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Vortex shedding from bluff bodies in a shear flow

By D. J. MAULL AND R. A. YOUNG
Engineering Department, University of Cambridge

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Experiments are described in which the vortex shedding from a bluff body and the base pressure coefficient have been measured in a shear flow. It is shown that the shedding breaks down into a number of spanwise cells in each of which the frequency is constant. The division between the cells is thought to be marked by a longitudinal vortex in the stream direction and this is supported by evidence from experiments where a longitudinal vortex was generated in an otherwise uniform flow.

1. Introduction

The vortex shedding from, and the base pressure on, bluff bodies placed in a uniform stream have been extensively studied for many years and excellent reviews have been published by Morkovin (1964), Marris (1964) and more recently by Berger & Wille (1972). There are, however, practical cases where the flow approaching the body is not uniform but is sheared, with the free-stream velocity varying in the direction of a generator of the body. One case of importance where there is such a velocity variation is that of a structure, such as a chimney, present in the earth's boundary layer. Since structural oscillations can be caused by the vortex shedding from such a body it is important to know if the presence of the shear in the oncoming stream can have much effect on the mechanism by which the vortices are shed.

Very little work has in fact been reported on the effect of shear. The effect of shear on the pressure distribution on bluff bodies has been investigated by Baines (1963) and Gould, Rayner & Ponsford (1968) amongst others, but the effect on the vortex shedding process has received very little attention. Chen & Mangione (1969) reported some measurements of the vortex shedding from circular cylinders in a shear flow and found that, within the accuracy of their measurements (about 10 %), the Strouhal number fd/u was constant along the length of the cylinder. In this Strouhal number, f is the frequency, d the cylinder diameter and u the local velocity at the height in the free stream corresponding to their measurement point on the cylinder. Thus they found that the vortex shedding frequency varied continuously along the body. A similar result was found by Maull (1969) in a preliminary investigation of the shedding from a flat plate normal to a shear flow, although in this case there was a slight variation of Strouhal number along the span of the plate which, at the time, was not thought to be significant. Shaw & Starr (1972), however, investigated shear flow past a circular cylinder and whilst giving no detailed results for the vortex shedding frequency stated that 'synchronized shedding' occurred over part of the cylinder.

The response of a tower of square cross-section was investigated by Whitbread (1968) and he showed that its response when placed in a shear flow was quite different to that in a uniform flow. In this case, however, in generating the shear flow quite high turbulence levels were produced which may have changed the response.

The primary difference between a uniform flow and a shear flow is the presence, in the shear flow, of vorticity whose vector is normal to the plane of the flow. As the shear flow approaches the body this vorticity vector is progressively turned until eventually the vorticity near the body is bent into the flow direction. At the trailing edge of the bluff body vorticity in the boundary layer whose vector is parallel to a generator of the body is shed and this rolls into the familiar Kármán vortex street. It is the interaction between this usual vorticity and the free-stream vorticity that is the subject of this paper.

If the body has a sharp trailing edge then the interaction between the main-stream vorticity and the body may be amenable to a theoretical treatment and a good review of this topic has been given by Hawthorne (1967).

2. Apparatus

The experiments were performed in a low-speed wind tunnel with a working section height l of 50·8 cm and a width of 71 cm. The shear flow was generated by means of a curved gauze as described by Maull (1969). The turbulence level was about 0·5 %, based upon the local velocity, which is much lower than the turbulence level produced by other methods of generating shear flows such as rods placed across the flow. The velocity profile produced by this gauze, measured at the position of the model, is shown in figure 1.

The model is shown in figure 2 and consisted of a semi-elliptic nose followed by a parallel-sided section. The chord of the model was 15·24 cm and the base thickness d was 2·54 cm. The model spanned the height l of the tunnel. All the experiments for the pressure distributions and the wake measurements were carried out at a Reynolds number of $2{\cdot}85 \times 10^4$ based on the base thickness d for both the shear flow and the uniform flow. In the case of the shear flow the velocity used in the Reynolds number was the stream velocity U at the centre-line of the tunnel at $y = 10d$.

Measurements of the vortex shedding were carried out using DISA hot-wire anemometers, the hot-wire signal being recorded on magnetic tape and subsequently analysed on a digital computer. No blockage corrections have been applied to the results.

