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Influence of end plates and free ends on the shedding frequency of circular cylinders

By DETLEV GERICH AND HELMUT ECKELMANN
Max-Planck-Institut für Strömungsforschung, D 3400 Göttingen, Federal Republic of Germany

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The cylinder end boundaries, whether they be end plates or simple free ends, alter the vortex-shedding mechanism near these boundaries. This effect has in the past usually been overlooked. In a region near an end plate or a free end (ranging from 6 to 15 cylinder diameters in length), the shedding frequency f_2 is found to be 10–15 % less than the regular Strouhal frequency f_S. The latter frequency is observed over the remaining cylinder length. The simultaneous occurrence of two frequencies results in a beat frequency, which is best observed at the junction of the two regions characterized by f_S and f_2 respectively. A third frequency f_3 with $f_S > f_3 > f_2$ is observed over the entire cylinder length when the cylinder is bounded by two end plates less than 20 to 30 cylinder diameters apart. Here the critical Reynolds number for the onset of shedding is shifted to about 60 and the laminar Reynolds-number range is extended from about 150 to about 250.

1. Introduction

The periodic wakes of circular cylinders have been investigated for more than a hundred years, following the discovery of this phenomenon by Strouhal (1878). The emphasis was usually focused on cylinders with high length-to-diameter ratios ($l/d \gtrsim 100$); therefore the influence of the boundary conditions has seldom been taken into account. These boundary conditions, whether they be walls, end plates or free cylinder ends, have a considerable influence on the shedding mechanism near the boundaries. For very low length-to-diameter ratios ($l/d \approx 15$), however, the shedding from a cylinder can be solely determined by the boundary conditions.

Kovasznay (1949) determined the critical Reynolds number at which the vortex shedding starts for a circular cylinder to be $R_c = 40$. He also found that the vortex street is stable and regular only below $R \approx 160$. Here and in the following, the Reynolds number $R = Ud/\nu$ will be based on the cylinder diameter d, the free-stream velocity U and the kinematic viscosity ν of the fluid. Since Kovasznay investigated only cylinders which were several hundred diameters long he never had a problem with the effects occurring at both ends of the cylinder. Roshko (1954) used for his investigations, like Kovasznay, cylinders with a length of 50 cm. His length-to-diameter ratios ranged from 79 to 2128. Although Roshko corrected his measurements, made in a closed test section, for tunnel blockage, he stated in his paper that 'no attempt is made to account for end effects'. Roshko confirmed Kovasznay's observations of the regular shedding below $R \approx 160$. In addition he found two other characteristic Reynolds-number ranges within the lower end of the shedding range, which he named as follows:

$$\text{stable range} \quad 40 < R < 150;$$

$$\text{transition range} \quad 150 < R < 300;$$

$$\text{irregular range} \quad 300 < R.$$

For both the stable and the irregular range (up to about $R = 2000$), Roshko gave empirical relations between the dimensionless frequency F or the Strouhal number S and the Reynolds number:

$$F = 0{\cdot}212\, R - 4{\cdot}5 \quad (50 < R < 150), \tag{1}$$

$$F = 0{\cdot}212\, R - 2{\cdot}7 \quad (300 < R < 2000), \tag{2}$$

$$S = 0{\cdot}212\left(1 - \frac{21{\cdot}2}{R}\right) \quad (50 < R < 150), \tag{3}$$

$$S = 0{\cdot}212\left(1 - \frac{12{\cdot}7}{R}\right) \quad (300 < R < 2000). \tag{4}$$

The dimensionless frequency $F = fd^2/\nu$ represents the product of Reynolds and Strouhal number $S = fd/U$ for the shedding frequency f on one side of the vortex street. We will call a shedding frequency that is in accordance with these formulae the Strouhal frequency f_S. This Strouhal frequency will be obtained from a sufficiently long cylinder.

Since the present paper is mainly concerned with the laminar range, no comprehensive review of the general literature will be given here. For more details, reference is made to the articles of Morkovin (1964) and Berger & Wille (1972). Five further papers dealing with the special problem of the boundary conditions on a cylinder are noteworthy. Shair *et al.* (1963) and Nishioka & Sato (1974) investigated the effect of confining walls on the stability of the steady wake behind a circular cylinder and found the critical Reynolds number R_c to have a pronounced increase if the length-to-diameter ratio of the cylinder is decreased. The three-dimensional structure of the wake of a circular cylinder was investigated by Gerrard (1966), experiments being made at three different Reynolds numbers, 85, 235 and 2×10^4, with length-to-diameter ratios of the cylinders as low as 87, 32 and 20 respectively. Gerrard was in a position to observe effects similar to those described in the present paper. The effects of end plates on the base pressure coefficient of a circular cylinder were investigated by Stansby (1974). His experiments were performed at Reynolds numbers $1{\cdot}6 \times 10^4$ and 4×10^4, and the geometry of the end plates was varied. Stansby found a substantial reduction of the base pressure for the low length to diameter ratios of his cylinders (8 and 16). Using flow-visualization Slaouti & Gerrard (1981) investigated the influence of a free end on the wake of a circular cylinder. They found a strong bowing of the vortex lines towards the end of their cylinders.

