11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

AN EXPERIMENTAL INVESTIGATION OF THE SEPARATING SHEAR LAYER FROM A CIRCULAR CYLINDER

Jie WU[1], J. SHERIDAN[1], J. SORIA[2], M.C. WELSH[2] and G.J. WALKER[3]

[1]Department of Mechanical Engineering, Monash University, Clayton, VIC 3168, AUSTRALIA

[2]CSIRO Division of Building Construction & Engineering, PO Box 56, Highett, VIC 3190, AUSTRALIA

[3]Dept Civil & Mechanical Engineering, University of Tasmania, GPO Box 252C,Hobart, TAS 7001, AUSTRALIA

ABSTRACT

The work described here is an experimental investigation of the separating shear layer from a circular cylinder in crossflow. An acoustic perturbation was applied to study the shear layer development in the near wake region. A scaling argument for the most amplified shear layer frequency suggests that the separating shear layer exhibits characteristics which are typical of the plane mixing layer. It is also found that the width of the separating shear layer can be made to grow more rapidly by applying a low level external excitation in the band of frequencies at which it becomes unstable. Most of the data presented was obtained at a Reynolds number of 4400.

NOTATION

D	diameter of cylinder (m)
f_t	shear layer instability frequency (Hz)
f_v	Strouhal vortex frequency (Hz)
f_s	Sound frequency (Hz)
Re	Reynolds number based on cylinder diameter
t	time (sec)
T	Strouhal shedding period (sec)
U_0	free stream velocity (m/s)
U_1	velocity at high speed side of shear layer(m/s)
U_2	velocity at low speed side of shear layer(m/s)
u	streamwise velocity(m/s)
u'	RMS of fluctuating velocity(m/s)
x	streamwise coordinate (m)
y	transverse coordinate (m)
y_c	shear layer centre position (m)
θ	shear layer momentum thickness (mm)
θ_0	initial shear layer momentum thickness (mm)

INTRODUCTION

Typical flow patterns for a circular cylinder in crossflow are shown in Fig. 1 (a),(b); the flow visualization pictures were taken in a water tunnel. Prior to the formation of the Strouhal vortex street, small scale vortices due to the shear layer Kelvin-Helmholtz(KH) instability develop and merge into the the primary vortex. The separating shear layer is extremely sensitive to external disturbances; it can be excited with low level perturbations. Fig.1(b) shows the shear layer being excited by a transverse velocity perturbation.

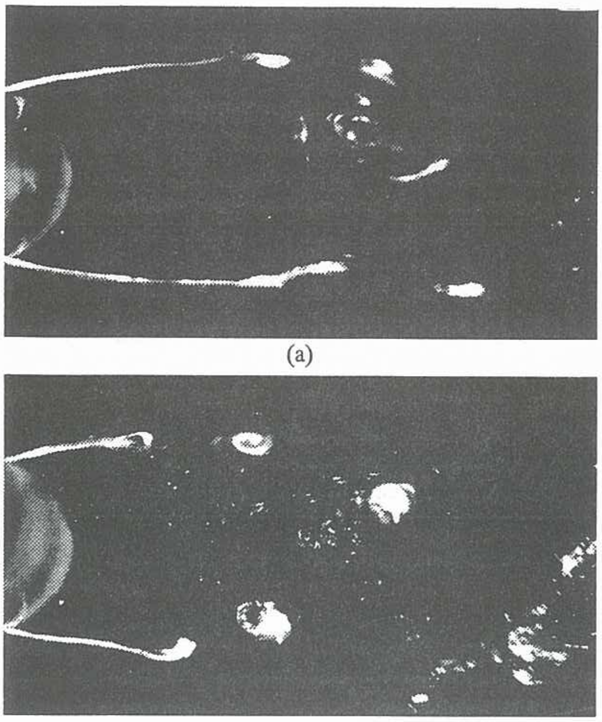
Bloor(1964) appears to have been the first to observe these secondary vortices. She noted their similarity to the Tollmien–Schlichting waves seen in boundary layers and suggested their possible importance as a route in the transition to turbulence. Wei and Smith (1986), using a flow visualization technique and hot-wire anemometry, examined this phenomenon in the Reynolds number range 1200-11000. They established a 0.87-power law relationship between the shear layer instability frequency and the Reynolds number. Kourta et al. (1987), using hot-film anemometry and flow visualization, studied the problem in the Reynolds number range 2000-60000. Their results showed that shear layer instability waves can be clearly identified in the power spectrum of velocity measured just downstream of the separation point. They found a 0.5-power law, the same as that found originally by Bloor (1964). They also observed non-linear interactions between the primary and secondary vortices in the velocity spectrum at low Reynolds numbers. They believed these to be a major event in the transition to turbulence of the wake. Filler et al. (1991) investigated the shear layer separating from a circular cylinder when perturbed by a rotational oscillation. They demonstrated the existence of two modes of the instability, corresponding to the primary and the secondary vortices.

