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Vortex shedding from a turbulent jet in a cross-wind

By H. M. MCMAHON, D. D. HESTER†
AND J. G. PALFERY
Georgia Institute of Technology, Atlanta, Georgia

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Measurements in the wake behind turbulent jets exhausting from a solid surface into a cross-wind indicate that vortex shedding occurs as in the case of flow past solid bluff bodies. The Strouhal numbers for flow past a circular and a blunt jet are in qualitative agreement with those for corresponding solid bodies, provided that the width of the spreading jet some distance from the surface is used rather than the jet exit plane dimension.

1. Introduction

When a jet issues from a surface into a cross-wind there is a complex interaction between the two flows. The jet plume spreads, deforms and deflects, as shown in figure 1, and the pressure distribution on the surface is affected considerably. This interference phenomenon has received considerable attention in recent years because of its importance in the VTOL problem (see, for example, Margason (1969) for a comprehensive bibliography). The wake region on the downstream side of the jet is presently the least understood region of the interference flow. Measurements are needed to describe the flow in the wake so that the wake may be modelled and an accurate analytical representation of the interaction formulated, particularly since the low surface pressures in this region contribute significantly to the adverse interference effect (lift loss) on the surface. Recent experiments at the Georgia Institute of Technology indicate that vortices are shed in the wake as a result of the jet–cross-wind interaction.

It is well known (see, for example, Roshko 1955, 1960) that there is a phenomenon of periodic vortex shedding associated with the flow past solid bluff bodies once a certain minimum Reynolds number is reached. The shedding frequency f may be expressed in dimensionless form in terms of the Strouhal number $S = fd/V_\infty$ where d is the breadth of the bluff body and V_∞ is the free-stream velocity. Above a Reynolds number of about 300 the Strouhal number is essentially constant. Measurements by Roshko (1953, 1954) show that for a circular cylinder the Strouhal number has a typical value of $S = 0{\cdot}21$ over the Reynolds number range from 1000 to 10 000 while for a flat plate set normal to the flow $S = 0{\cdot}135$ over the same Reynolds number range. Roshko further showed that when a thin partition or splitter plate is placed along the centre line of the wake downstream of a cylinder the vortex shedding is stopped and the base suction is reduced.

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† Present address: Pratt and Whitney Aircraft, West Palm Beach, Florida

The existence of a periodic motion in the wake of a jet in a cross-flow was noted by Gordier (1959). His experiments with dye injection behind a jet in a water tunnel showed that the wake fluid was partially entrained into the jet and that this action proceeded in a definite periodic manner. Pratte & Baines (1967) studied a circular jet of smoke in a wind tunnel and observed that a separation of the cross-flow occurred just behind the maximum width with two attached vortices present in the wake as in flow around a cylinder at low Reynolds number. These vortices were not shed. The maximum free-stream Reynolds number for these tests was about 500. McAllister (1968) studied a circular water jet in a cross-flow in a water tunnel. Flow visualization using small particles as well as dye indicated that vortices were shed alternately from each side of the jet. The range of Reynolds numbers for these tests was 2000 to 6000 based on jet exit diameter and free-stream velocity. Measurements of shedding frequency were made from the dye observations. The shedding frequency was found to depend upon whether the jet exhausted from a flat plate or from a jet located one jet diameter below a free surface. For the flat plate case (the one of interest here) the Strouhal number based on jet exit diameter varied from $S = 0{\cdot}103$ for a jet to free-stream velocity ratio $V_j/V_\infty = 3{\cdot}83$ to $S = 0{\cdot}019$ at $V_j/V_\infty = 34$. Reilly (1968) performed experiments introducing smoke into a jet issuing from circular and slot nozzles in a flat plate. The tunnel free-stream velocity was 10·5 ft/sec. High-speed movies (3200 frames/sec) were taken of the jet from the circular nozzle at $V_j/V_\infty = 3$. He reported that two distinct eddy groups are periodically shed from different regions of the jet. One group ('side' eddies) is shed alternately from the sides of the jet and then travels downstream in approximately the same direction as the jet, merging with the main jet plume

