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VORTEX SHEDDING FROM CYLINDERS IN NEAR AXIAL FLOW

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ABSTRACT

Results of an investigation of vortex shedding from cylinders having very large length-to-diameter ratios, with their axes yawed at small angles β to the flow direction are presented. Yaw angles varied from 0° to 10°, a range not previously investigated; the range of flow Reynolds number Re_d was 100 to 5000.

It was found that, over a range of Reynolds number depending on yaw angle, vortices can be shed at much smaller yaw angles than previously expected. The dependence of the measured vortex-shedding frequencies on Reynolds number and yaw angle shows that relationships previously established between shedding frequency and cylinder Reynolds number for large angles of yaw become invalid at very small yaw angles.

1. INTRODUCTION

On the basis of results obtained in their experimental investigation of thick turbulent boundary layers on very long cylinders in axial flow, Luxton et al. (1984) suggested that the stripping of retarded inner-layer fluid from the cylinder by turbulent cross-flows, accompanied by the generation of high instantaneous velocity gradients at the cylinder surface, could be responsible for the high levels of vorticity production necessary to sustain such a thick boundary layer. In later work by Bull et al.(1986), additional support for this hypothesis came with the identification of propagating fronts of low speed fluid in the boundary layer. This, in turn, raised the possibility that stripping of retarded fluid from the cylinder might be associated with localised vortex shedding, induced by turbulent cross-flows. As a consequence an investigation was undertaken of vortex shedding from cylinders yawed at small angles from the flow direction.

Here the results for the vortex-shedding characteristics of cylinders in near-axial flow, which appears not to have been previously investigated, are presented, and an attempt made to integrate them with existing data for larger yaw angles.

Nomenclature

d = cylinder diameter
f = vortex shedding frequency
F = non-dimensional frequency parameter, fd^2/ν
Re_d = Reynolds number Ud/ν
Re_n = Reynolds number $U \sin\beta\, d/\nu$
St = Strouhal number fd/U
St_* = Calculated St based on $U \sin\beta$ (Eqn.[1])
U = Free stream velocity
x = Streamwise coordinate
α = angle of shedding, relative to cylinder axis
β = angle of yaw, angle between cylinder axis and flow direction
δ_* = boundary layer displacement thickness
ν = kinematic viscosity of fluid

2. VORTEX SHEDDING FROM YAWED CYLINDERS

Vortex shedding from circular cylinders with their axes normal to a flow (i.e. at yaw angles of β=90° in the terminology used here) has received considerable attention in the past in its own right, and results for this case have also been used extensively as a basis for correlating data for cylinders at other inclinations to the flow.

Detailed quantitative knowledge of regular vortex shedding from circular cylinders normal to a flow stems from the pioneering hot-wire investigations of Kovasznay (1949) and Roshko (1954). These early works identified the various vortex shedding regimes and the Reynolds number ranges in which they occur — in particular the regime of regular vortex shedding for $50 < Re_d < 150$, which is of direct interest in this investigation. For this range, Roshko established the linear relationship

$$F = 0.212\, Re_d - 4.5\ . \qquad [1]$$

Over the succeeding years many investigators 'discovered' various discontinuities in the F - Re_d relationship or variations from equation [1]; in most cases these have proved to be peculiarities of particular test facilities. Variations in end conditions were examined by Slaouti et al.(1981) and found to produce gross changes in the flow. Williamson (1988) has shown that, because of this extreme sensitivity to end conditions, spans up to 240 diameters long can be influenced by end effects. By measuring the shedding angle α, and transforming the measured Strouhal number St_α to $St = St_\alpha/\cos\alpha$, Williamson has produced a single continuous Strouhal-number/Reynolds-number curve for the regime of regular shedding. This correlation is based on the assumption that in the absence of end effects, shedding takes place parallel to the cylinder axis, an assumption which can not necessarily be extended to yawed cylinders.

Early investigations of vortex shedding from yawed cylinders were conducted by Hanson (1966) and Van Atta (1968) for yaw angles in the range 15° < β < 90°. These indicated that for large angles of yaw 90° > β > 55° vortex-shedding characteristics can be related to the component of flow velocity normal to the cylinder axis, independent of the axial component. For angles of yaw β < 55° the flow behaviour deviates from this 'independence principle', increasingly so as β decreases.

Experiments at larger Reynolds numbers, by Chiu et al.(1967) for 3900 < Re_d < 21,200 and 30° < β < 90°, Smith et al.(1972) for 1000 < Re_d < 10,000 and 30° < β < 90°, and Knauss et al.(1976) for 300 < Re_n < 1200 and β = 60°, all support the 'independence principle' for large angles of yaw.