In the present study, flow visualization was conducted in a water tunnel. A transverse oscillation of the velocity field was imposed through flexible mounted test section walls to excite shear layer vortices. Further quantitative measurements were conducted in a wind tunnel, where sound was applied in a similar manner, to study the dynamic process of the shear layer development.

EXPERIMENTAL FACILITIES

Open-jet Wind Tunnel

The experimental arrangement is shown schematically in Fig. 2. Air from the fan is directed through a diffuser to a settling chamber containing screens and a honeycomb. The air then passes through an 8:1 contraction



(a)

(b)

Figure 1: Flow visualization of the separating shear layer from a circular cylinder: $D = 25.1mm, U_0 = 0.110m/s, Re = 2260, f_v = 0.933Hz$. (a) Natural Shedding. (b) Forced at 4.38 Hz and $u'/U_0 \approx 3\%$

to form an open jet which has an outlet section of 244 mm square. The operating range of the tunnel was 0–15m/s. The mean velocity profile in the core of the jet was uniform within ±0.5%, while the longitudinal turbulence level was typically 0.3% when bandpass-filtered between 0.1 and 2 kHz.

Two loud-speakers were positioned downstream of the jet 350 mm apart. They were connected in anti-phase and driven by a function generator via an audio amplifier to produce a sinusoidal acoustic standing wave across the flow with harmonics at least 30 dB below the fundamental. The acoustic particle velocity was estimated to be around 10 mm/s, or about 0.5 % of free stream flow velocity.

An acrylic circular cylinder of 25.1 mm diameter and 244 mm length fitted with two endplates was used as a test model.

A TSI hot-wire anemometer was used to measure the longitudinal velocity. The hot-wire sensor was automatically positioned by a two-axis stepper motor traversing mechanism controlled by a personal computer.

The streamwise and lateral stepping resolutions were 0.2 mm and 0.01mm respectively.

A Boston 12-bit A/D board interfaced to the PC was used for data acquisition. The data sample length was typically 20×8192 at a sampling frequency of 2000 Hz, corresponding to 1600 Strouhal vortex cycles.

FFT calculations and spectral analysis were carried out using the "Signal Technology" Interactive Laboratory System (ILS) software.