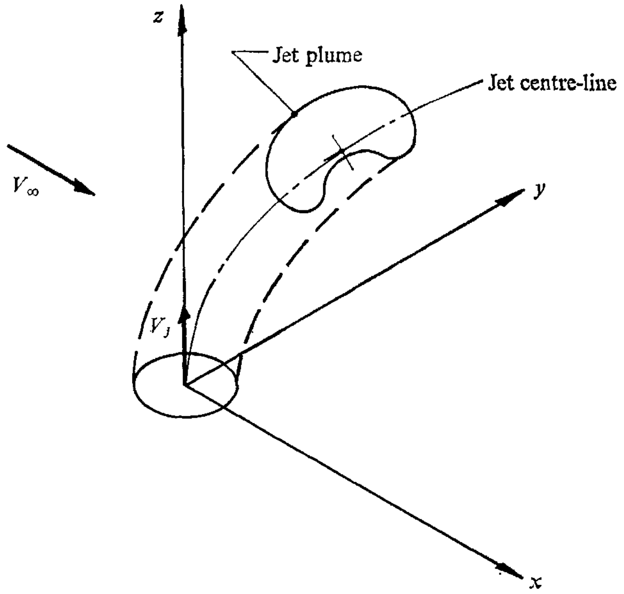

Figure 1. Jet plume geometry.

approximately five diameters downstream of the exit port. Based on the 0·5 in. jet exit diameter, the Strouhal number of these eddies was estimated to be 0·26 at a free-stream Reynolds number of 2600.

This paper presents flow visualization and quantitative hot-wire measurements which show that vortex shedding is associated with a turbulent air jet issuing at 90 degrees from a flat plate into a cross-wind. Results for circular and slot jets are presented. In addition, tests show that a splitter plate stops vortex shedding as in the solid body case, which suggests a possible method of reducing the lift loss associated with the jet–cross-wind interaction.

2. Experimental arrangement

The experiments were conducted in the 9 ft subsonic wind tunnel at the Georgia Institute of Technology. Free-stream velocity for most of the tests was 50 ft/sec, corresponding to a Reynolds number of 26000 per inch. Since compressibility in the jet flow was significant, an equivalent velocity ratio is used which is the square root of the jet to free-stream momentum flux

$$\lambda = (\rho_j V_j^2)^{\frac{1}{2}}/(\rho_\infty V_\infty^2)^{\frac{1}{2}}.$$

Values of $\lambda = 8$ and 12 are considered.

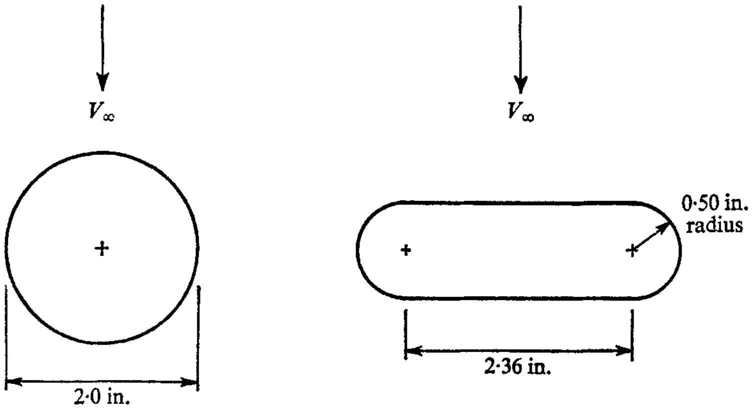

FIGURE 3. Jet exit configurations.

A flat plate 66 in. wide and 48 in. in the stream direction was installed near the bottom of the circular test section as shown in a view looking upstream in figure 2 (plate 1). A hole in the centre of the plate accepts a nozzle block which bolts to the top of the vertical jet supply pipe and fits flush with the plate surface. Two nozzle blocks were used in order to vary the jet exit geometry. The two exit configurations, which have the same area, are shown in figure 3 and are termed 'circular' and 'blunt'.

