*13th Australasian Fluid Mechanics Conference*
*Monash University, Melbourne, Australia*
*13-18 December 1998*

# HOT WIRE MEASUREMENTS IN THE WAKE OF MODIFIED CIRCULAR CYLINDERS

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## ABSTRACT

The influence of the introduction of axial slits and/or notches to circular cylinders on vortex shedding was investigated experimentally. The main focus of this study was on the variation of Strouhal number ($St_D$) with Reynolds number ($Re_D$), the determination of drag coefficient ($C_D$) at $Re_D \approx 2200$ and the measurement of velocity fluctuations and spectra using single and cross hot wire probes. It was found that all of the modifications had an influence on the $St_D/Re_D$ relationship, in particular for the cylinder with a slit normal to the flow (henceforth referred to as cylinder b) (see Figure 1)), $St_D$ always was higher than for the unmodified circular cylinder, cylinder a). $C_D$ values for cylinder c) were found to be significantly large, (more than twice that of a circular cylinder). The normalised fluctuation ($u'/U_o$) distribution showed a double maxima and the normalised Reynolds shear stress ($\overline{uv}/U_o^2$) was increased more than twice, for cylinder c) at x = 40D. Significant changes were also found in the strength and stability of periodic vortices shed from cylinders b) and c).

## INTRODUCTION

The phenomenon of vortex shedding from cylinders has been the focus of much attention in recent years. Inspection of literature on the variation of $St_D$ ($= nD/U_o$ where n if the vortex shedding frequency, D is the cylinder diameter and $U_o$ is the free-stream velocity) with $Re_D$ ($=U_oD/\nu$ where $\nu$ is the kinematic viscosity) shows considerable variation between different experiments, which suggests that this phenomenon is not as yet, completely understood.

Attempts to control vortex shedding mainly concentrate on preventing the phenomenon because of the adverse effects of lateral pressure fluctuations associated with vortex shedding. On the other hand very little attempt has been made to increase the strength and stability of vortex shedding even though an advantage would be to improve mixing in the wake. It may also prove beneficial in the design vortex flow meters.

It has been shown that by introducing tabs on the downstream side (rear stagnation point) or spiral form of roughness on the surface, the deleterious effects of vortex shedding can be reduced due to the communication of pressure fluctuations being suppressed or modified. Improvement of vortex shedding should occur when the communication is enhanced. Igarashi (1977, 1982) found that for a circular cylinder with an axial slit normal to the flow, vortex shedding was stronger and more stable than for a normal circular cylinder.

To produce strong and stable vortex shedding, Popiel et al (1992, 1993), modified a cylinder by introducing a slit normal to the flow and a concave notch in the rear. From flow visualisation experiments in water, Popiel et al claim that the introduction of this concave rear notch provided a more natural shape to cause unhindered vortex formation. Their measurements indicated that the $St_D$ remained almost constant (0.20 ± 2%) over a wide range of Reynolds numbers ($250 < Re_D < 43000$). These observations should make this modified cylinder very attractive for use in a vortex flow meter.

Another important criterion that would make a bluff body more attractive for use in a vortex flow meter is low drag to reduce the head loss in pipelines when a flow meter is in use. Knowledge of $C_D$ for modified cylinders is therefore useful in such applications. The aim of the current work is to examine the relationship between $St_D$ and $Re_D$ for the six modified cylinders shown in Figure 1 at relatively low $Re_D$. Measurements were made at several distances downstream in the wake to determine $C_D$. Distributions of normalised mean ($U/U_o$) and fluctuation ($u'/U_o$ and $v'/U_o$) velocities are presented along with normalised distributions of Reynolds shear stresses ($\overline{uv}/U_o^2$). Traces and spectra are presented to reveal the strength and periodicy of the vortex shedding from these cylinders.