The motive for our investigations came from the idea to design and construct a probe for the measurement of the flow velocity by means of the shedding frequency from a circular cylinder in the stable range. Since for this range (i) a pure sinusoidal hot-wire signal can be observed, the frequency of which is easy to measure with an electronic counter, and (ii) a simple velocity–frequency relation is known from the work of Roshko, it was believed that a simple probe would be obtained by mounting a short circular cylinder directly in front of a hot-wire probe. The frequencies measured with such a probe, however, were always less than those predicted from Roshko's formula. A detailed investigation of this phenomenon showed that the length-to-diameter ratio and the boundary conditions of the cylinder used are very important parameters for the shedding frequency obtained with cylinders of low aspect ratios.

2. Experimental arrangement

The wind tunnel used for this investigation is of open-circuit type. An octagonal inlet covered by filter mats is followed by a honeycomb, driving fan, diffuser, second honeycomb, four screens of different mesh size, quadratic settling chamber and a two-dimensional 5:1 contraction to a 9·50 m long, 1·40 m high and 0·28 m wide test section. For the velocity range from 0·2 to 10 m/s an AC motor with a variable speed gear, and for higher velocities up to 30 m/s, a variable speed DC motor is used. The measurements were made 50 cm downstream of the contraction, midway between the top and bottom plates and a few centimetres upstream of two Plexiglas windows in either side wall which give easy access to the test section. Depending on the flow speed at this location, the boundary layers on both side walls are about one to two centimetres thick. This results in a potential core region of at least 24 cm in which the velocity across the channel is constant and in which the turbulence level is 0·06 % at 1 m/s, increasing to 0·14 % at 5 m/s. The flow speed is controlled by counting the pulses (180 pulses/revolution) from a generator coupled to the fan shaft. The relation between the fan frequency and the flow velocity in the test section was obtained by a Prandtl tube in combination with either a Betz manometer ($U_\infty > 6$ m/s) or a Reichardt pressure balance.

The cylinders investigated were copper, brass or stainless-steel wires of various diameters. Those wires with diameters up to about 1 mm were stretched across the test section through pinholes in the side walls. Tension on the wires was produced by a mechanism normally used for stretching strings of guitars, mounted on a rigid steel frame outside the wind tunnel. By this means the characteristic frequency of the wire could be chosen high enough to avoid interactions with the shedding frequency. The cylinder diameter was always determined in the strained condition. Cylinders more than 2 mm diameter were supported in two notched metal strips fixed to the inner sides of the walls.

The shedding from a cylinder of diameter d was detected with a hot-wire probe always located at $x/d = 10$, $y/d = 2$ and $z = 140$ mm, midway between the side walls and on one side of the Kármán vortex street. The origin of the coordinate system used is situated on one wall; x denotes the oncoming flow direction, y the direction normal to the cylinder axis, and z the direction parallel to the cylinder axis and normal to x. The length-to-diameter ratios of the cylinders investigated were 70 to 280. The shedding frequency was measured either by counting the zero-crossings of the hot-wire signal or with the Lissajous method. The hot wire was always oriented parallel to the cylinder axis. There was no difference when it was positioned perpendicular to the cylinder axis in preliminary tests.

3. Experimental results

When a flow field of a cylinder is investigated in the open test section of a closed-loop-type wind tunnel, end plates are normally applied to eliminate the so-called end effects in an attempt to simulate an infinitely long cylinder. The following experiments show, however, that both end plates and free ends alter the shedding of a cylinder in the neighbourhood of these boundaries.

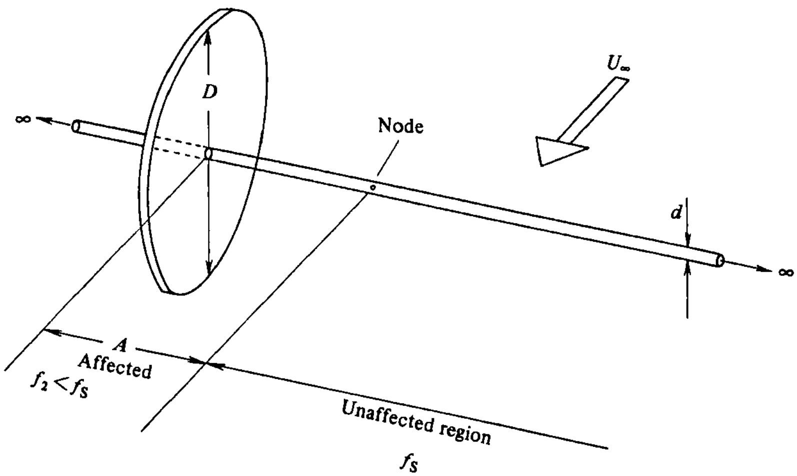

FIGURE 1. Experimental setup.

3.1. *Vortex shedding from a cylinder with one end plate*

In order to understand better the influence of end-plates, the following experiment was carried out. A hot-wire probe is placed in the stable, i.e. laminar, wake ($50 \lesssim R \lesssim 150$) of a cylinder at $x/d = 10$, $y/d = 2$ and $z = 140$ mm. A movable end plate is mounted on the cylinder such that it can easily be slid along the cylinder axis. As long as the end plate is sufficiently far away from the hot-wire probe, say at $z/d \geqslant 100$, the velocity fluctuations detected by this probe are steady both in frequency and amplitude. If the end plate is moved toward the probe the envelope of the extrema of the velocity signal (initially two horizontal straight lines) becomes sinusoidal, its amplitude reaching a maximum before arriving at the probe. Prior to the maximum, a counter shows the Strouhal frequency f_S, and behind the maximum a lower frequency f_2. In the following, the location of the maximum where also the shedding frequency changes unsteadily from f_S to f_2 will be named a node. Figure 1 shows the experimental setup. The region A between end plate and node will be called the affected region.