In an attempt to visualize the flow phenomena in the wake region above the plate an inclined tuft screen was installed behind the jet as shown in figure 4 (plate 2). The effect of the flow on the tufts was recorded by a high-speed movie camera (240 frames/sec). An oil film applied to the plate surface showed a negligible change in flow pattern with and without the tuft screen.

The hot-wire probe was mounted in an actuator (shown with a pressure probe installed in figure 2) with the probe axis horizontal and aligned in the spanwise (y) direction. The single wire on the probe was aligned vertically in the z direction. The output of the standard constant-temperature hot-wire circuit was fed to an oscilloscope and also to a wave analyzer. The centre frequency of the analyzer was tuned by applying a known frequency from an external oscillator. The wave analyzer output, representing data signals falling within a 5 Hz bandwidth around the centre frequency, was read on a true r.m.s. meter. The meter reading was not steady, indicating that the shedding was not of absolutely constant period. The data represents a visual time average of the meter reading at each centre frequency.

For some tests a splitter plate 24 in. × 24 in × $\frac{1}{16}$ in. made of sheet aluminium was mounted vertically on the centre-line behind the blunt jet.

3. Results

Examination of the tuft screen motion pictures for the blunt jet configuration revealed the presence of periodic eddies behind the jet in the wake region, as can be seen in figure 5 (plate 3). The movies for the circular jet showed a similar phenomena except that the magnitude of the disturbance was not as large as for the blunt case. The hot-wire measurements confirmed that the vortex street is stronger behind the blunt jet. Analysis of the motion pictures enabled the shedding frequency to be determined and the results are shown in table 1. Interpretation of the pictures was difficult, and the values are approximate. The dimension used in calculating the Strouhal number in table 1 is the diameter of the circular jet exit and the breadth of the blunt jet exit perpendicular to the free-stream direction.

The centre-line of the plume for the two jets (defined as the line of maximum total pressure in the plume) had previously been measured in the centre (x, z) plane. Vertical traverses indicated that the periodicity of the flow behind both jets becomes stronger with decreasing height z at least down to $z = 4$ in., which was the minimum height possible with the actuator. Accordingly, the shedding frequency was measured at $x = 4$ in., $y = 2$ in., $z = 4$ in. for various conditions. Typical plots of energy versus frequency for the circular and blunt jet are shown in figure 6, with the ordinate being the r.m.s. output of the wave analyzer at a given centre frequency divided by the unfiltered r.m.s. output of the hot wire (i.e. at all frequencies). It is seen that the predominant energy is at 25 and 18 Hz respectively, and these frequencies were used to form the Strouhal numbers. The results are summarized in table 1. Here again, the dimension used in calculating the Strouhal number is the diameter of the circular jet exit and the breadth of the blunt jet exit. The value $S = 0{\cdot}083$ for the circular jet at $\lambda = 12$ was unchanged when the tunnel was run at $V_\infty = 25$ ft/sec with λ held constant. There is a second peak in the blunt jet spectrum which is at twice the shedding frequency. This harmonic has been noted in measurements behind a solid cylinder (Roshko 1953) and was attributed to the centre of the wake feeling the shed vortices from both sides. No second peak is evident in the data taken behind the circular jet.

The variation in energy content $(\overline{u^2})$ of the vortex-shedding peak in the spectrum at 18 Hz with distance above the plate is shown in figure 7 for the case of the blunt jet. The energy contained in the peak (in excess of the energy level due to turbulent fluctuations) has been referenced to the value at $z = 4$ in.

