with results obtained in full scale suggests the experimental results followed previously-observed trends with the turbulence parameter $I_u \cdot \mathrm{LSR}^{-1/3}$.

7.1.2 Oscillating Cylinder

General

Lift forces for the oscillating cylinder were decomposed into components correlated with motion, and residual. For all flows, coefficients extracted from the residual forces were similar to those measured with the cylinder fixed.

Increases in spanwise correlation of lift were observed as amplitude of oscillation increased, and could be accounted for by motion-correlated forces which were well-correlated along the span.

The influence of cylinder motion on lift was greatest in smooth subcritical flows, and when the frequencies of fixed-cylinder vortex shedding and cylinder oscillation were close.

Smooth subcritical flow

Lock-in, defined by frequency capture of vortex shedding, was observed at $\alpha_{\text{nom}} = 3\%$, over the reduced velocity range $4.79 < V_r < 5.14$, but not at any of the lower amplitudes of motion or other flows.

Outside the lock-in range, spectra of lift exhibited two peaks, one at the cylinder oscillation frequency and one at the fixed-cylinder Strouhal frequency. When motion-correlated forces were extracted, the spectral peaks at the oscillation frequencies were removed.

The motion-correlated component of lift was found to have an approximately constant value through the lock-in range, while the phase of lift with respect to cylinder motion varied. This corresponds with the change in phase of vortex shedding near the critical reduced velocity previously observed at higher amplitudes of motion by Ongoren and Rockwell (1988), among others.

Motion-correlated forces tended to rise as amplitude of motion increased, over the whole range of reduced velocities investigated ($3 < V_r < 6$). Coefficients of motion-correlated lift expressed in the forms of added mass parameter (C_a) and aerodynamic damping coefficient (K_a) tended to reduce in magnitude as amplitude of forced oscillation increased. The behaviour of motion-correlated forces with changes in reduced velocity and the magnitudes of those forces were similar to those for other experimental observations at comparable Reynolds numbers. It was thought that the magnitudes of motion-correlated forces were likely to scale with the magnitude of lift on the fixed cylinder, and on this basis that the magnitudes of motion-correlated forces observed were also larger by a factor of about two than would be observed on a high aspect ratio cylinder in low-blockage flow.

Smooth supercritical flow

Cylinder motion did not re-establish vortex shedding in the smooth supercritical flow. Motion-correlated forces were smaller than for subcritical flow, and showed little variation with changes in reduced velocity. Aerodynamic damping was slightly positive.

Turbulent flows

In all turbulent flows, motion correlated forces were small and were much less sensitive to changes in reduced velocity than for smooth subcritical flow. Behaviour was similar in all the turbulent flows, C_a generally in the range 1–2, falling with increased V_r. K_a tended to rise as V_r increased, but values were rather small, ~ 0.1.

As was the case for the forces on the fixed cylinder, it is unlikely that the observations can be extrapolated directly to full scale flows of higher Reynolds numbers with similar turbulence intensities but lower turbulence length scale ratios.

7.2 Response Prediction

The significance of the results in relation to the cross flow vortex-induced vibration response prediction model introduced by Vickery and Basu (1983 a) are discussed here; only the most important findings which bear directly on the model will be raised. The ability of the model to accurately predict response amplitudes is a separate issue which deserves further experimental investigation, as discussed in the next section.

In general terms, the experimental results did not conflict strongly with the assumptions and parameters of Vickery and Basu's model, but cannot be used directly as input to the model, particularly in the turbulent transcritical flows, due to a mis-match of turbulence length scale to cylinder diameter ratios (LSRs) between model and full scale.

A plot of values of sectional σ_{C_l} against the turbulence parameter $I_u \cdot \mathrm{LSR}^{-1/3}$ for the most turbulent flows (fig. 5.44) shows that the values follow the trend previously observed for full scale results by Vickery and Daly (1984), suggesting that this is indeed a valid parameter for variations in σ_{C_l} (and by implication other parameters such as the spectral bandwidth B and correlation length Λ). Since the model in its present form (Vickery & Basu 1983 a, Simiu & Scanlan 1986) does not recognize variation of σ_{C_l} with $I_u \cdot \mathrm{LSR}^{-1/3}$, this is a possible area for modification.

The spanwise correlation length of lift forces (ΛD) observed in the most highly turbulent flow ($I_u = 18\%$) was $1.5\,D$, while the value for $Re > 2\times10^5$ which Vickery and Basu provide (see Simiu & Scanlan 1986, eqs. 10.2.16) is $1.0\,D$. There have been very few, if any, measurements of correlation lengths on smooth cylinders in transcritical, turbulent flows. Since it seems likely that spanwise correlation of vortex shedding would only increase with increased turbulence LSRs appropriate to full scale structures in transcritical flows, it may be advisable to increase the value of Λ used in the model.

The underlying assumption of the model that lift forces on oscillating cylinders may be decomposed into a motion-correlated part which varies with oscillation amplitude and a residual random part which is unaffected by oscillation amplitude appeared to be reasonable, at least for the comparatively low amplitudes of motion (up to $3\%\,D$) used here. In addition, the assumption that observed increases in spanwise correlation lengths of lift forces can be accounted for by the contribution of motion-correlated forces was supported by the experimental results. No comment can be made as to how appropriate the decomposition is for the purposes of response prediction; this question still needs experimental investigation (see below).