The more recent work by Ramberg (1983) for 150 < Re_d < 1100 and 30° < β < 90° shows the limited validity of the independence principle. Ramberg further concludes that "slantwise shedding at angles other than the cylinder yaw angle is intrinsic to inclined cylinders in the absence of end effects", due to a component of vorticity associated with the flow component parallel to the cylinder axis, which causes the net vorticity vector to become inclined to the cylinder axis.

In the investigation by Shirakashi et al.(1986) for 800 < Re_d < 55,000 and 45° < β < 90°, flow visualisation by smoke streaks showed that the flow over a yawed cylinder is highly three-dimensional in nature. Only when the secondary flow behind the cylinder was suppressed (by plates in the cylinder wake) did the shedding frequency become equal to that for a cylinder subject to only the normal velocity component of the flow. From these observations, it was concluded that data correlations resulting from the application of the independence principle are largely fortuitous.

From the foregoing it is clear that interaction between the axial and normal components of the flow becomes greater as the yaw angle β decreases (i.e. as the cylinder axis approaches alignment with the flow direction) and as the Reynolds number Re_d is reduced.

The development of very thick turbulent boundary layers on cylinders at zero yaw (Luxton et al.,1984) and the extreme sensitivity of such boundary layers to small angles of yaw (Willmarth et al.,1977) suggest that interaction effects are likely to have a dominant influence on vortex shedding at small β.

3. EXPERIMENTAL FACILITY AND PROCEDURES

Experiments were conducted in the 300 by 650 mm by 3 m long rectangular test section of a closed-circuit low speed wind tunnel. The air speed in the test section can be continuously varied from 0 to 27 m/s, although the minimum stable speed is about 1 m/s. The growth of the boundary layers on the walls of the parallel test section causes acceleration of the free stream: the increase in velocity over the length of the test section is in the order of 5%.

The test cylinder consisted of a length of nylon fishing line anchored at its upstream end in the tunnel contraction by wire stays, and tensioned by means of a pulley and a 5 kg weight at its downstream end. The angle of yaw could be varied both by movement of the pulley along a horizontal slide, and by adjusting the upstream stays. The maximum yaw angle attainable was 10°.

The air speed was determined by means of a Pitot-static probe, located at the same streamwise position as the frequency-measuring probe. The dynamic pressure was measured by a null balance manometer with a resolution of 0.01 mm using a fluid of specific gravity 0.826. For air speeds greater than 22 m/s a water manometer with a resolution of 0.2 mm was used.

Velocity fluctuations were measured by a 5 μm diameter tungsten hot-wire, operated by a TSI IFA 100 constant temperature anemometer. The frequencies of periodic velocity fluctuations were obtained from the analogue anemometer signal by a Hewlett-Packard HP 3582A spectrum analyser, which performs a fast Fourier transform of the digitised signal. When regular vortex shedding occurs, the frequency spectrum of the velocity fluctuations shows a single dominant spike at the vortex-shedding frequency.

At the limits of this regular shedding regime, the dominant spike rapidly decreases in strength, and increases in width until it fades into the spectrum of the background turbulence.

The hot-wire probe was located 2700 mm (3000 diameters) downstream of the start of the test section, so that vortex shedding from only one side of the cylinder was detected.

A second probe was located 2200 mm upstream of the first, and its output processed simultaneously with that of the first probe, using the dual channels of the anemometer and the spectrum analyser. Owing to the velocity gradient along the test section, probe #2 detects a different frequency from probe #1, but the two probes yield the same frequency-velocity relationship when account is taken of the true local velocities. Although the second probe produces no additional data, it does provide a very useful facility for detecting lock-on of vortex shedding to the cylinder's natural vibrational frequencies. When cylinder vibration and lock-on occur, both probes detect the same frequency despite differences in local velocity. Vibrational interference can then be avoided by changing the natural vibrational frequency of the cylinder by adding additional cylinder-tensioning weights.

4. RESULTS AND DISCUSSION

4.1 Physical parameters

The flow may be described by the set of variables (x,d,β,U,ν,f). From the expectation that any flow dependence on x would be greatest at minimum β, and the knowledge that in the extreme case (β=0) the flow approaches an asymptotic state within 2000 diameters downstream of the origin of the boundary layer (Luxton et al.,1984), the current results obtained at x = 3000 diameters will be assumed to be independent of x.

For the remaining set of five variables the implied relationship in terms of non-dimensional parameters is $F = F(\beta, Re_d)$. An alternative to the non-dimensional frequency parameter F, is the Strouhal number St, where $St = F/Re_d$. Although the use of Strouhal number is more common, the use of F allows the effects of frequency and flow velocity to be separated.