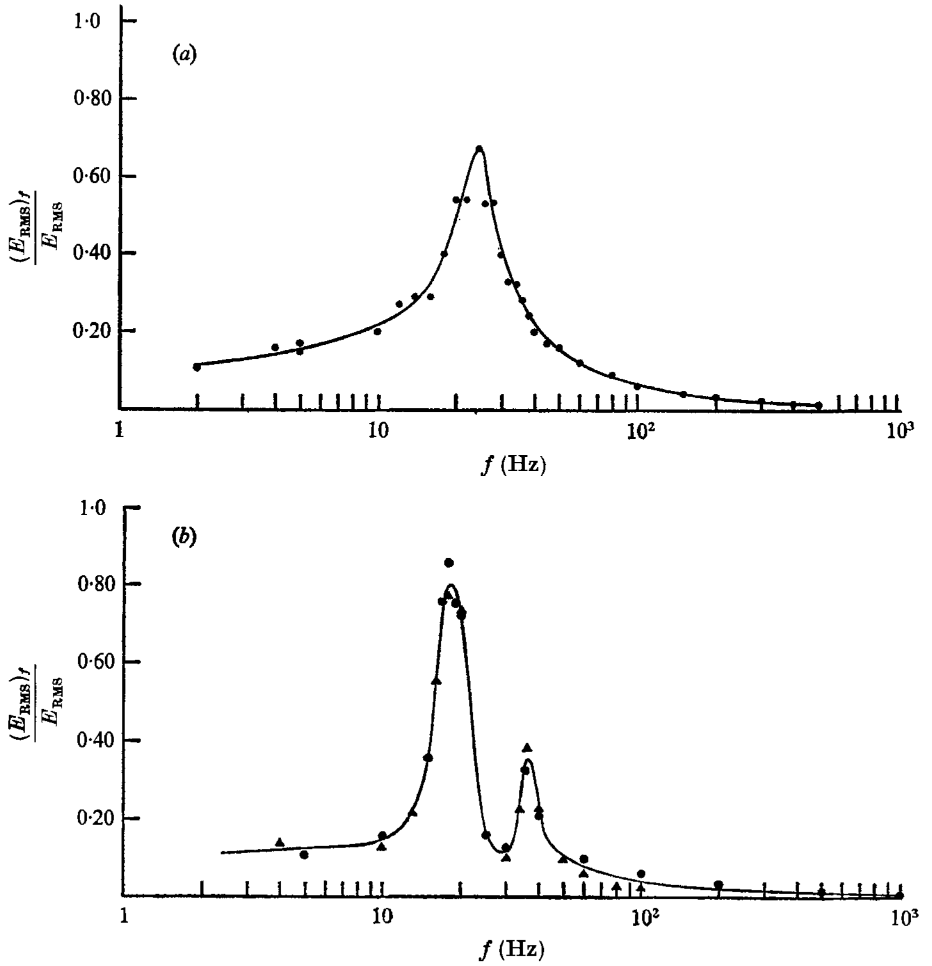

FIGURE 6. Wake energy at $x = 4$ in., $y = 2$ in., $z = 4$ in., $V_\infty = 50$ ft/sec. (*a*) Circular jet, $\lambda = 12$. (*b*) Blunt jet, $\lambda = 8$.

One further test was made with the blunt jet. A splitter plate was installed which ran from immediately behind the jet exit to the plate trailing edge. The signal from the hot wire both with and without the splitter plate is contrasted in the oscilloscope traces in figure 8 (plate 4). The energy distribution is shown in figure 9.

4. Discussion

The measurements provide quantitative evidence that there is vortex shedding behind a turbulent jet in a cross-wind. The physical model of the flow field in the wake must await the results of more extensive measurements which are

Jet exit configuration	Strouhal number S			
	$\lambda = 8$		$\lambda = 12$	
	Tuft screen	Hot wire	Tuft screen	Hot wire
Circular	0·09	0·093	—	0·083
Blunt	0·13	0·10	0·09	0·10

