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On vortex formation from a cylinder. Part 2. Control by splitter-plate interference

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Control of vortex formation from a circular cylinder by a long plate in its wake is examined over the Reynolds number range $140 < Re < 3600$. There are two basic flow regimes: a pre-vortex formation regime, in which the plate precludes formation of a large-scale vortex upstream of the tip of the plate; and a post-vortex formation regime in which one or more large-scale vortices are formed upstream of the edge. The unsteady pressure loading at the tip of the plate increases by over an order of magnitude during transition from the pre- to post-vortex formation regime. If the plate is located near the cylinder, it is possible to more than double the vortex formation length, relative to the case of the free wake. Moreover, these observations suggest that: there is a minimum streamwise lengthscale for development of the absolute instability of the near wake and thereby the large-scale vortex; and the vortex formation length may also be influenced by the downstream vorticity dynamics. When the plate is located downstream of the initially formed vortex, effective control is possible when the near-wake fluctuation level and mean base pressure of the corresponding free (non-impinging) wake are sufficiently small. This occurs in the low and moderate subcritical regimes; the substantial control by the wake-plate interaction in this range of Reynolds number implies low strength of the absolute instability of the near wake. However, in the pure von Kármán regime, self-control of the near wake dominates that imposed by the wake–edge interaction, suggesting a strong absolute instability of the near wake.

1. Introduction

In recent years, much attention has been devoted to self-sustained oscillations of jets and mixing-layers impinging upon leading-edges/corners. Rockwell & Naudascher (1979) and Rockwell (1983) assess some recent advances in this class of flow-structure interaction, which encompasses the fundamental aspects of: disturbance amplification in the shear layer of finite streamwise length between the upstream separation and the downstream impingement edges; vorticity field leading-edge interaction in the impingement region and the associated unsteady pressure field there; upstream influence from the impingement region to the sensitive region of the shear layer near separation, viewed as a dipole (Powell 1961); and conversion of this upstream influence to unsteady vorticity fluctuations in the sensitive region of the shear layer near separation. These overall features of the oscillation, as well as jumps in oscillation frequency as streamwise lengthscale or mean flow speed are varied, are well-established (Powell 1961). Such frequency jumps are usually accompanied by corresponding jumps in characteristic velocity fluctuation amplitude within the shear layer or in pressure at the impingement surface. Other established features of

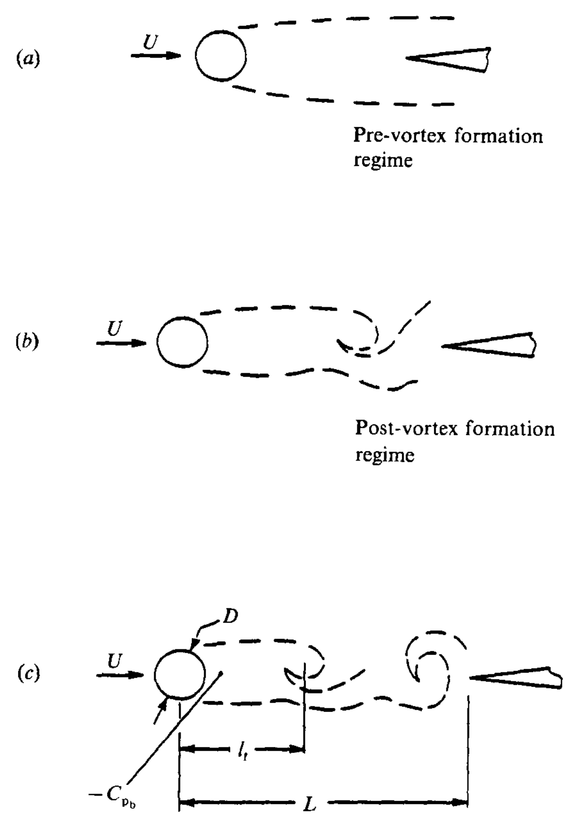

FIGURE 1. Definition of parameters associated with wake-edge interaction and schematics of pre-vortex formation and post-formation regimes.

this class of flows are: a well-defined exponential growth region of the amplifying disturbance, described by spatial stability theory; and a direct relation between the mechanism of vortex distortion at the impingement surface, the localized loading of the surface, and the upstream influence.