4.2 Regular vortex shedding limits

For cylinders normal to the flow, regular vortex shedding occurs for 50 < Re_d < 150 (Roshko,1954). The present work (using 0.90, 1.93 and 2.95 mm diameter cylinders) shows that vortices can be shed from yawed cylinders at much smaller angles of yaw than previously believed, and that the maximum Reynolds number for which regular vortex shedding occurs varies with yaw angle (figure 1).

Vortex shedding does not stop or start abruptly at the boundary indicated: there is a gradual change from well defined regular vortex shedding to no shedding over a range of Reynolds number. The measurements indicate that the width of the transition range is approximately 10% of the Reynolds number at the boundary.

Figure 1 shows only results for $\beta > 1°$; at smaller angles still, down to about 0.5°, continuous but somewhat irregular vortex shedding was detectable.

No lower Reynolds-number limit on vortex shedding was detected, suggesting that, if one exists, it corresponds to a flow speed below the minimum stable flow speed of the wind tunnel.

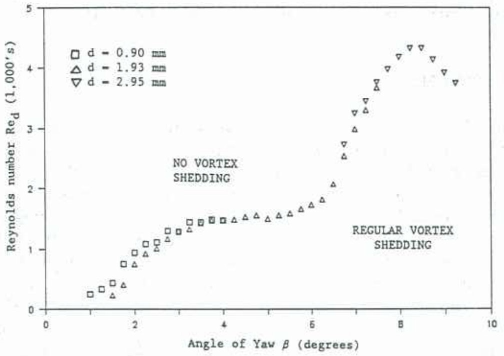

Figure 1. Vortex-shedding regimes for circular cylinders at small yaw angles, as a function of yaw angle and Reynolds number based on free stream flow velocity.

The form of the boundary in figure 1 is little altered if the Reynolds number Re_n based on the flow velocity component normal to the cylinder is used rather than Re_d (figure 2). That the upper limiting value of Re_n is not constant at a value of 150 and the lower limiting value of Re_n if any, is very much below 50 is further evidence that the independence principle has little relevance at these small angles of yaw.

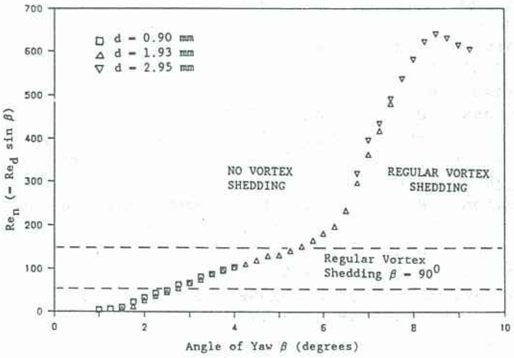

Figure 2. Vortex-shedding regimes for circular cylinders at small angles of yaw, as a function of yaw angle and Reynolds number based on flow velocity component normal to cylinder axis.

4.3 Vortex shedding frequencies

Shedding frequencies were measured for a 0.90 mm diameter circular cylinder over a range of Reynolds numbers for angles of yaw β (from the axial direction) up to 10°. Results for the variation of the non-dimensional frequency parameter F with Reynolds number at various constant values of β are shown in figure 3.

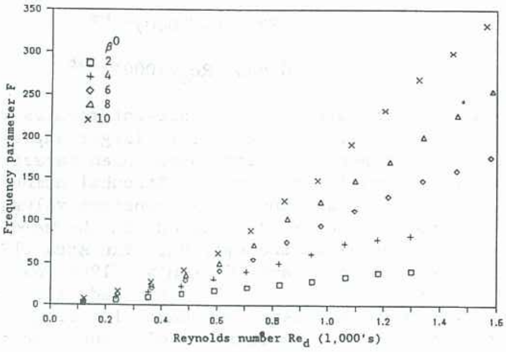

Figure 3. Experimental data for dependence of frequency parameter F on Reynolds number at constant yaw angle.

The data of figure 3, clearly, do not show the simple linear relationship exhibited by cylinders normal to the flow. At small angles of yaw the effect of Reynolds number on the boundary layer may be a contributing factor to this behaviour. It is known that in the case of vortex shedding from a flat plate, of thickness t, with a blunt trailing edge the shedding frequency is determined not by t but by the modified thickness $(t + 2\delta_*)$ where δ_* is the displacement thickness of the boundary layer which forms on the plate. By analogy, $(d + 2\delta_*)$ rather than d might be expected to be the relevant length scale for shedding from cylinders at small yaw angles. For $\beta = 0$, δ_* may be in the order of several cylinder diameters under the conditions of the present experiments and increases as Re_d is decreased (Luxton et al.,1984). It is therefore possible that the non-linearity of the F - Re_d curves of figure 3 is due to boundary layer effects; but the available boundary layer data for small β are not sufficiently comprehensive to allow quantitative estimates of this effect to be made.