TABLE 1

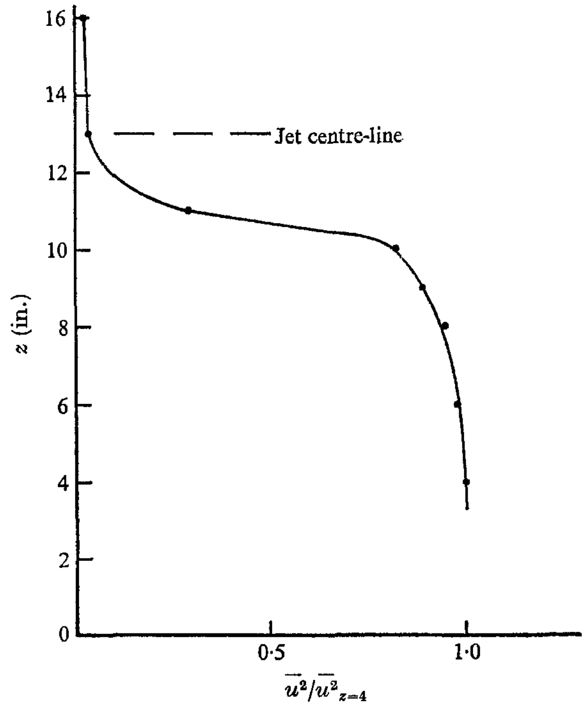

FIGURE 7. Variation of energy of periodic fluctuations at 18 Hz with height above plate. $x = 4$ in., $y = 2$ in., $V_\infty = 50$ ft/sec, blunt jet, $\lambda = 8$.

now in progress. The shedding phenomena behaves as that behind a solid body in that it is suppressed by a splitter plate. However, the Strouhal number associated with the circular jet is less than one half that associated with a solid cylinder. Further, the blunt jet shows an increase in Strouhal number over that of a circular jet while the corresponding solid body cases show an opposite trend. While one would not expect agreement between the jet and solid body *a priori* because of the different boundary conditions for the shedding, these differences can be partially explained by the choice of dimension used in forming the Strouhal number.

Once the jet leaves the exit plane it grows and distorts. Thus the proper dimension to use in the Strouhal number is not the exit dimension but rather some dimension representing the distorted jet. A spread factor has been determined from smoke tunnel photographs of the circular jet by Crowe & Riesebieter (1967). However, as they point out, the factor is not valid for small distances from the exit. The data of Jordinson (1956) two diameters above the plate indicates an effective circular jet width (based upon an edge criterion corresponding to $\frac{1}{4}$ of the maximum velocity in the cross-section) of about 1·75 times the exit diameter. A limited amount of total pressure rake data at $z = 5$ in. for this experiment gives a width of approximately 2·2 diameters. Taking this value of 2·2 diameters as the proper dimension gives $S = 0{\cdot}205$ at $\lambda = 8$. Recalling that $S = 0{\cdot}21$ for a solid cylinder, it appears that the use of a more meaningful dimension than that of the exit for the spreading circular jet yields a value of Strouhal number consistent with the solid cylinder.

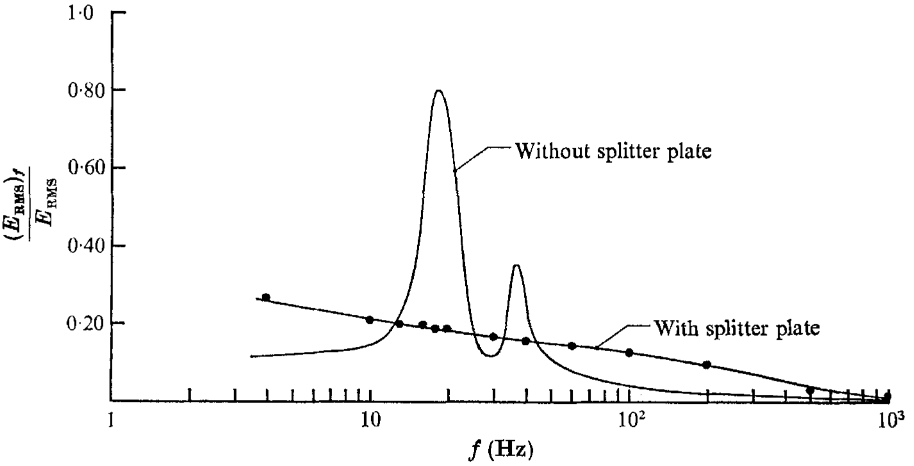

FIGURE 9. Effect of splitter plate on wake energy. $x = 4$ in., $y = 2$ in., $z = 4$ in., $V_\infty = 50$ ft/sec, blunt jet, $\lambda = 8$.