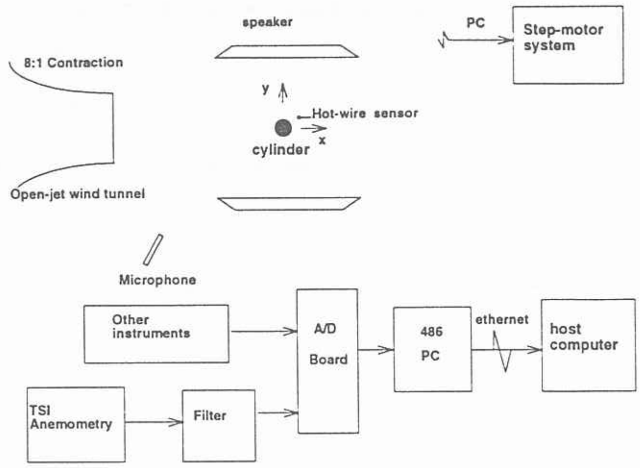


Figure 2: Experimental set-up in a wind tunnel

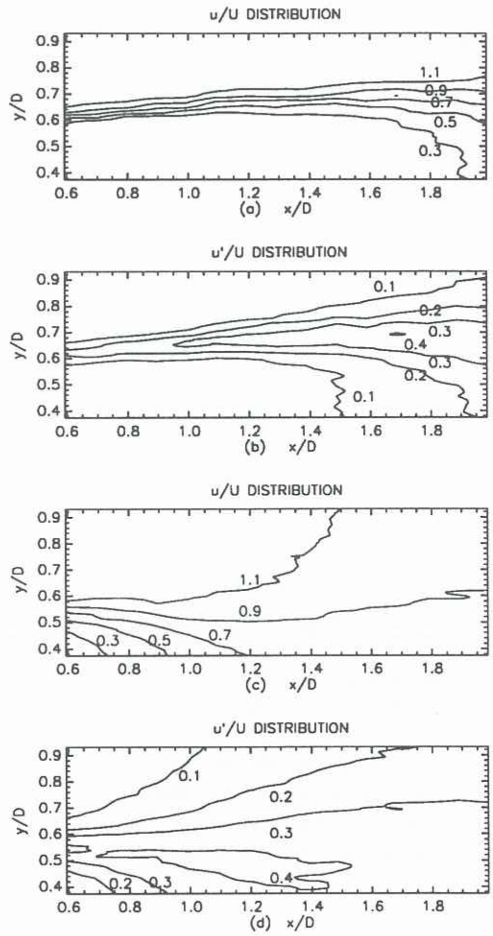


Figure 3: Time-mean longitudinal velocity profile around the separating shear layer, $Re = 4400, U_0 = 2.6m/s, D = 25.1mm$: (a) u/U distribution at natural shedding. (b) u'/U distribution at natural shedding. (c) u/U distribution at forced shedding, forcing frequency $f_s = 120.9$ Hz (d) u'/U distribution at forced shedding

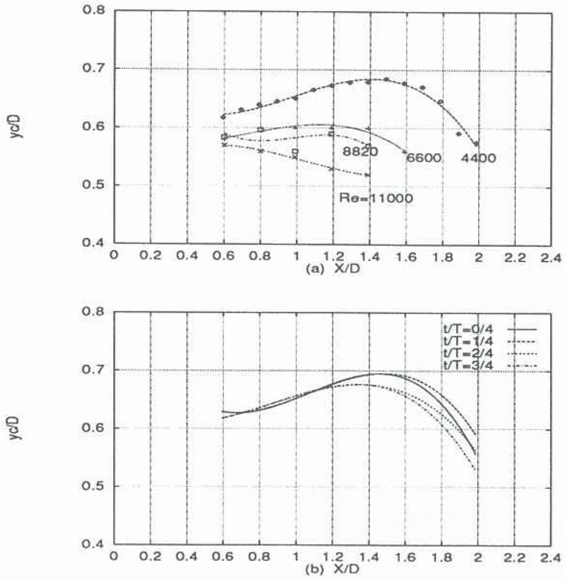


Figure 4: The shear layer locus: natural shedding. (a) Time-mean shear layer over a range of Reynolds number. (b) Phase-averaged shear layer, Re = 4400.

Water Tunnel

Extensive experimental observations were carried out using flow visualization in a water tunnel. Details of the water tunnel have been described by Welsh et al. (1991). Hydrogen bubbles illuminated by laser light were used to visualize the flow.

RESULTS

Time-mean Velocity Profile

The time-mean longitudinal velocity field was measured at 435 spatial points, at 15 streamwise stations. Since the flow can reverse in the region immediately behind the cylinder, the measurements started at y/D=0.39, in the vicinity of the separating shear layer position, where a pronounced velocity gradient is observed. The velocity at the low speed side of the shear layer is practically zero.

Contours of velocity u and RMS of the fluctuating velocity u', normalized with the free stream velocity U_0 are shown in Fig. 3 (a) and (b).

It is clear that the maximum u' occurs where the velocity gradient of the shear layer is highest.

Fig. 3 (c),(d) show the effects of applying a perturbation to the time-mean velocity distribution. The forcing frequency was 120.9 Hz and the amplitude was approximately 0.5% U_0. The Strouhal vortex frequency was 19.53 Hz. The forcing frequency was chosen to be comparable with the most amplified frequency of the shear layer. Perturbing the shear layer causes it to spread more rapidly.