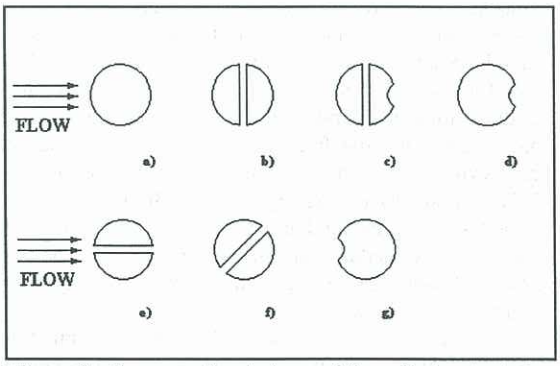

**Figure 1** : Cross-sectional views of the cylinders tested.

## EXPERIMENTAL METHOD

Experiments were conducted in a 320 x 320mm test section of an open circuit wind tunnel with low free-stream turbulence (< 0.1%). A Zener speed controller enabled the velocity of the air flow to be varied continuously between 0.3m/s corresponding to ($Re_D \approx 60$) and 10m/s ($Re_D \approx 2300$).

The cylinders tested had a nominal diameter of 3mm and were mounted from holes drilled in either side of the test section walls. No attempt was made to modify the end conditions to force parallel vortex shedding by using splitter plates. The ratio of slit width to cylinder diameter was approximately 0.16 for cylinders b) and c). The ratio of notch radius to cylinder radius was approximately 1.0 for both cylinders c) and d). Three modified cylinders were made for these experiments (cylinders b) , c) and d)); e) and f) correspond to cylinder b) rotated though different angles and g) corresponds to cylinder c) rotated through 180°.

Both a single hot wire probe and a cross wire probe with 5μm elements operated in a constant temperature mode were used in the present investigation Strouhal numbers were estimated using a HP3528A spectrum analyser.

Velocity profiles were obtained from measurements in the wake at different locations downstream of the cylinders (x/D = 20, 30 and 40). Hot wire signals were digitised using a 12 bit a/d converter and were subsequently processed on a PC.

## RESULTS AND DISCUSSION

### Variation of Strouhal Number with Reynolds Number

The results for the variation of $St_D$ with $Re_D$ are shown in Figure 2. Both of the two plots contain for reference, the results of the circular cylinder measurements. The distribution of $St_D$ with $Re_D$ for cylinder a) is in good agreement with that of Roshko (1956). The discontinuity at $Re_D \approx 170$ obtained for cylinder a) appears similar to either the "Mode A or B" discontinuity identified by Williamson (1996) as a three dimensional vortex shedding transitional regime.

Cylinder b) gave a larger value of $St_D$ for the range of $Re_D$ covered than cylinder a) indicating that the normal slit has the effect of increasing the frequency of vortex shedding. There was negligible difference in $St_D$ values between cylinders a) and d) for $Re_D < 400$, though for $Re_D > 400$, $St_D$ values were larger for cylinder d) compared to a). Cylinder c) combined both modifications of cylinders b) and d) but the $St_D$ are larger for this cylinder than for cylinder a) for $Re_D < 500$, it is less for $Re_D > 500$. The effect of the individual modifications of cylinders b) and d) were not additive and suggest that the free shear layer characteristics of these cylinders may be different. $St_D$ values for cylinder f) like cylinder b) are also higher than cylinder a) over the range tested suggesting that the slit at 45° to the flow still caused vortex shedding at a higher frequency. The two other cylinders tested were also found to vary only slightly from cylinder a).

Unlike Popiel et al, $St_D$ values are not found to remain constant at $0.20 \pm 2\%$ for $Re_D \geq 250$ though it remained nearly constant $Re_D \geq 600$. At $Re_D = 2090$, spectra indicated that $St_D = 0.205$ which is in reasonable agreement with Popiel et al's result. A different slit width to cylinder diameter ratio (0.16 against 0.25) and notch radius to cylinder diameter ratio (1.0 against 1.1) may partly explain the difference between the results.