Typical hot-wire signals of the experiment described are reproduced in figure 2. The uppermost trace shows a signal at $R = 57$ obtained in the unaffected region, i.e. when the end plate is far enough away from the probe. The other three traces show probe signals at three different Reynolds numbers, for the case in which the hot-wire probe is located at the node distance from the end plate. There are eleven oscillations per envelope at $R = 57$ and only six at $R = 154$. Phase discontinuities between the various wave parcels indicated that the signal detected by the hot-wire probe is generated by a superposition of two different oscillations. To distinguish whether this superposition is caused by a modulation or by a beat, the spectrum of the hot-wire signal at the node was measured. Figure 3 shows this spectrum for a cylinder of 1 mm diameter at $R \approx 100$. Two peaks with nearly equal energy at $f_1 = 230$ Hz and $f_2 = 201$ Hz and the difference frequency $\Delta f = 29$ Hz can easily be recognized. The identification of other maxima is also indicated in figure 3. The occurrence of the difference frequency Δf accounts for a beat phenomenon. This could mean that two Kármán vortex streets, each with a different frequency, are shed from the same cylinder at the same time, one with f_2 in the neighbourhood of the end plate and another with f_S on the remaining part of the cylinder.

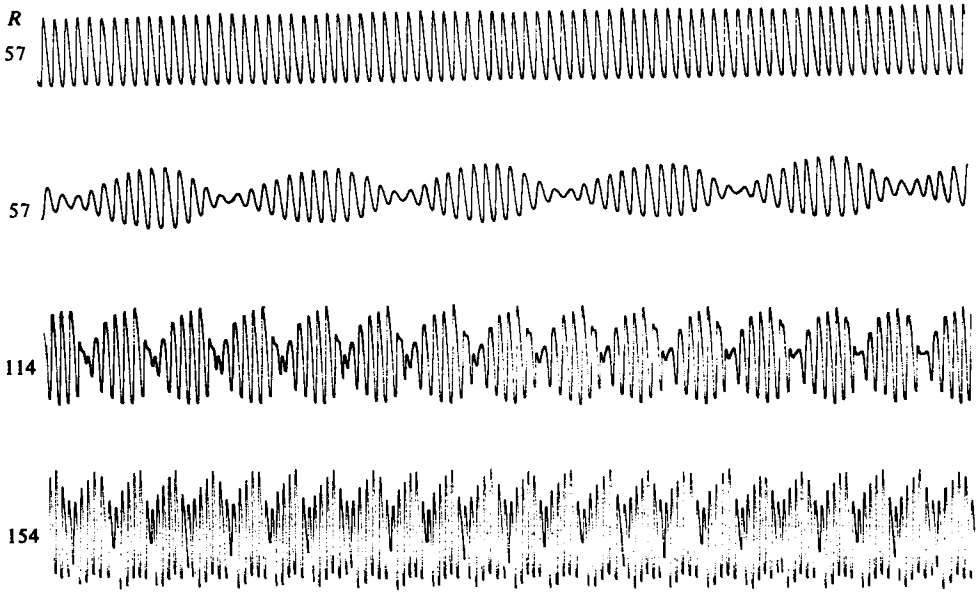

FIGURE 2. Hot-wire signals taken from the unaffected region (top) and at the node for various Reynolds numbers. Cylinder diameter $d = 1$ mm, end-plate diameter $D = 50$ mm.

The shedding from the affected region was further investigated for various cylinder and end-plate diameters. Figure 4 shows the Strouhal-number–Reynolds-number dependence for three cylinder diameters and a 50 mm end plate, together with values obtained in the unaffected region of the 1 mm cylinder. It should be noted that f_2 can be measured in the entire affected region. Roshko's frequency–velocity relation (3) for the laminar-wake region is also plotted for comparison. The values in the affected region are independent of the cylinder diameter and fall within a small range of scatter, about 15 % below Roshko's relation. In another run shown in figure 5, the cylinder had a diameter of $d = 1$ mm and the end-plate diameter D was varied. Again a deviation from Roshko's relation can be observed, but now the deviation increases with increasing end-plate diameter. The extension of the affected region A was also measured: the discussion of the results appears in §3.2. There is another effect originating from the end plate that is noteworthy. The critical Reynolds number R_c at which the vortex shedding starts in the affected region is shifted from about 50 to a slightly higher Reynolds number. As long as $50 < R < R_c$, vortices are shed only from the unaffected region of the cylinder and hence no beat will occur. The amplitude of the oscillations fades away in the affected region.

The deviation from Roshko's frequency–velocity relation observed for the laminar wake also continues into the irregular-wake range (figure 6). Although in this case no phase relation along the cylinder axis exists, and therefore no beat can be observed, the Strouhal numbers measured in the affected region lie well below those appearing in Roshko's relation (4) for the irregular range. Again values obtained for the same end plate – but different cylinder diameter – collapse onto a single curve. We note here that when measurements are plotted on a (S, R)-graph they scatter more than when plotted on a $(F\,(= SR), R)$-graph. In the following we shall use the latter form.