3. Results

3.1. *Uniform flow*

The variation of the base pressure coefficient C_p along the span of the model is shown in figure 3 for the case of uniform flow. As has been noted before in many investigations the base pressure is far from constant across the span with only

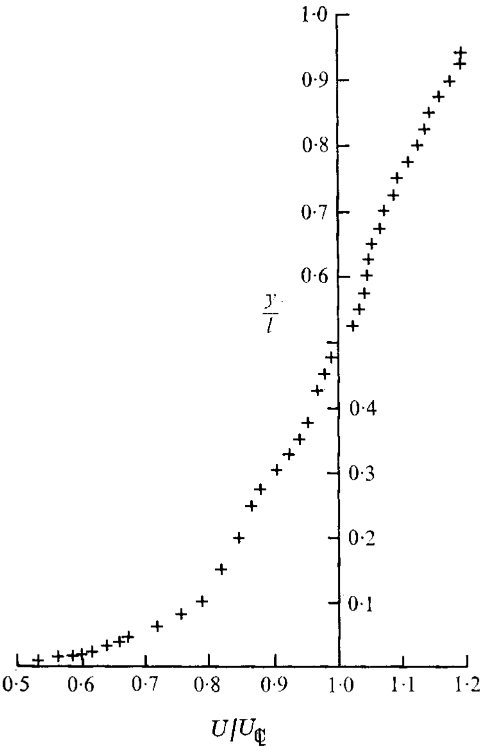

FIGURE 1. Velocity profile across the wind tunnel. $U_{℄}$ is the velocity on the tunnel centre-line ($y/l = 0{\cdot}5$).

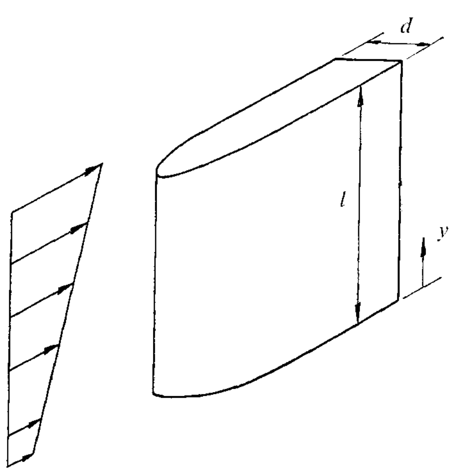

FIGURE 2. The body tested.

a small region in the centre where the flow could possibly be said to be two-dimensional. The regions $y/d < 8$ and $y/d > 13$ are dominated by effects due to the boundary layers on the floor and roof of the tunnel producing strong trailing vortex systems in these regions. The asymmetry of the pressure distributions is due to slightly differing floor and roof geometries. The boundary layers on the

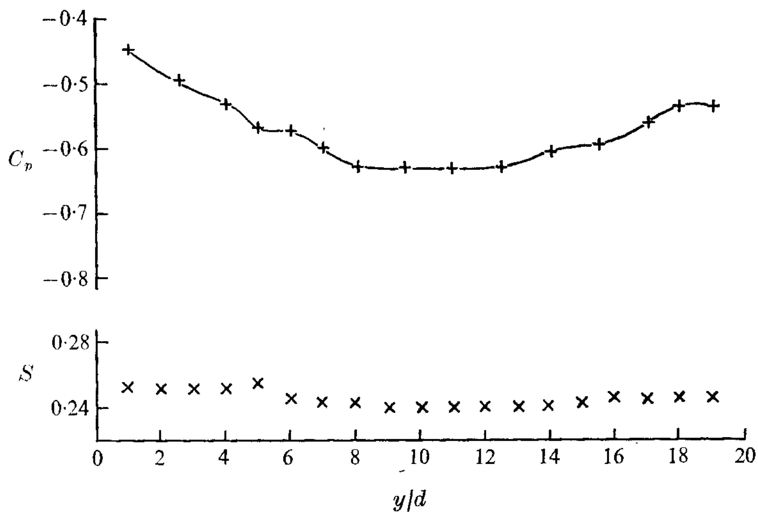

FIGURE 3. Uniform flow. +, base pressure coefficient across the span; ×, Strouhal number across the span.

floor and roof of the tunnel at this Reynolds number extend over the regions $0 < y/d < 1{\cdot}5$ and $18{\cdot}5 < y/d < 20$, for the uniform-flow case. Thus their influence on the base pressure is over a distance much greater than their thickness.

A hot wire placed six base thicknesses downstream of the base and two base thicknesses out from the centre-line of the wake was used to measure the vortex shedding frequency for different positions y along the span. The hot-wire records were digitally analysed and the Strouhal number $S = fd/U$, where U is the free-stream velocity, corresponding to peaks in the power spectral density is also plotted on figure 3. It is noticeable that in the regions influenced by the end effects there is a change in Strouhal number and this change occurs where there is a change in slope of the curve of C_p against y/d. At $y/d = 5$ two distinct peaks are discernible in the spectra, indicating that at this point the hot wire was picking up vortex shedding frequencies from the centre of the span and from the root region.