The relative value of the Strouhal number for the circular and blunt jet as compared with the circular and blunt solid body also appears consistent if an effective jet width is used in forming the Strouhal number. Rake measurements at $z = 5$ in. show that the blunt jet at $\lambda = 8$ deforms to a width (using a $\frac{1}{4}$ velocity edge criterion) about 1·30 times the jet exit, yielding a corrected Strouhal number of 0·13. The value for a bluff flat plate is 0·135.

It is difficult to reconcile the motion of the shed vortices as measured here with that observed by Reilly (1968). He noted that the 'side' eddies merged with the jet plume approximately five diameters downstream of the jet exit. A hot-wire measurement behind the blunt jet at the plate trailing edge ($x = 24$ in.) and 4 in. above the plate surface indicated a frequency spectrum similar to that of figure 6(*b*) except that the energy contained in the vortex-shedding peak at 18 Hz had decayed to 95 % of its value at $x = 4$ in. Thus the shed vortices would seem to be travelling in a downstream direction along the plate rather than in the same direction as the jet. If the vortices are behaving like those behind a solid body in that the vortex is composed of free-stream fluid rather than jet fluid, then it is possible that smoke pictures are misleading since, as Reilly (1968) pointed out, the smoke in the jet does not mix into the main stream in sufficient quantity to make a portion of an eddy in the main stream visible.

An evaluation of the importance of the role played by these shedding vortices in the overall jet–cross-wind interference problem is not yet possible. Present results indicating values of jet Strouhal number consistent with corresponding solid bodies suggest that the drag of the jet plume near the exit is not much different from that for a similar solid body. However, these vortices may significantly influence the way external fluid is entrained into the wake or into the jet plume.

The low surface pressure in the wake region behind a jet contributes significantly to the integrated suction force generated by the jet–cross-wind interaction and also to the appearance of large pitching moment changes. Results with a splitter plate behind a solid cylinder (Roshko 1954) show that when the splitter plate inhibits the periodic vortex formation the base pressure is increased considerably. Thus a splitter plate behind a jet may, since it does inhibit shedding, serve to increase the surface pressure in the wake region where an increase would be very desirable. The solid cylinder results indicate that the plate need not be as large as the one used here, and perhaps one a few jet diameters in extent might give a significant improvement. This aspect of the problem is now being studied experimentally.

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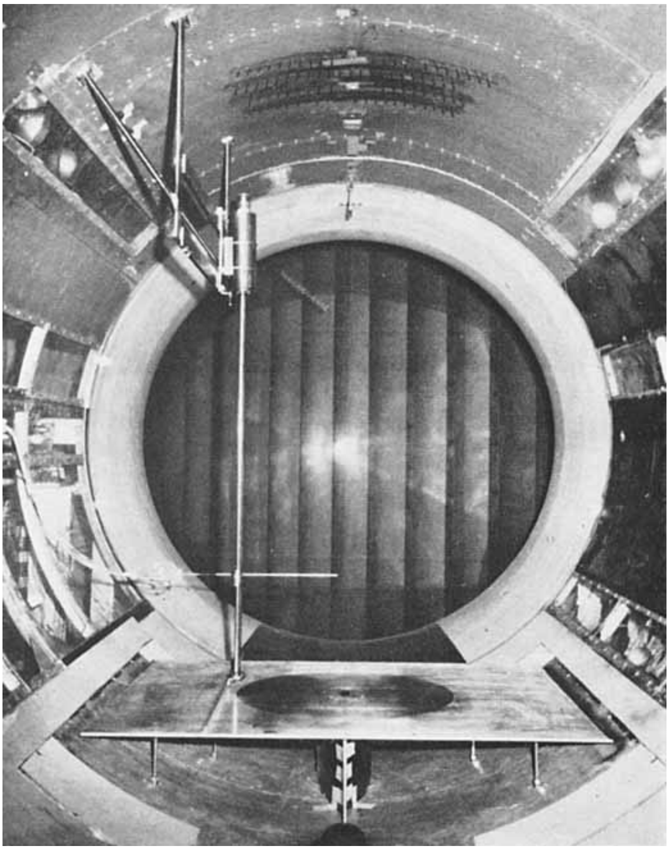