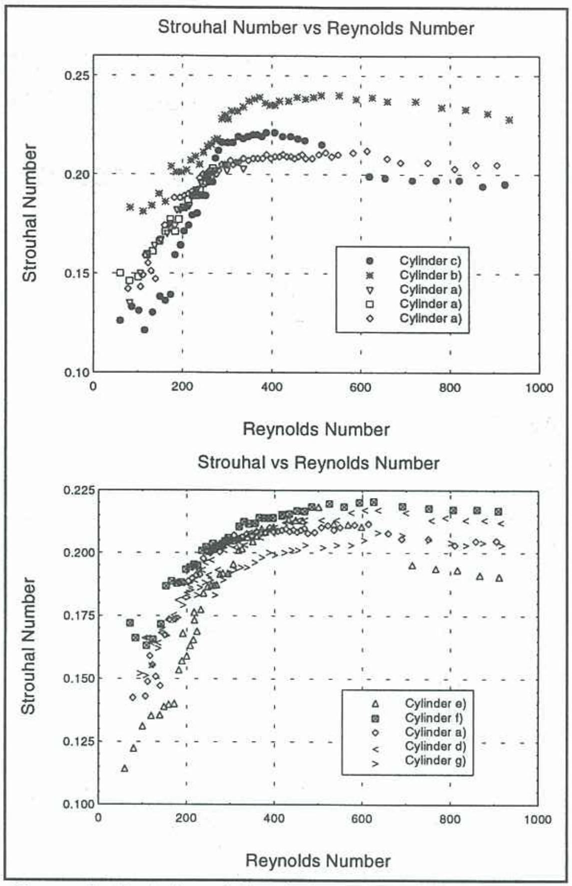

**Figure 2** : Variation of Strouhal number with Reynolds number.

### Drag Coefficient

Taylor (1937) suggested that Reynolds normal stresses may produce an error in the estimated value of $C_D$. Antonia and Rajagopalan (1990) found that contributions from Reynolds normal stresses for a circular cylinder, became negligible at x ≥ 30D. $C_D$ was evaluated as below:

$$C_D = \frac{-2F}{U_o^2 D} \tag{1}$$

where F (the kinematic force per unit length) is made up of two components, one due to the mean velocity profile and the other due to the fluctuation velocity profiles, as below:

$$F = \int_{-\infty}^{+\infty} U(U - U_o)dy + \int_{-\infty}^{+\infty}\left(\overline{u^2} - \overline{v^2}\right)dy \tag{2}$$

where u and v are the fluctuating velocity components in the x and y directions respectively. For the single hot wire measurements given at x = 30D, the fluctuating component of equation (2) was ignored.

### Single Hot Wire Measurements

Normalised mean velocity ($U/U_o$) vs ($y/D$) profiles from the single hot wire measurements at x = 30D are presented in Figure 3 and the estimates of $C_D$ are given in Table 1. $C_D$ for cylinder a) was found to be in reasonable agreement with values found in literature (Zdravkovich 1990). It can be seen that the velocity defect is considerably larger for cylinder c) than for the other cylinders. The mean velocity profiles (not shown here) from measurements done at small x/D locations showed that $C_D$ increased rapidly at first before eventually reaching an asymptotic value at x = 30D. Cylinder c) exhibited this asympotic nature only for $x/D \geq 40$.

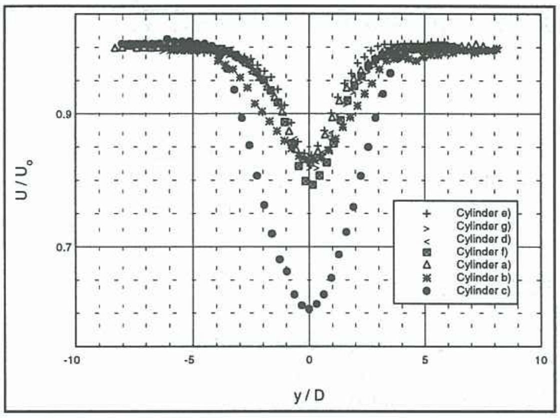

**Figure 3** : Normalised Mean Velocity Profiles (Single Hot Wire Measurements at x = 30D).

| Cylinder | $Re_D$ | x/D | $C_D$ (mean) |
|---|---|---|---|
| a) | 2120 | 30 | 0.941 |
| b) | 2120 | 30 | 1.407 |
| c) | 2090 | 30 | 2.463 |
| c) | 2090 | 40 | 2.523 |
| d) | 2115 | 30 | 1.004 |
| e) | 2330 | 30 | 0.817 |
| f) | 2320 | 30 | 0.880 |
| g) | 2105 | 30 | 1.005 |