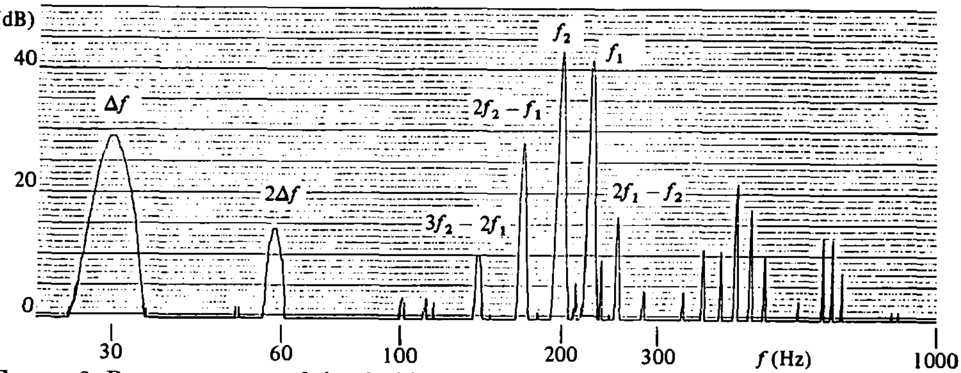

FIGURE 3. Power spectrum of the shedding frequency measured at the node for a cylinder of $d = 1$ mm with end-plate diameter $D = 50$ mm, $R \approx 100$.

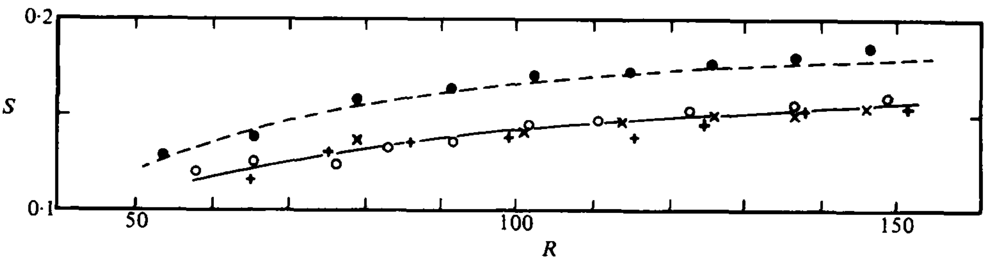

FIGURE 4. Influence of the cylinder diameter d on the Strouhal number, measured in the affected region of an end plate of 50 mm diameter. ×, $d = 1$ mm; ○, 2 mm; +, 3 mm; ●, 1 mm, no end plate; ---, Roshko's relation (3).

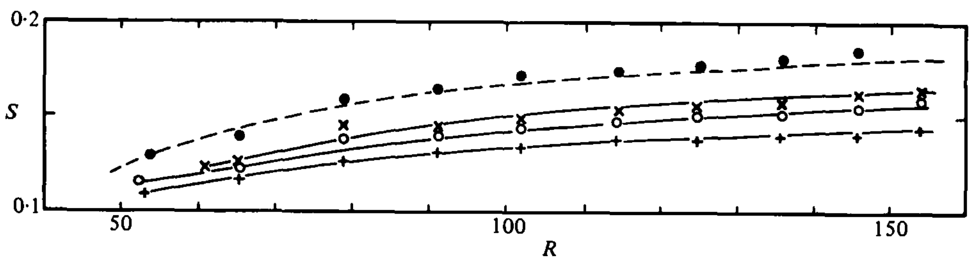

FIGURE 5. Influence of the end-plate diameter D on the Strouhal number, measured in the affected region with a 1 mm cylinder. ×, $D = 20$ mm; ○, 50 mm; +, 100 mm; ●, no end plate; ---, Roshko's relation (3).

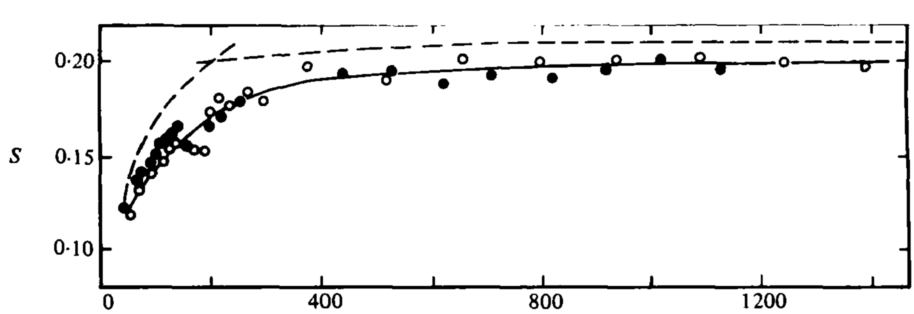

FIGURE 6. Same as figure 4 for a further extended Reynolds-number range. ---, Roshko's relations (3) and (4).

3.2. *Vortex shedding from a cylinder with two end plates*

The experimental setup remains the same as that described in §3.1 except that two movable end plates are mounted on the same cylinder. The hot-wire probe is again placed in the laminar wake of the cylinder at the given location in the centre of the wind tunnel and on one side of the wake. If both end plates are simultaneously moved toward each other, the probe signal, which is steady both in frequency and amplitude at the beginning (figure 7*a*), starts to fluctuate as described in §3.1 for the case of one end plate. When the distance Δz between the two end plates is equal or less than $2A$, the fluctuations suddenly disappear and a steady signal can be observed (figure 7*b*). In this experiment, the nodes connected with the two end plates were moved against each other and cancel when they fall together. For comparison the signal from one node is given in figure 7 (*c*). The new shedding frequency f_3 obtained for $\Delta z < 2A$ is less than the Strouhal frequency f_S but greater than the frequency f_2 observed in the affected region of one end plate. Now only one shedding frequency f_3 exists in the entire region between the two end plates.