The locus of the time-mean shear layer centre, based on the maximum u', is plotted in Fig. 4(a), for a range of Reynolds number. The phase-averaged velocity distribution was also recorded. The reference signal for phase-averaging was taken by a hot-wire sensor located downstream of the cylinder outside the wake, where a near pure periodic Strouhal vortex velocity fluctuating signal could be detected. The locii of the shear layer at four phase positions, each 90 degrees apart, are plotted in Fig. 4(b). The flapping of the shear layer due to the primary vortex shedding is only evident downstream the primary vortex formation region ($x/D > 1.2$).

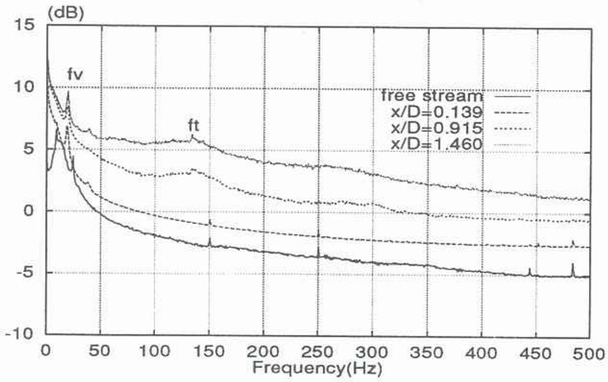


Figure 5: Velocity spectra of the shear layer: natural shedding

Velocity Spectra

Longitudinal velocity fluctuation spectra were obtained at a number of x locations for a Reynolds number of 4400. In order to include the background effects on the shear layer development, two hot-wire sensors were used. One was placed in the free stream, and the other was traversed along the shear layer. The results for unperturbed flow are shown in Fig. 5. The Strouhal shedding frequency was 19.53 Hz. The shear layer instability wave can only be detected in the velocity spectrum for $x/D > 0.7$ for a Reynolds number of 4400. A peak corresponding to shear layer frequency at $f_l \approx 133.0Hz$ can be found for $x/D > 0.7$. A high frequency disturbance($\approx 480Hz$) embedded in the free stream was damped out at downstream positions; because the frequency was outside the range of the shear layer amplification region.

Scaling Analysis For The Shear Layer Instability Frequency

The measurement of the shear layer frequency was conducted using a perturbation method; this helped to improve the accuracy of the measurement. Detailed results have been reported by Sheridan et al.(1992).

The most amplified shear layer KH instability frequency f_l can be predicted from linear instability theory (Ho and Huerre 1984)

$$\frac{\theta_0 f_l}{U} \approx 0.032 \qquad (1)$$

U is the average velocity of the shear layer, $U = (U_1 + U_2)/2$, where U_1 and U_2 are flow velocities at the high and low speed sides of the shear layer. Since $U_2 \approx 0.0$, $U_1 \propto U_0$, and $f_v D/U_0 \approx 0.2$, we have the following equation

$$\frac{f_l}{f_v} = c\frac{D}{\theta_0} \qquad (2)$$

Where f_v is the Strouhal vortex frequency and θ_0 is the momentum thickness of the shear layer behind

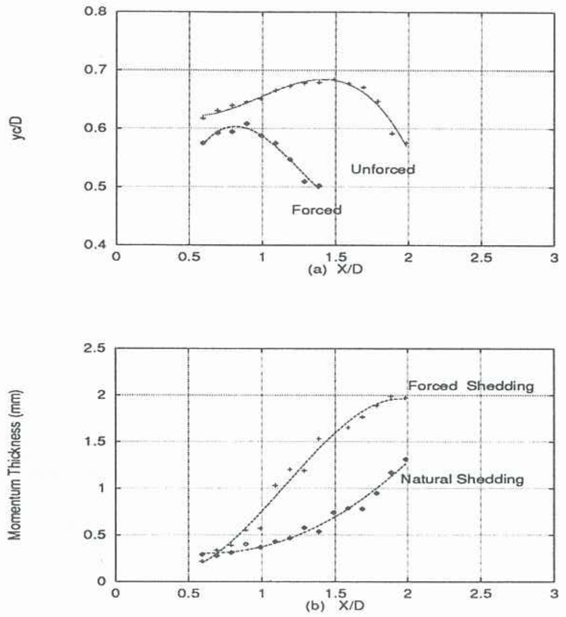


Figure 6: The influence of the perturbation on the separating shear layer, f_s = 120.9 Hz (a) time-mean shear layer locus (b) time-mean shear layer momentum thickness

the separation point. If $U_2 = 1.2U_0$, then c is found theoretically to be 0.096. The time-mean velocity profile across the separating shear layer from the cylinder was measured over a Reynolds number range of 4400 to 11000; c is found experimentally to be around 0.090 in this range. This indicates a close resemblance of the separating shear layer to the classic plane mixing layer.