There is therefore a situation, in this uniform-flow case, where large changes in the base pressure coefficient can occur in regions where the Strouhal number remains constant. There is also evidence that vortex shedding is occurring in cells and that the boundary of these cells is marked with a change in slope of the base pressure curve.

3.2. *Shear flow*

We now turn to the case of shear flow in the approaching stream. In this case the Strouhal number may be defined and the base pressure non-dimensionalized using either the centre-line velocity or the velocity in the undisturbed free stream corresponding to the point y along the span under consideration. The variation of the base pressure coefficient along the span non-dimensionalized with the local free-stream velocity is shown on figure 4, where it is compared with

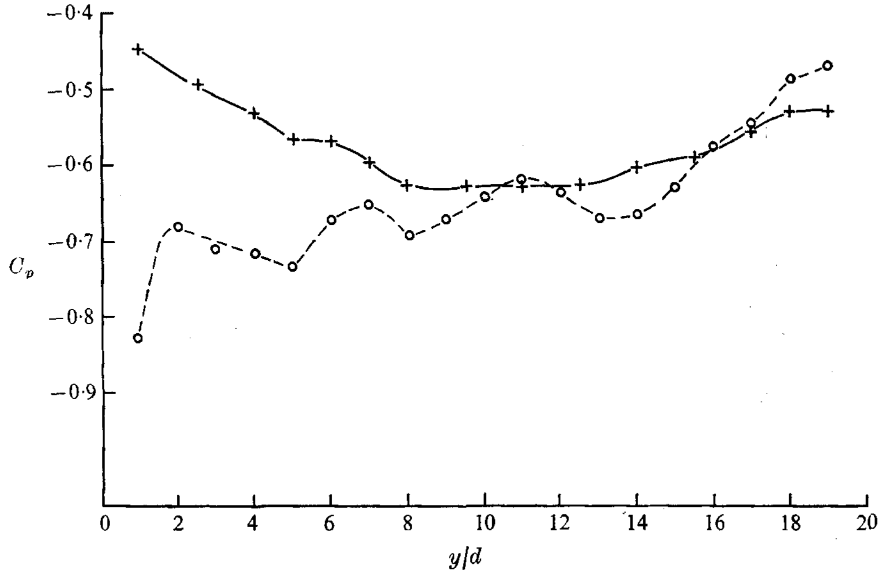

FIGURE 4. Base pressure coefficient across the span. +, uniform flow; ○, shear flow, based on the local velocity.

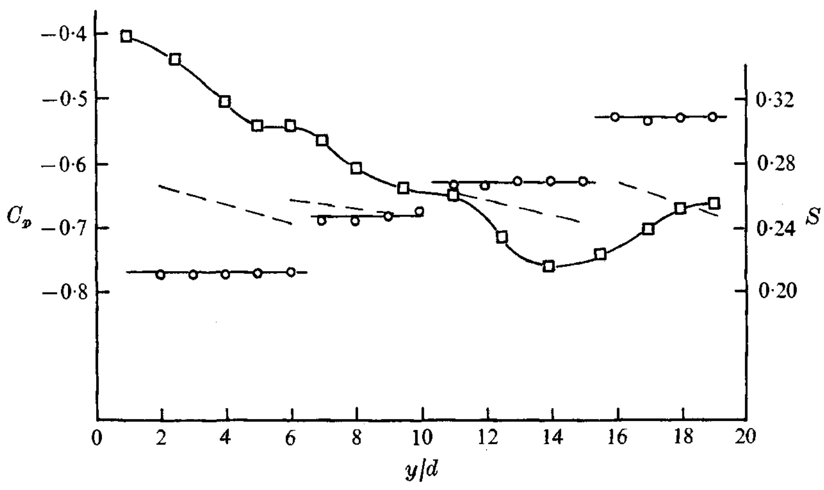

FIGURE 5. Shear flow. □, base pressure coefficient based on the centre-line velocity; ○, Strouhal number based on the centre-line velocity; – – –, Strouhal number based on the local velocity.

the case of uniform flow. It is obvious that the local pressure coefficient is not equal to the uniform-flow value, at least for the shear flow used here.

The base pressure coefficient and the Strouhal number based on the centre-line velocity are shown in figure 5. The frequency spectra from which these Strouhal numbers have been calculated are shown on figure 6, where the bandwidth for the analysis was 3·16 Hz and the signal was recorded for 99·8 s.