**Table 1**: Drag Coefficient ($C_D$) from single hot wire measurements.

### Cross Wire Measurements

Since cylinder c) had such significantly different $U/U_o$ and $u'/U_o$ distributions (see Olsen and Rajagopalan 1997) and a large $C_D$, a cross wire probe was used to obtain u', v' and Reynolds shear stress $\overline{uv}$, for comparison with a circular cylinder. Distributions of $U/U_o$, $u'/U_o$ and $v'/U_o$ against y/D are presented in Figures 4 and 5. Again it was found that the velocity defect for cylinder c) was much larger than for cylinder a) though, the centre-line velocity defect was somewhat less for the cross wire probe measurements. A double maxima in $u'/U_o$ for cylinder c) was also found with the cross wire probe although a distinct double maxima in $v'/U_o$ at x = 40D was not found.

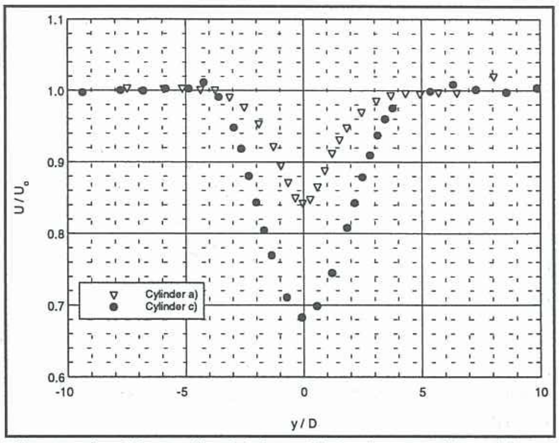

**Figure 4** : Normalised Mean Velocity Profiles (Cross Wire Measurements at x = 40D).

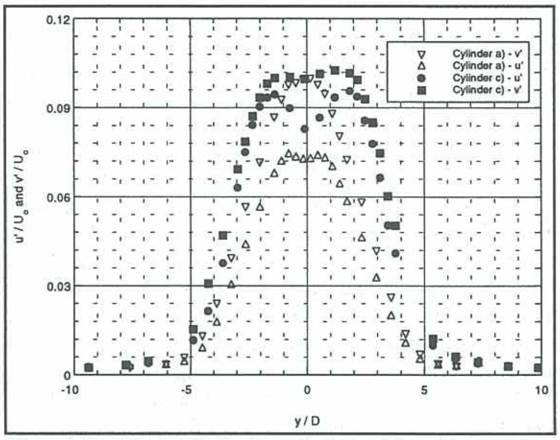

**Figure 5** : Normalised u' and v' Profiles (Cross Wire Measurements at x = 40D).

The cross wire probe seems to under-estimate the values of $C_D$ obtained by using a single hot wire probe by 8% and 20% for cylinder a) and c) respectively. Estimates of $C_D$ values from cross wire measurements are presented in Table 2. These differences may be attributed to the fact that cross wire probe introduces a larger disturbance to the flow compared to a single hot wire.

The normalised distribution of Reynolds shear stresses, $\overline{uv}/U_o^2$ for cylinders a) and c) are presented in Figure 6. The spread in the y direction, at x = 40D is similar for both cylinders. Interestingly the maximum Reynolds shear stress for cylinder c) was found to be more than twice that of cylinder a). This improved correlation between between u and v suggests that the strength of vortices is increased for cylinder c).

| Cylinder | $Re_D$ | $C_D$ (mean) | $C_D$ (fluctuating) | $C_D$ (total) |
|---|---|---|---|---|
| a) | 2150 | 0.863 | -0.034 | 0.829 |
| b) | 2075 | 2.031 | -0.025 | 2.006 |