FIGURE 2. Flat plate model in wind tunnel.

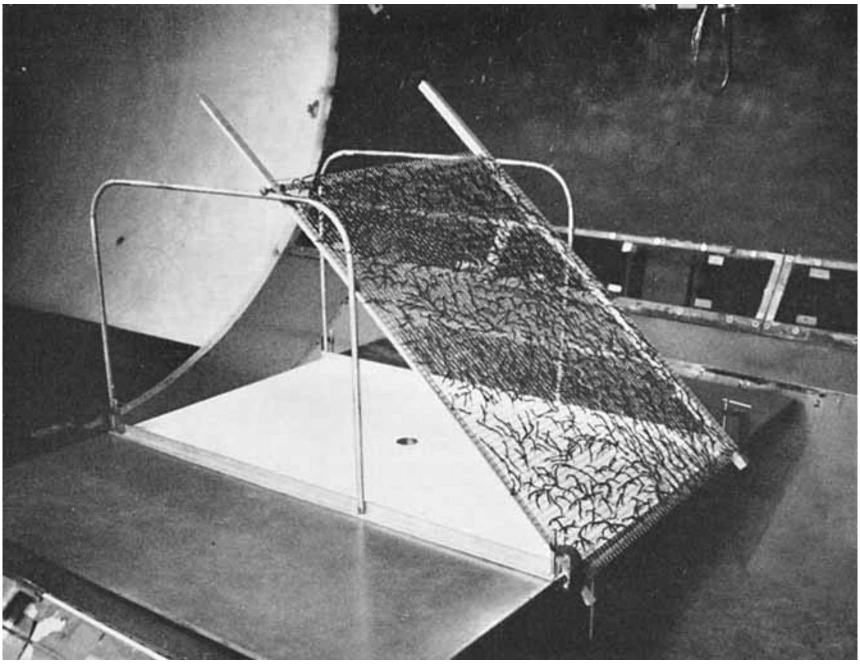
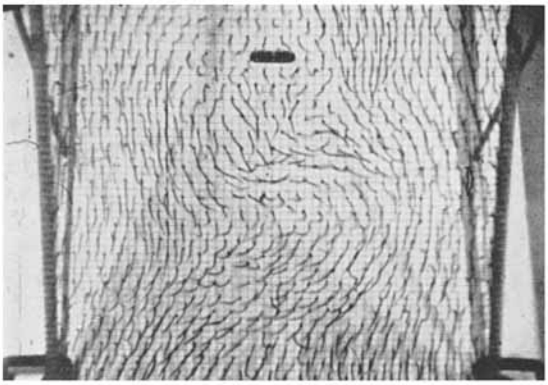
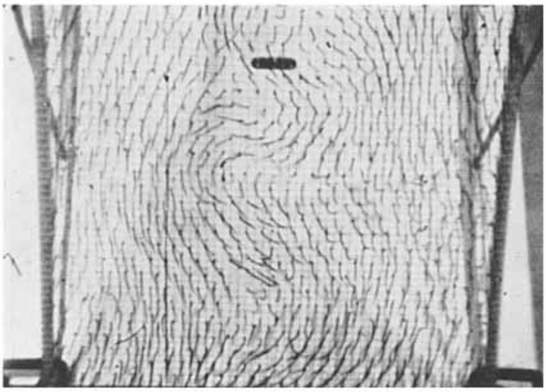