A quantitative comparison of the various shedding frequencies f_S, f_2 and f_3 as functions of the Reynolds number is given in figure 8. Here the non-dimensional frequency $F = fd^2/\nu$ is used instead of S. Our results obtained without an end plate follow Roshko's relation (1) well for the stable wake range. The shedding frequencies measured with one end plate in the affected region or with two end plates (for $\Delta z \lesssim 2A$) are also straight lines, which both lie below Roshko's relation. It is remarkable that the laminar range is extended from $R \approx 160$ to about 250 for both one and two end plates. This extension is considerably greater than the change of the upper-limit Reynolds number caused by the turbulence level of the flow. The onset of the shedding from a cylinder with two end plates is, as in the case of one end plate, shifted from $R_c \approx 50$ to about 60.

Evidence in support of our findings appears in at least four other papers. Shair *et al.* (1963) reported an increase of the critical Reynolds number for cylinders of low aspect ratios mounted between wind-tunnel walls. Using end plates Nishioka & Sato (1974) found both an increase of the critical Reynolds number with decreasing end plate distance and a systematically lower shedding frequency for $l/d = 6{\cdot}5$. With an experimental setup similar to ours, Okude (1978) obtained lower shedding frequencies in the vicinity of an end plate and an extension of the laminar range to higher Reynolds numbers. In his towing-tank experiment Gerrard (1978) measured shedding frequencies well below Roshko's relation; he also reports a lower scatter of his data in the range $150 < R < 300$, both of which are probably caused by the low aspect ratio of the cylinder used ($l/d = 14$).

The size of the affected region A produced by an end plate depends on both cylinder and end-plate diameters. Figure 9(*a*) shows the dependence on end-plate diameter D for a 1 mm cylinder. The open circles are mean values of A_S and A_2 measured on either side of the node for which a counter with a given trigger level first displayed f_S or f_2 respectively. The full circles were obtained from measurements with two end plates. They represent half of the distance between the two end plates for the case that the fluctuations in the hot-wire signal suddenly disappear, as described above. Although with this latter method the distance $2A$ is easier to determine the scatter is about the same as with one end plate. Figure 9(*b*) shows the dependence on the cylinder diameter for an end plate of 50 mm. The values of A obtained for one end plate here are smaller than those for two end plates.

We are aware that figure 9 is given in a dimensional form; otherwise a direct

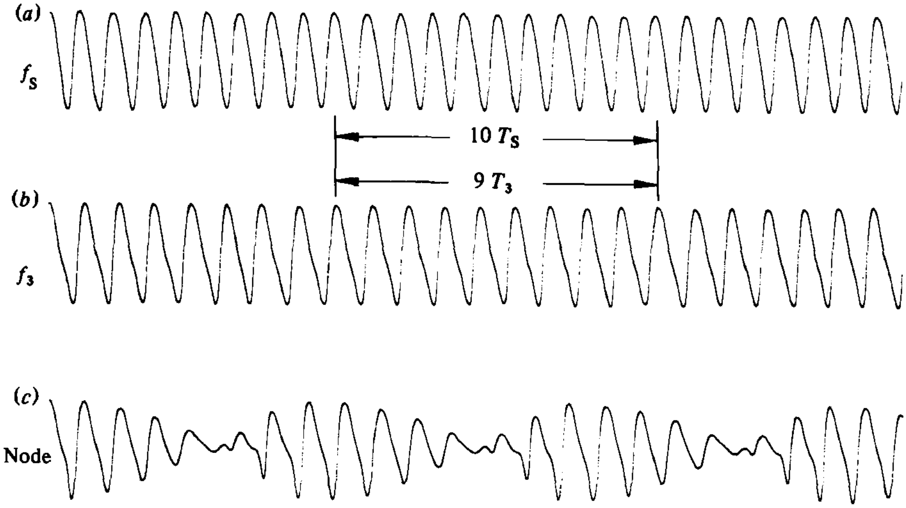

FIGURE 7. Hot-wire signals taken (*a*) from the unaffected region, (*b*) with two end plates $\Delta z \approx 2A$, and (*c*) with one end plate at the node $R = 83$, $d = 1$ mm, $D = 50$ mm.