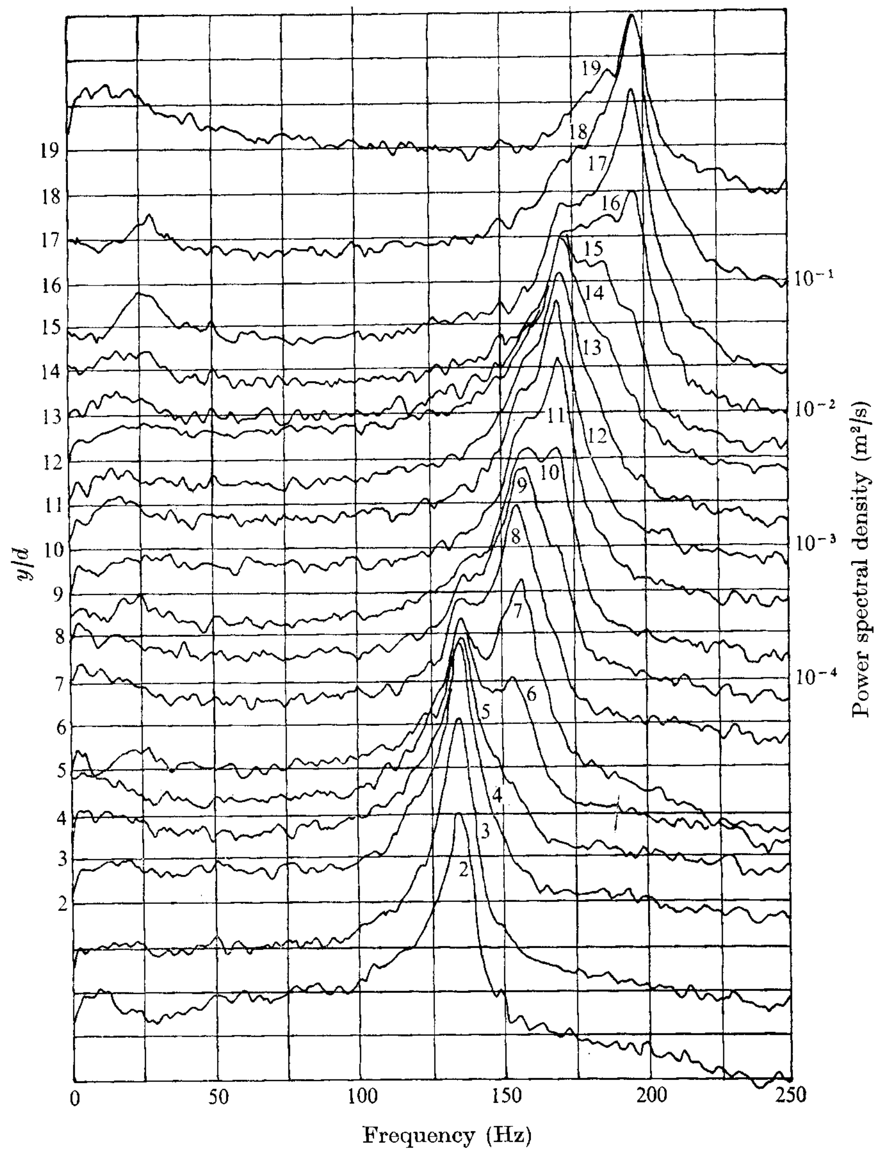

FIGURE 6. Frequency spectra for shear flow at various positions across the span.

4. Discussion

From figure 5 it may be seen that in the shear-flow case the frequency of vortex shedding appears along the span of the model in four cells and in each cell the frequency is constant. Thus, referring to the frequency spectra of figure 6 we can see that for $0 \leqslant y/d \leqslant 6$ the main shedding frequency is about 135 Hz with a jump at $y/d = 7$ to 160 Hz. This frequency is present until $y/d = 10$, when the shedding frequency changes to 170 Hz, and this frequency then continues to $y/d = 15$. Finally at $y/d = 16$ a frequency of 190 Hz appears. At some values of

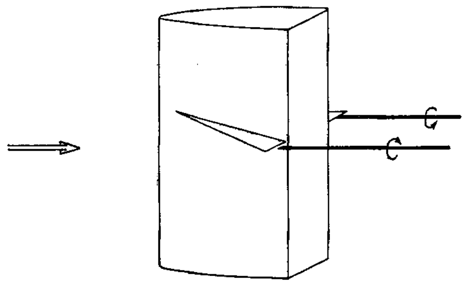

FIGURE 7. Model with vortex generators.

y/d, for instance at $y/d = 7$, two peak frequencies occur when the hot wire is picking up signals from two cells.