Influence Of Excitation On Shear Layer

Time-mean velocity profiles under an external low level forcing condition are shown in Fig. 3(c),(d). The forcing frequency is comparable with the most amplified instability frequency. Modification of the shear layer due to forcing is obvious. The locus of the shear layer is plotted for both the unforced and forced cases, in Fig. 6 (a). Under a forced condition the shear layer is substantially "pushed" inward to the centre of the wake, reducing considerably the area of the dead fluid zone; the formation length of the primary vortex is also reduced.

The streamwise variation of momentum thickness θ for both natural and perturbed conditions is shown in Fig. 6(b). Due to the external forcing the entrainment process of the irrotational fluid into the secondary vortices is enhanced, causing more rapid thickening of the shear layer. When no forcing is used: $d\theta/dx = 0.022 - 0.043$. Under the low level ($\approx 0.5\% U_0$ and 133.9Hz) forcing, $d\theta/dx \approx 0.062$, a significant increase.

DISCUSSION

The experimental results presented here show that the shear layer from the cylinder prior to the formation of the Strouhal vortex street has similar characteristics to those of the classic plane mixing layer. In the plane mixing layer the main driving force for the shear layer development is the formation of the spanwise quasi-two-dimensional vortical structure due to the KH instability. The fluid entrainment process, and therefore heat and momentum transfer, can be greatly enhanced by exciting the mixing layer, even for small amplitude perturbations.

The development of the shear layer behind a cylinder can also be greatly modified through the application of an external perturbation. When external forcing is applied the shear layer position can be altered causing a smaller "dead-flow" zone and hence reducing the Strouhal vortex formation length and thickening the shear layer. Corresponding modifications of many practically important parameters, e.g. increase in heat transfer coefficient, change of drag can be expected.

CONCLUSION

Before interacting with each other to form the Strouhal vortex street, the separating shear layer from a circular cylinder in crossflow exhibit a mixing layer type KH instability. Excitation of the separating shear layer has a marked influence on unsteady flow in the shear layer and significantly modifies the mean flow pattern downstream of the cylinder.

Acknowledgement

Wu J. and Dr Sheridan J. acknowledge the support of an Australian Research Council Grant.

REFERENCE

Bloor, M.S. (1964), "The transition to turbulence in the wake of a circular cylinder", *J. Fluid Mech.*, 19, 290-304.

Filler, J. R., Marston P. L. and Mih, W.C. (1991), "Response of the shear layers separating from a circular cylinder to small-amplitude rotational oscillations", *J. Fluid Mech.*, 231, 481-499.

Ho, C.M. and Huerre, P. (1984), "Perturbed Free Shear Layers", *Ann. Rev. Fluid Mech.*, 16, 365-424.

Kourta, A., Boisson, H.C., Chassaing, P. and Ha Minh, H. (1987), "Nonlinear interaction and the transition to turbulence in the wake of a circular cylinder", *J. Fluid Mech.*, 181, 141-161.

Sheridan,J., Soria J., Wu,J., and Welsh, M. C. (1992) "The Kelvin-Helmholtz Instability of the Separating Shear Layer From a Circular Cylinder", to appear in *Bluff-Body Wakes, Dynamics and Instabilities*, Gottingen, Germany, 7-11 Sept. 92

Wei, T. and Smith, C.R. (1986), "Secondary vortices in the wake of circular cylinders", *J. Fluid Mech.*, 169, 513-533.

Welsh, M.C., Hourigan, K., Welch, L.W., Downie, R.J., Thompson, M.C. and Stokes, A.N. (1991), "Acoustics and Experimental Methods: The Influence of Sound on Flow and Heat Transfer", *Experimental Thermal and Fluid Science*, 3, 138-152.