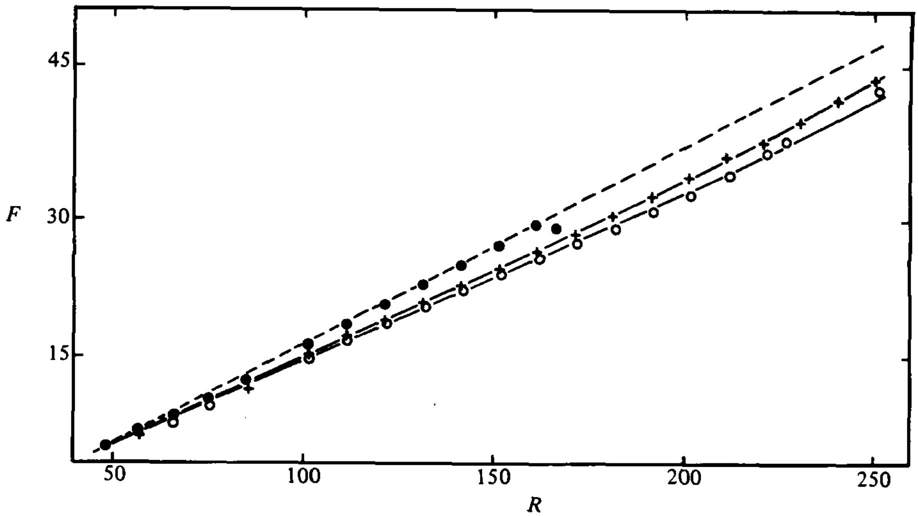

FIGURE 8. Influence of either one or two end plates on the non-dimensional shedding frequency. +, two end plates with $\Delta z \approx 2A$; ○, one end plate; ●, in the unaffected region; ---, Roshko's relation (1). $d = 1$ mm, $D = 20$ mm.

comparison with the free end results (§3.3) would not be possible. In the case of the free end an appropriate length is missing for normalization. For the end-plate experiment D could be a suitable length.

3.3. *Vortex shedding from a free end*

The experimental setup to investigate the free-end influence on the shedding from a circular cylinder is very similar to that of the end-plate experiment. The cylinder is supported only on one tunnel wall and extends over $\frac{2}{3}$ of the channel width, i.e. from $z = 0$ to $z \approx 186$ mm. At the beginning, the hot wire probe is located at $x/d = 10$, $y/d = 2$ and $z = 120$ mm. For Reynolds numbers up to about 160 the velocity

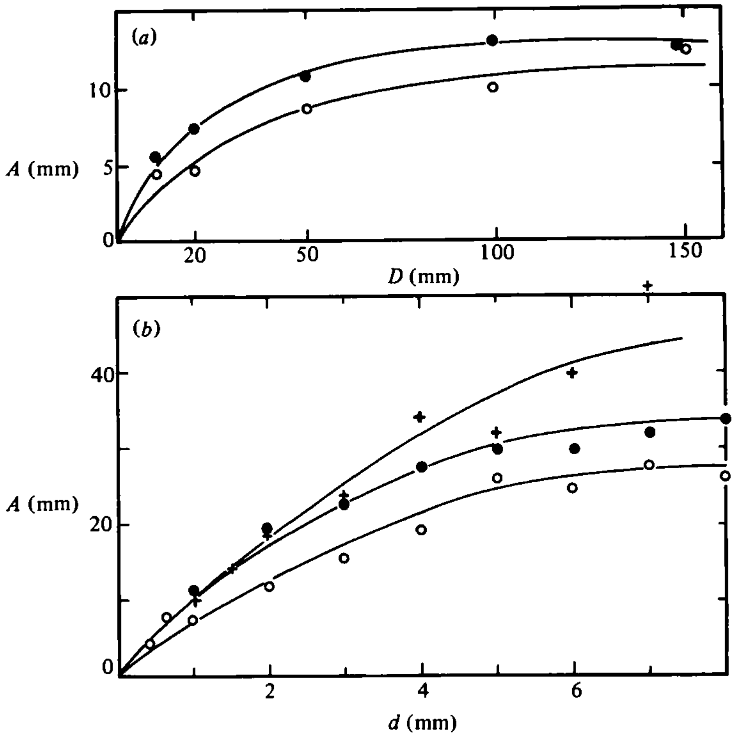

FIGURE 9. Extension of the affected region A for end plate and free cylinder end at $R = 150$. ○, one end plate A; ●, two end plates $2A/2$; +, free end A. (a) $d = 1$ mm; (b) $D = 50$ mm.

fluctuations detected by the probe are steady both in frequency and amplitude. The Strouhal frequency measured corresponds to the value for the infinitely long cylinder. If the hot-wire probe is now moved towards the free end, the hot-wire signal starts to fluctuate periodically. From this point on, everything is similar to the end-plate experiment. By the interaction of the two shedding frequencies f_2 and f_S originating from the affected and unaffected regions a node is produced too. Hot-wire signals from the node and from the unaffected region look very similar to those reproduced in figure 2. In the affected region the amplitude of the hot-wire signal fades away as the probe is moved towards the free end, indicating that no shedding occurs from the tip. The spectrum of the hot wire signal measured at the node is shown in figure 10. For mechanical reasons a 2 mm cylinder had to be used for this experiment, hence lower frequencies are observed in the stable range. The spectrum, however, is very similar to that obtained with an end plate (figure 3). Owing to the lower frequency limit of the spectral analyser used, the difference frequency at $\Delta f = 13$ Hz is out of range.

The dependence of the non-dimensional frequency F on the Reynolds number for a cylinder with a free end is given in figure 11. The shedding frequency f_2 in the affected region is also in this case distinctly smaller than f_S. The size of the affected region A is shown in figure 9, together with the end-plate data. The dependence on the cylinder diameter is very similar to the end-plate case, with the only difference being that the affected region is about one cylinder diameter longer.