One interpretation of this change in Strouhal number is that the flow attempts to maintain a constant Strouhal number based on the local velocity, but that the coherence of the shed vortices requires a constant frequency over certain lengths. From $y/d = 2$ to $y/d = 19$ the Strouhal number based on the local velocity varies in a band from 0·24 to 0·27 as shown on figure 5.

Comparison between the Strouhal number and the base pressure coefficient on figure 5 shows that the division between the cells of frequency is also apparent on the curve of pressure coefficient. At $y/d = 6$ the slope of the pressure coefficient curve shows a marked change and another change occurs at $y/d = 10$. In the uniform-flow case (figure 3) there is again a change in the slope of the pressure coefficient curve at $y/d = 6$, where the Strouhal number undergoes a change. Within each cell the pressure coefficient can vary, whilst the vortex shedding frequency remains constant.

The effect of the shear flow in the stream, whether it is coming from the boundary layers on the floor and roof of the tunnel as in the case of the uniform flow or is distributed throughout the flow as is the case in the shear flow, is to divide the vortex shedding and pressure distribution into spanwise cells. If we take the case of the shear flow, the effect of the body is to turn the vorticity vector, which was originally normal to the plane of the flow, progressively into the stream direction near the body. We then have an interaction between this free-stream vorticity, now in the flow direction, and the vorticity which rolls up into a vortex street.

Smoke photographs of the flow indicated that the divisions between the cells were marked with longitudinal vortices lying in the free-stream direction and it is postulated that these vortices are due to a rolling up of the original distributed vorticity into concentrated trailing vortices at the base. In order to test whether a longitudinal vortex could alter the vortex shedding the model was equipped with a slender delta wing as shown in figure 7 and tested in the uniform flow. When the delta is put at incidence to the flow a strong longitudinal vortex will be produced as sketched in figure 7. The vortex shedding frequency and base pressure coefficient measured across the span are shown on figure 8 and it is evident that a significant change in shedding frequency was produced, although the mechanism which produces this change in shedding frequency is not known.

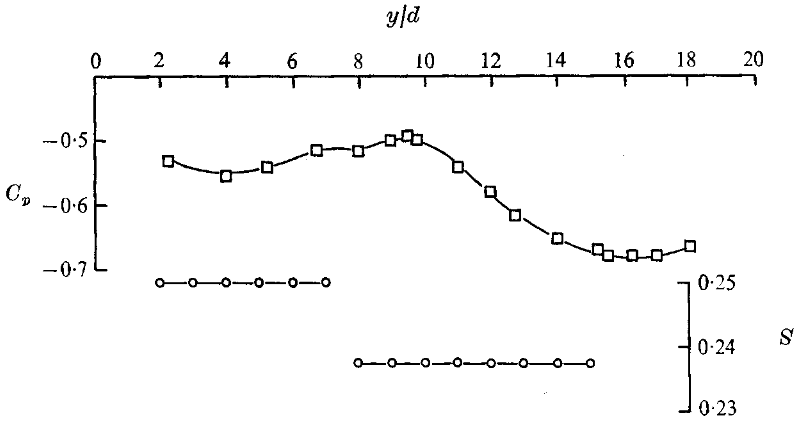

FIGURE 8. Uniform flow over model with vortex generators. ○, Strouhal number; □, base pressure.

The trailing edge of the delta was at $y/d = 10$, but the longitudinal vortices formed were convected downwards towards the tunnel floor so that at the hot-wire position, six base thicknesses downstream, they were approximately at $y/d = 8$.

At a low Reynolds number, Gaster (1971) found that introducing a slight distortion into an otherwise non-uniform flow produced two different vortex shedding frequencies from a circular cylinder. At a much higher Reynolds number Kuethe (1972) introduced longitudinal vorticity into the wake of a flat plate by placing vortex generators at the trailing edge, and found that a large number of these generators completely suppressed the vortex shedding. A notched aerofoil with a blunt trailing edge as tested by Tanner (1972) produced large changes in base pressure which were possibly accompanied by the suppression of the vortex street by longitudinal vortices produced by the serrations.

5. Conclusions

It has been shown that vortex shedding from a bluff body in a shear flow can occur in spanwise cells, the frequency being constant in each cell. It is suggested that a longitudinal vortex marks the boundary of each cell and that these longitudinal vortices come from the rolling up of the initial vorticity in the stream. The presence of a longitudinal vortex in an otherwise uniform flow can cause a jump in shedding frequency along the span of the body with a consequent variation in the base pressure coefficient. The mechanism of the formation of the cells and the parameter governing the number of cells are not known and remain topics for further research.

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