**Table 2**: Drag Coefficient ($C_D$) from cross wire measurements.

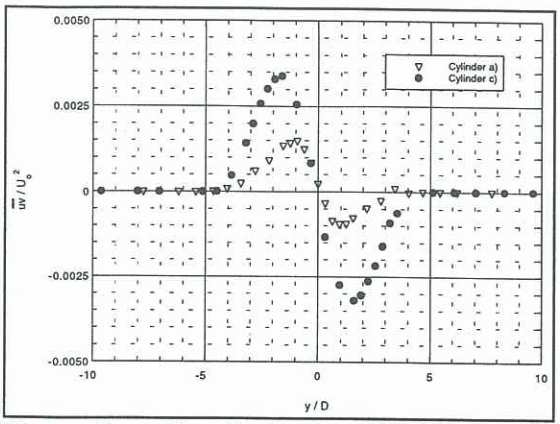

**Figure 6** : Normalised Reynolds Shear Stress Distribution.

### Hot Wire Trace Signals

To provide some visual information on the strength and stability of shed vortices, from cylinder c) compared to cylinders b) and a), u signals from the single hot wire probe at x = 5D are presented in Figure 7. Also shown in the same figure are spectra for these cylinders at x = 5D.

The signals were obtained by placing the hot wire at a location where the vortex shedding was at a maximum. For cylinder c), the hot wire probe was located y = 1D, whereas for both cylinders b) and a) it was y = 2.5D. It can be seen that the amplitude of vortex shedding is increased by the inclusion of a slit normal to the flow (cylinder b)) whilst a further addition of a concave rear notch has the effect of both increasing the amplitude of vortex shedding and improving the stability. Cylinder c) exhibited good periodicy at y = 2.5D, although the amplitude of the trace signal at this location was lower than cylinders b) and a). This suggests that the concave rear notch of cylinder c) helps to form vortices closer to the flow centre-line than the other two cylinders.

### CONCLUSIONS

The variation of $St_D$ with $Re_D$ was significantly altered by the modifications made to a circular cylinder. In particular, the cylinder modified similar to that of Popiel et al gave a reasonably constant $St_D$ for $Re_D$ between 600 and 2090.

Values for $C_D$ for cylinder c) being at least twice that of a circular cylinder, was the largest of all of the cylinders tested. The cylinder with a slit normal to the flow (cylinder b)) yielded $C_D$ significantly different for the circular cylinder. The other cylinders did not exhibit any significant variation in $C_D$ values. For cylinder c), Reynolds shear stresses were found to have a maximum value of approximately 2.5 times. Hot wire traces showed that cylinder c) gave the strongest and most stable vortex shedding compared to the other cylinders.

Finally, the results show that in terms of improving strength and periodicy of vortices, the cylinder of Popiel et al was superior followed by the cylinder with a slit normal to the flow. This cylinder however did not give a reasonably constant value of $St_D$ for the range of $Re_D$ examined. It would also appear from the results that the stronger the vortices shed, the higher the $C_D$.

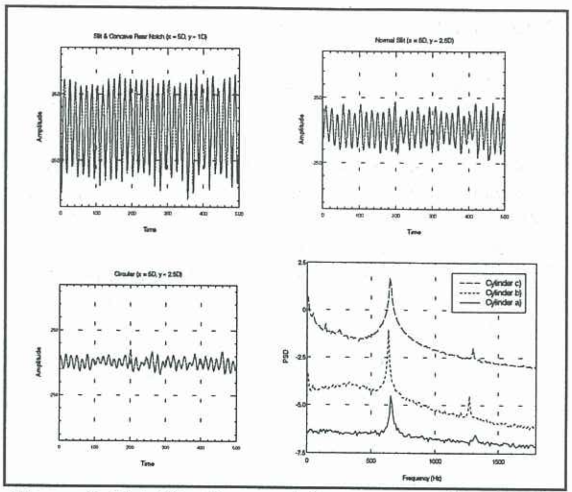

**Figure 6** : Hot Wire Trace and Spectra at x = 5D. (Real time in seconds on trace axes is (Time/$10^4$))

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