Although the foregoing cases of mixing-layer and jet-edge oscillations are well-investigated, relatively little is known of the effect of a finite streamwise lengthscale, or impingement length, on the near wake of a bluff body (figure 1). In contrast to the foregoing cases of jets and mixing-layers, bluff-body flows are characterized by a region of negative base pressure between the separating shear layers. The existence of this region, associated with the formation length of vortices behind the body, will most likely produce a different character of near-wake response to upstream influence from wake-edge interaction. Strong upstream influence from Biot-Savart induction (Rockwell 1983) or from that associated with a region of absolute instability (Monkewitz & Nguyen 1986), may provide a strong self-control of the near-wake instability. These concepts are studied in detail in Part 1 (Unal & Rockwell 1988).

Indeed, recent investigations of wakes from cylinders and blunt trailing-edges at selected values of Reynolds number by Smith & Karamcheti (1978) and Johnson & Loehrke (1984) show that the frequency jumps so pronounced in jets and mixing-layer-type flows do not appear to be present in instabilities of wakes from cylinders and blunt trailing-edges. However, the underlying physical grounds for this apparent lack of sensitivity of bluff-body instabilities have not been established. In the event that the leading-edge of a (finite-length) splitter plate is located very close to the base of a cylinder, then moved successively downstream, there is a sudden jump in Strouhal number from a relatively low value to practically that of the classical vortex street (Roshko 1954). These measurements suggest that when a splitter plate is located sufficiently close to the body, the vortex street cannot develop, and the oscillation is dominated by an instability of the shear layer separating from the cylinder. There have been a wide variety of empirical studies of splitter plates located downstream of cylinders, as summarized by Zdravkovich (1987). Attenuation of the large-scale vortex shedding and vibrational response, as well as a reduction in mean drag are clearly attainable, but little is known of the corresponding flow structure. Clearly, further insight into the mechanisms associated with such near-wake control would also provide information on the mechanism of vortex shedding.

Figure 1 provides an overview of the parameters associated with the wake–edge interaction. By 'edge' is meant the leading-edge of the long plate. It also depicts basic regimes of the near-wake region based on visualization studies herein. If the plate is located sufficiently close to the body, vortex formation does not occur upstream of it; consequently, this regime is called the pre-formation regime (figure 1*a*). On the other hand, if the streamwise lengthscale L is sufficiently long such that pronounced vortex formation does occur, the regime is defined as post-formation (figure 1*b*). Herein, vortex formation upstream of the leading-edge of the plate is defined to occur when irrotational fluid is drawn across the wake centreline by the formation process. Depending upon the particular flow conditions and the lengthscale L, the vortex formation length l_f can actually be shortened or lengthened substantially in this post-formation regime (figure 1*c*).

From the foregoing, it is evident that there are a number of unresolved features of bluff body–wake interaction. Among them is the possibility of attenuating the onset of large-scale vortex formation behind the body. Or, in cases where such formation does occur, controlling the formation length and frequency of the vortices. In the case where the plate is located sufficiently close to the body such that the large-scale vortex cannot develop, near-wake instabilities may still be present. The issue arises as to whether the spectral content of the separated shear layer from the cylinder shows evidence of the large- and small-scale vortex instabilities present in the corresponding non-impinging flow. Finally, the nature of the fluctuating pressure field on the surface of the leading-edge of the plate remains unclarified. It is expected to be a function of the flow regime as defined in figure 1, as well as the phase of arrival of the vortices upon the top of the plate. The investigation described herein attempts to resolve these issues.