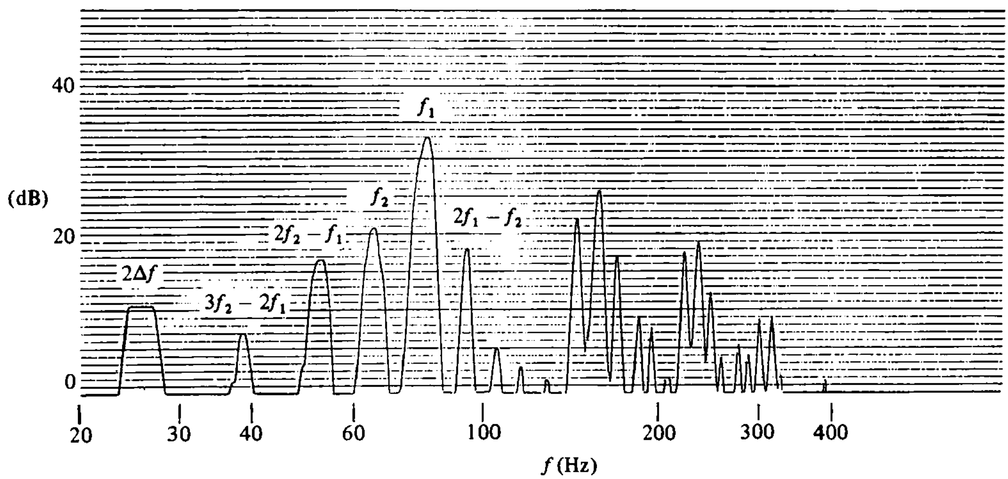

FIGURE 10. Power spectrum of the shedding frequency measured at the node for a cylinder with free end. $R = 150$, $d = 2$ mm.

3.4. *Vortex shedding from a cylinder with two free ends*

A further experiment shows that an analogy to the shedding from a cylinder with two end plates exists. To realize a cylinder with two free ends, a pipe of 1·2 mm outer diameter was supported on a 0·1 mm string which was stretched across the test section. The cylinder was located in the middle of the test section and the hot-wire probe had the same position as for the end-plate experiments. For sufficiently long cylinders two nodes originating from the free ends occurred. By successive shortening of the cylinder the two nodes moved towards each other and cancelled as described for two end plates. The shedding frequency obtained is within the range of accuracy identically to the frequency f_2 measured in the affected region of a free end (figure 11). The cylinder length for which a single frequency along the entire cylinder exists is $2A = 23$ mm. This is in good agreement with the results shown in figure 9. The probe signals look qualitatively the same as shown in figure 7.

4. Discussion and conclusions

Most of the work known from the literature is concerned with the wake flow of sufficiently long cylinders. The results are presented in form of Strouhal–Reynolds-number relations. The formulae of Roshko (1954), Tritton (1959, 1971), Berger (1964) and Kohan & Schwarz (1973) are well known. These formulae give different shedding frequencies for the same Reynolds number. Berger & Wille (1972) explain this discrepancy by the different turbulence levels of the onflow. Recently Friehe (1980) could reproduce the frequency discontinuity that was first described by Tritton (1959). The intention of this article is neither to propose a new frequency law, nor to reopen a discussion as to various flow modes, but simply to point out the importance of geometry at the cylinder end.

In the past, several researchers have investigated the three-dimensional structure of the Kármán vortex street occurring along the span of a circular cylinder. To our knowledge, the boundary conditions at the cylinder ends were never systematically changed. The emphasis was usually focussed on the structure outside the regions

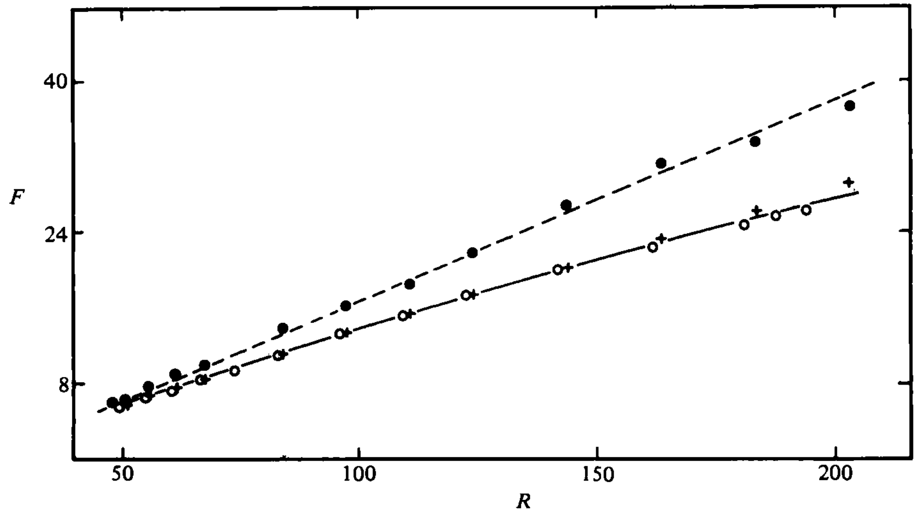

FIGURE 11. Influence of one and two free ends on the non-dimensional shedding frequency. +, two free ends with $\Delta z \approx 2A$; ○, one free end; ●, in the unaffected region; ---, Roshko's relation (1). $d = 1{\cdot}2$ mm.

influenced by the boundary condition of the cylinder. By accident a few measurements were made in the neighbourhood of a wall or end plate or near a free end.