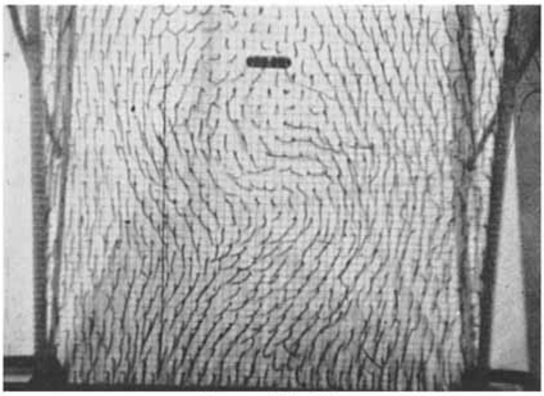
FIGURE 4. Tuft screen.



Frame N



Frame $(N+6)$



Frame $(N+13)$

FIGURE 5. Motion pictures of tuft screen, blunt jet, $\lambda = 8$.

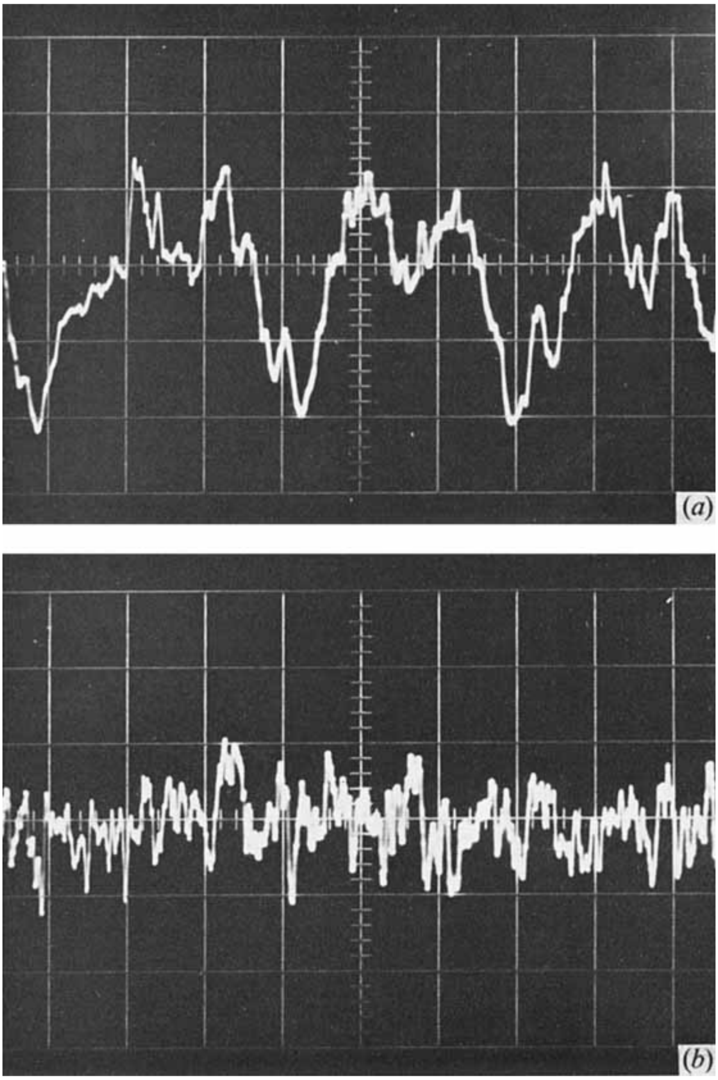


FIGURE 8. Effect of splitter plate on wake periodicity.
$x = 4$ in., $y = 2$ in., $z = 4$ in., $V_\infty = 50$ ft/sec, blunt jet, $\lambda = 8$.
Oscilloscope: 20 msec/cm; 0·20 volts/cm.
(*a*) Without splitter plate; (*b*) with splitter plate.