2. Near-wake of cylinder in absence of downstream edge

The flow regimes of the bluff-body wake from a cylinder are a strong function of Reynolds number (Morkovin 1964; Roshko & Fiszdon 1969; Gerrard 1978). As Reynolds number varies, there are corresponding changes in magnitude of negative base pressure, vortex formation length, and circulation of the vortices in the downstream wake. In view of the strong dependence of these parameters on Reynolds number, we expect that the sensitivity of the near-wake region to the presence of a splitter plate will be a function of Reynolds number as well. Figure 4 of Part 1 (Unal & Rockwell 1988) shows these velocity fluctuations normalized by mean velocity U_e at the edge of the shear layer. It is evident that the initial fluctuation levels $\tilde{u}_e$ and $\tilde{u}_m$ of the separating shear layer closely follow the variation in absolute value of the base pressure coefficient C_{p_b}. Details of the associated flow mechanisms are discussed in Part 1.

The initial fluctuation level $\tilde{u}_e$ or $\tilde{u}_m$ is associated with the magnitude of the upstream influence in the free wake arising from: Biot-Savart induction; and/or, upstream influence from a region of absolute instability. The perturbations from the upstream influence of wake–plate interaction may not be sufficiently large, in some cases, to overcome these inherently high levels. On the other hand, for the range of Reynolds number where fluctuation levels are low, the susceptibility of the near-wake will be considerably greater.

The foregoing reasoning holds, of course, for the case where the leading-edge of the plate is located in the downstream region of the wake such that the initial region of the vortex street forms without interference. In the event that the edge of the plate is located closer to the body, the initial vortex formation is altered. In this case, the character of the wake controlled by the plate, relative to that of the free wake, becomes more complex. In the following, we address these features.

3. Near-wake of cylinder in presence of downstream plate

To characterize the effect of the wake–plate interaction on the near-wake region, the velocity fluctuation field was characterized in conjunction with flow visualization. To ensure that the wake from the trailing edge of the plate did not influence the upstream cylinder wake–leading edge interaction, the plate was very long compared to the cylinder diameter D, *i.e.* $L_p/D = 24$. Figure 2 shows the velocity fluctuation amplitude measured at the edge of the shear layer at a number of streamwise locations. At a relatively low Reynolds number of $Re = 142$, the fluctuation amplitudes exhibit no ordered jumps with increasing lengthscale L/D. This remarkable lack of alteration of the near-wake field with streamwise lengthscale L/D is due to the strong self-control of the near wake; the initial fluctuation levels are high, as discussed in conjunction with figure 4 of Part 1. Moreover, for values of $L/D \gtrsim 3$, there are no detectable fluctuations in the near wake, suggesting that the separated layers remain quasi-laminar until the streamwise lengthscale L/D is sufficiently large to allow evolution of the disturbance leading to large-scale vortex formation. On the other hand, at higher values of Reynolds number corresponding to $Re = 785$ and 3645, the initial fluctuation levels in the free wake are substantially smaller than at $Re = 142$ (see figure 4 of Part 1). As a consequence, the streamwise lengthscale L/D has a pronounced effect on fluctuation amplitude in the near-wake region. In both cases, at small values of L/D beyond which exponential growth occurs, there are ordered 'stages' of near-wake fluctuation amplitude; as will be demonstrated subsequently, these variations in the near-wake amplitude are associated with changes in vortex formation length.

To provide physical insight into the behaviour of the near-wake fluctuation field with changes in L/D, extensive flow visualization was undertaken, as depicted in figures 3 and 4. Figure 3, showing the case of $Re = 142$, reveals that for $L/D = 2.8$, there is no evidence of wake oscillation; the separating shear layers are effectively partitioned by the insertion of the edge. At $L/D = 3.2$, there is onset of the large-scale instability leading to the initial stage of the vortex street formation. At successively larger values of L/D, the vortex street wake develops towards the free (non-impinging) wake structure. At each value of L/D photos corresponding to $t/T = 0, \frac{1}{4}$, and $\frac{1}{2}$ are shown where T is the period of the wake oscillation. By comparing