The value of $K_{a0} \simeq 6.5$ observed at critical reduced velocity in smooth subcritical flow is higher than the value which Vickery and Basu suggest (approximately 2 for smooth subcritical flow, see Simiu & Scanlan 1986, eqs. 10.2.17, 10.2.18). As noted in the last section, the experimental value is probably about twice as large as would be expected for a high aspect ratio cylinder in smooth subcritical, low blockage flow. With this, $K_a \approx 3$, which is still higher than the value proposed by Vickery and Basu. Perhaps more significantly for the form of the model, comparatively high negative values of $\partial K_a/\partial \alpha$ (approximately -85) were observed, while the model proposes a value of zero. If K_a can only fall at an increasing rate as amplitude of oscillation increases (as the model suggests), the maximum limiting amplitude of vibration predicted for a freely-vibrating cylinder in the limit $K_s \rightarrow 0$ would be approximately $6.5/85 = 7.6\%$ of cylinder diameter, significantly lower than values suggested by Vickery and Basu (typically of the order of half a cylinder diameter). In addition, and of more practical significance, at amplitudes of motion well below the limiting value, negative values of $\partial K_a/\partial \alpha$ act to significantly reduce the influence of negative aerodynamic damping.

In the highly turbulent transcritical flows, comparatively small positive values of K_a were observed (approximately 0.1, compared to values near 0.2 and above suggested by the model in flows of similar turbulence intensity). Some of the model's predictions were violated; the prediction that K_a would drop with increased turbulence intensity was not found to hold, and neither did the form of the variation of motion-correlated force coefficients with reduced velocity follow trends established in smooth subcritical flow, as suggested by the model. This does not necessarily imply that the model's predictions would not hold in full scale, since the comparatively low values of turbulence LSR (≈ 0.5) used in the experiments were much smaller than is typically the case in full scale. However, it may be the case that motion-correlated forces are influenced by turbulence in other ways than the quasi-steady variation suggested by the model (again, the parameter $I_u \cdot \mathrm{LSR}^{-1/3}$ may be significant). The influence which cylinder motion can exert on vortex shedding may be disrupted when there is significant turbulent energy at length scales comparable to the cylinder diameter.

7.3 Recommendations for Future Work

Further investigations of lift forces on fixed and oscillating circular cylinders in high Reynolds number turbulent flows are needed. The present experiments offer some indication that Reynolds number independence may be reached at lower Reynolds numbers in turbulent than in smooth flows, but underline the need to correctly model turbulence length scale as well as turbulence intensity; this will be difficult to achieve in wind tunnel tests. In addition, it seems that the characteristics of the flow at Reynolds numbers beyond the subcritical range are sensitive to end effects, indicating the need for high aspect ratio cylinders.

More study of the effects of independent variation of cylinder aspect ratio and tunnel blockage on lift forces is warranted. In particular, one aspect that has not yet been addressed experimentally is the possible effect of cylinder blockage on the spanwise correlation of vortex shedding. Due to possible Reynolds transition effects, it would be best to investigate the effects in a flow regime which is insensitive to Reynolds number variation, or alternatively to investigate the effects using cross-sections which display Reynolds insensitivity.

The effect of turbulence with large length scale ratios on motion-correlated forces is still unknown. With circular cylinders, it is difficult to investigate the effects of turbulence independently of transition effects, so again it is recommended that the investigation be carried out either in a Reynolds regime in which turbulence does not promote transition effects, or alternatively with a cross-section which shows Reynolds number and angle of attack insensitivity.

Regarding measurement of forces on oscillating structures, the problems of correction for inertial component of transducer signal are likely to be less severe when pressure, rather than direct force measurement techniques are used. While it is possible that distributed/manifolded pressure measurements might be used in lieu of many separate sensors, it would be very difficult, if not impossible, to correctly account for inertial signals in that case, since the amount of correction required would vary with the distance of the each pressure tapping from the model centreline (this would not be a problem for example when measuring lift on a rectangular section). Unfortunately, pressure sensors are expensive, however fewer sensors would be needed for the measurement of long-time-average motion-correlated force coefficients, since motion-correlated pressures could be obtained location-by-location.

The issue of the importance of possible intermittency of motion-correlated forces for prediction of free vibration response amplitudes is unresolved. It may be possible to investigate this using computer simulation techniques.

More generally, the ability of response prediction models, such as that proposed by Vickery and Basu (1983 a) to predict response amplitudes given good measurements of all parameters involved, is still open to question. As observed previously by Bearman (1984), experiments are needed in which both free and forced vibrations can be employed with the same experimental rig. The Reynolds numbers to be employed are not particularly important when the utility of the prediction model is under consideration, except that narrow-band vortex shedding is needed. Design of suitable equipment requires some care, since it is not easy to produce a rigid, high aspect ratio, instrumented cylinder for forced oscillation work yet at the same time achieve the low values of the mass-damping parameter K_s which are needed for free vibration. It may be easier to produce such a rig using water, rather than air, as the working fluid.

An interesting related avenue of investigation would be to examine the effects of separate variation of mass ratio and damping on the free-vibration response of circular cylinders; the need to achieve a wide range of mass ratio again indicates that water be the working fluid. Flow visualization and force measurement would be useful adjuncts to such a study.

Finally, many of the basic problems of bluff-body fluid dynamics and aeroelasticity are beginning to fall within the reach of computational fluid dynamics. It seems likely that computational methods will be useful for resolving the basic mechanisms of fluid-structure interaction, even though the achievable Reynolds number range seems, for the immediate future at least, to be restricted. This indicates that computational techniques will soon start to provide guidance for experimental investigations at higher Reynolds numbers.