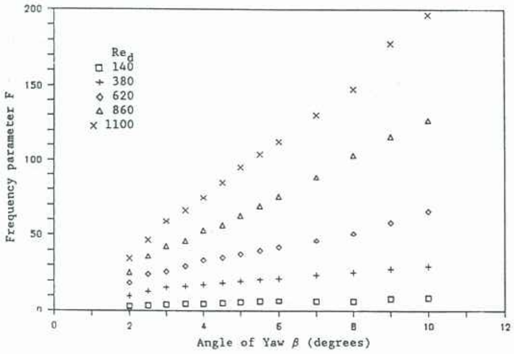

Figure 4. Interpolated data for variation of frequency parameter F with yaw angle at constant Reynolds number.

Cross-plots of mean lines through the experimental points of figure 3 showing the variation of F with β at various constant values of Reynolds number are shown in figure 4. From these curves an empirical representation of the experimental results has been obtained. It takes the form

$$F = A\beta^n, \qquad [2]$$

where A and n are both functions of Reynolds number and given by

$$A = 28 + 782\,(Re_d/1000)^{2.66} \qquad [3]$$

$$n = 0.46 + 0.483\,(Re_d/1000)^{1.06} \qquad [4]$$

To assess consistency of the present results with previously published data for larger angles of yaw, the present results have been recast (by interpolation) in the form of Strouhal number as a function of yaw angle, at constant values of the Reynolds number Re_n based on the velocity component normal to the cylinder. Van Atta (1968) presented his own and Hanson's (1966) data in this form for Re_n = 50, 80 and 150, and comparison with them is made in figure 5. Although the constraints of the present experimental setup did not allow an overlap of results, the trends in the two sets of data with variation of yaw appear to be quite consistent.

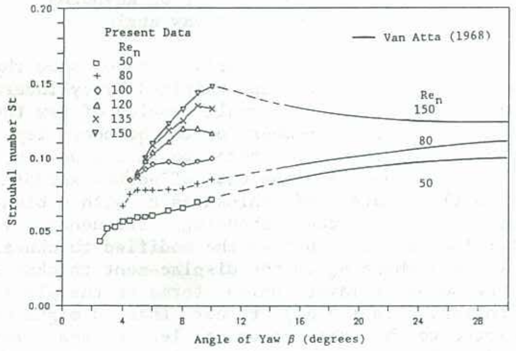

Figure 5. Interpolated data for variation of Strouhal number with yaw angle at constant normal Reynolds number, and comparison with data for larger yaw angles.

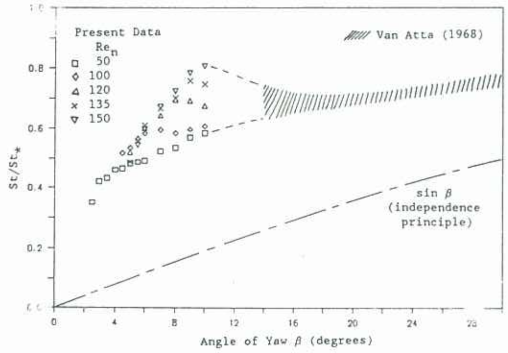

Figure 6. Interpolated data for variation of normalised Strouhal number with yaw angle at constant normal Reynolds number, and comparison with data for larger yaw angles.

Van Atta also found that the effect of Reynolds number apparent in figure 5 could be accounted for, and a good collapse of data obtained, by replacing the Strouhal number by its ratio to the Strouhal number St_* appropriate to a cylinder normal to a flow with velocity U sin β. The value of St_* was obtained by using equation [1] with Re_d replaced by Re_n. However at small β the ratio St/St_* was found to diverge significantly from the value sin β which is implied by the independence principle. Comparison of the present data with those for larger yaw angles on this basis is shown by figure 6. As in figure 5, the results show quite good continuity with those of Van Atta(1968) and Hanson(1966), but the use of St_* does not produce a collapse of the data at small β. Further, the increasing deviation of the value of St/St_* from sin β as the yaw angle approaches zero again represents increasing departure from the independence principle.

5. CONCLUSION

Results for vortex shedding from circular cylinders yawed to the flow direction have been obtained for small angles of yaw $0° < \beta < 10°$, a range which has not previously been investigated. The Reynolds number range over which regular vortex shedding occurs at any given yaw angle has been established. The data for the frequency of shedding provide a smooth continuation of previously published data for larger yaw angles, in terms of the frequency parameter F as a function of yaw angle at fixed Reynolds number. However the use of the Strouhal number St_* as a correlation parameter, which is successful at large β, fails at small yaw angles.

In general the results indicate that the independence principle (i.e. the notion that the components of fluid velocity normal and parallel to the cylinder axis can be regarded as independent) is not valid at small yaw angles and low Reynolds numbers.

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