Gerrard (1966) investigated the wake of a cylinder with several hot-wire probes simultaneously. Because of problems with a non-uniform velocity distribution in the test section of his wind tunnel, Gerrard mounted the cylinders between two end plates to cut a uniform-velocity section out of the flow. The end plates used were R.A.F. 30 aerofoil sections. The first experiment was made at $R = 85$ with five hot wires placed simultaneously at various spanwise positions in the wake of his cylinder. All but one of the probes were sufficiently far away from the aerofoils. This probe showed a 16·7 % lower frequency than the four other probes, since it was placed only 7 cylinder diameters away from one of the end plates. A difference frequency of this magnitude occurred as a beat upon the two signals measured near the end plate and at the adjacent probe position. Gerrard explained the different frequencies by his imperfect free-stream conditions. We believe, however, that one of his probes was located in the affected and the rest of the probes in the unaffected region. The two probes on either side of the node showed the same behaviour as described in §3.1 of this paper. For another experiment at $R = 235$, Gerrard used a thicker cylinder but kept the probes at the same locations as for $R = 85$. The fifth probe was now only 2·5 diameters away from the end plate and showed again a 13 % lower shedding frequency than the other probes. Finally, at $R = 2 \times 10^4$ Gerrard used a 1 in. diameter cylinder spanning now the whole wind-tunnel working section of 20 in., yielding $l/d = 20$. It is not surprising to us that Gerrard stated in his paper 'When the vortices are all turbulent there is much less modulation of the signal than there is at lower Reynolds numbers...'. We believe that at this rather low cylinder aspect ratio, even if the Reynolds number is higher than in our experiment described in §3.2, the two wind-tunnel walls stabilize the flow field in the same manner as end plates.

In the stable range ($50 \lesssim R \lesssim 150$) the shedding frequency of a circular cylinder is a very sensitive indicator for the flow velocity. Small changes in the velocity are immediately followed by a change in the shedding frequency. If a cylinder is tapered, it is expected that for a constant flow velocity each cylinder diameter should show a different shedding frequency. The experiment of Gaster (1971) with a slightly tapered cylinder (over a length of 152·4 mm the diameter changes from about 3·2 mm to about 1·9 mm), however, yielded four cells, in each of which the frequency was constant. The positions of the cell boundaries were found to be relatively insensitive to changes in the velocity of his tunnel flow. The shedding frequencies in the cells were always lower than would be estimated from the smallest local diameter of the cylinder. Gaster's tapered cylinder was terminated on one side concentrically into a cylindrical part of about 12 mm diameter and terminates on the other side as a free end. The two cells on either side had about the dimensions compatible with our figure 9. A beat was observed by Gaster when the hot-wire probe was located between two neighbouring cells.

In the same paper Gaster doubts that the shedding law proposed by Roshko is universal for the particular configuration used in his experiments. We believe that such a law is only valid for a sufficiently long cylinder and only outside the affected regions, whether they be caused by the influence of walls, end plates or free cylinder ends. Inside these affected regions, shedding frequencies lower than those calculated from Roshko's formula are obtained. From Gaster's (1969) experiment with two slender cones a cell structure along the span of the cones can also be derived. This is evident from his hot-wire recordings taken for a fixed free-stream velocity at various spanwise positions. Depending on the Reynolds numbers the beat frequencies he measured amounted to 8–12 % of the shedding frequency at the various positions. This result is in accordance with a cell structure along the span of the cones with a frequency difference of 8–12 % between the neighbouring cells. In our experiments the shedding frequency in the affected region is also smaller by this order of magnitude than that in the unaffected region. In addition a similar Reynolds-number dependence is observed. The systematic deviation to smaller frequencies might be caused in our case by the boundary layer developing on the inner side of an end plate or a wall. Inside this boundary layer the velocity is smaller than on the remaining part of the cylinder, yielding a lower shedding frequency for this region. A kind of a 'lock-in' effect, well known from electronics, then forces a unique but lower shedding frequency upon the whole affected region. The same happens in Gaster's (1971) tapered-cylinder experiment, where four different shedding frequencies were forced upon the four cells.

The 'lock-in' must be a rather strong effect. At a Reynolds number of 55 – which is for our experiment only slightly higher than the critical Reynolds number – no shedding will occur from the affected region. Also in this case, the whole cell near the end plate or free end reveals a common behaviour. Shair *et al.* (1963) measured the critical Reynolds number R_c for cylinders confined by two walls. For cylinders having a length-to-diameter ratio $l/d \approx 5$ they found an increase of R_c from about 40 (for $l/d \rightarrow \infty$) to about 140. This shows again how strong the 'lock-in' effect can be if only one cell fits in between the confining walls of the cylinder.

End-plates can also stabilize the shedding from a cylinder, as the experiment described in §3.2 shows. If the distance between two end plates is only a little smaller than the dimension of two end cells, a unique frequency is measured from end plate to end plate and the upper limit of the laminar range is extended from 160 to about 250. Gaster (1971) reported that in his case a pair of end plates as far as 70 cylinder diameters apart stopped a spanwise wandering of transition points (region between cells) produced in a distorted flow field.

An alteration of the shedding mechanism caused by the free end of a cylinder can also be expected because the pressure field is 'short-circuited' around the cylinder tip. This effect occurring at the very end of the cylinder influences a region of several cylinder diameters and forces upon this region a different shedding frequency, the amplitude of which smoothly decays toward the cylinder tip. Taneda (1952) investigated the free-end part of a cylinder by flow visualization and postulated the existence of closed vortex loops. In his photographs a region about 6–8 diameters wide shows a deformation of the separated vortices. Both the extension of the affected region and the looping of the vortices of Taneda which account for the smooth decay of the shedding at the cylinder tip are in accordance with our results.

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