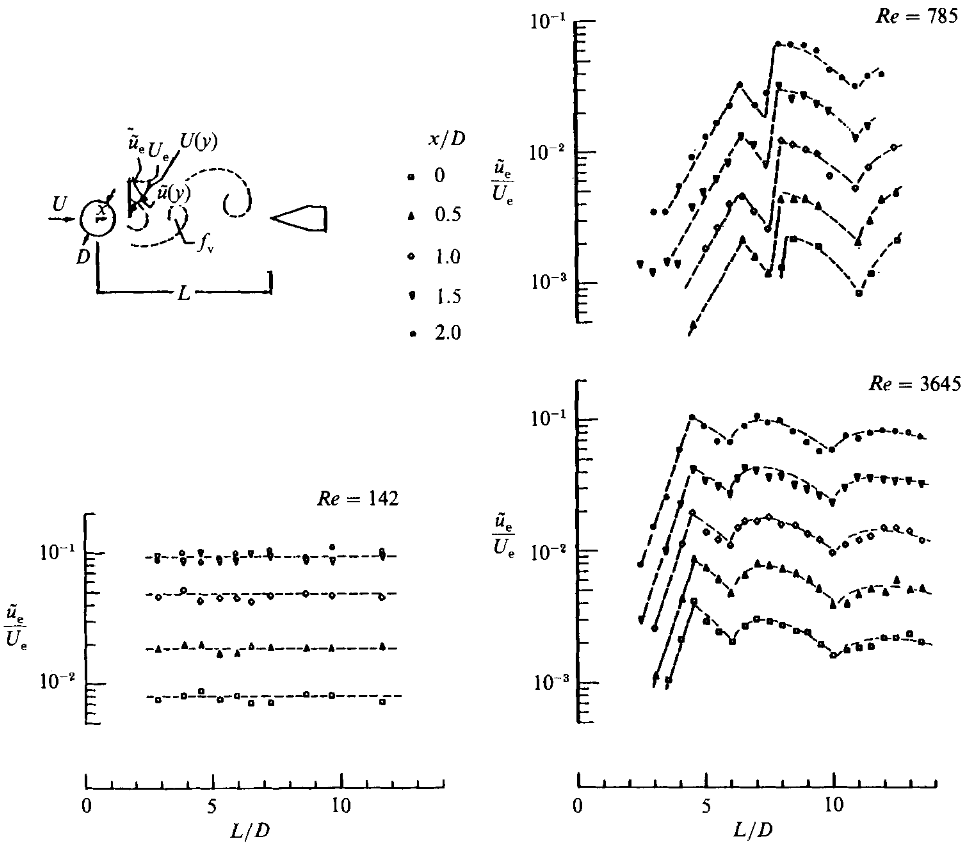

FIGURE 2. Variation of fluctuation level at edge of shear layer $\tilde{u}_e$ in near-wake region as a function of streamwise lengthscale L/D.

the near-wake structure at a given value of t/T for varying L/D, it is evident that it experiences no significant alteration. This invariance of the near-wake structure is in accord with the corresponding invariance of the near-wake fluctuation levels $\tilde{u}_e/U_e$ shown in figure 2 at $Re = 142$. It appears that once the wave breaks into oscillation at $L/D \sim 3$, the upstream influence from the near-wake region dominates that associated with the wake–edge interaction. The strong self-control of the absolute instability, Biot-Savart induction, or a combination of them, evidently plays a central role. This finding is in contrast to observed oscillations of a wide variety of jet and mixing-layer configurations (Rockwell & Naudascher 1979); in these cases, the upstream influence from the shear layer–edge interaction controls the oscillation.

However, at higher Reynolds number ($Re = 785$) shown in figure 4, there are substantial variations in the wake structure with L/D. Correspondingly, the fluctuation level near separation and the base pressure are lower relative to the foregoing case of lower Reynolds number ($Re = 142$). (See figure 4 of Part 1.) These lower values suggest weaker self-control of the near wake in the absence of the plate. Therefore, we expect enhanced susceptibility to upstream influence from the interaction region of the leading edge of the plate.

Figure 4 shows that the near-wake region is effectively split by the presence of the plate for $L/D \leqslant 5$. As L/D increases from 4 to 5, there is increasing evidence of large-

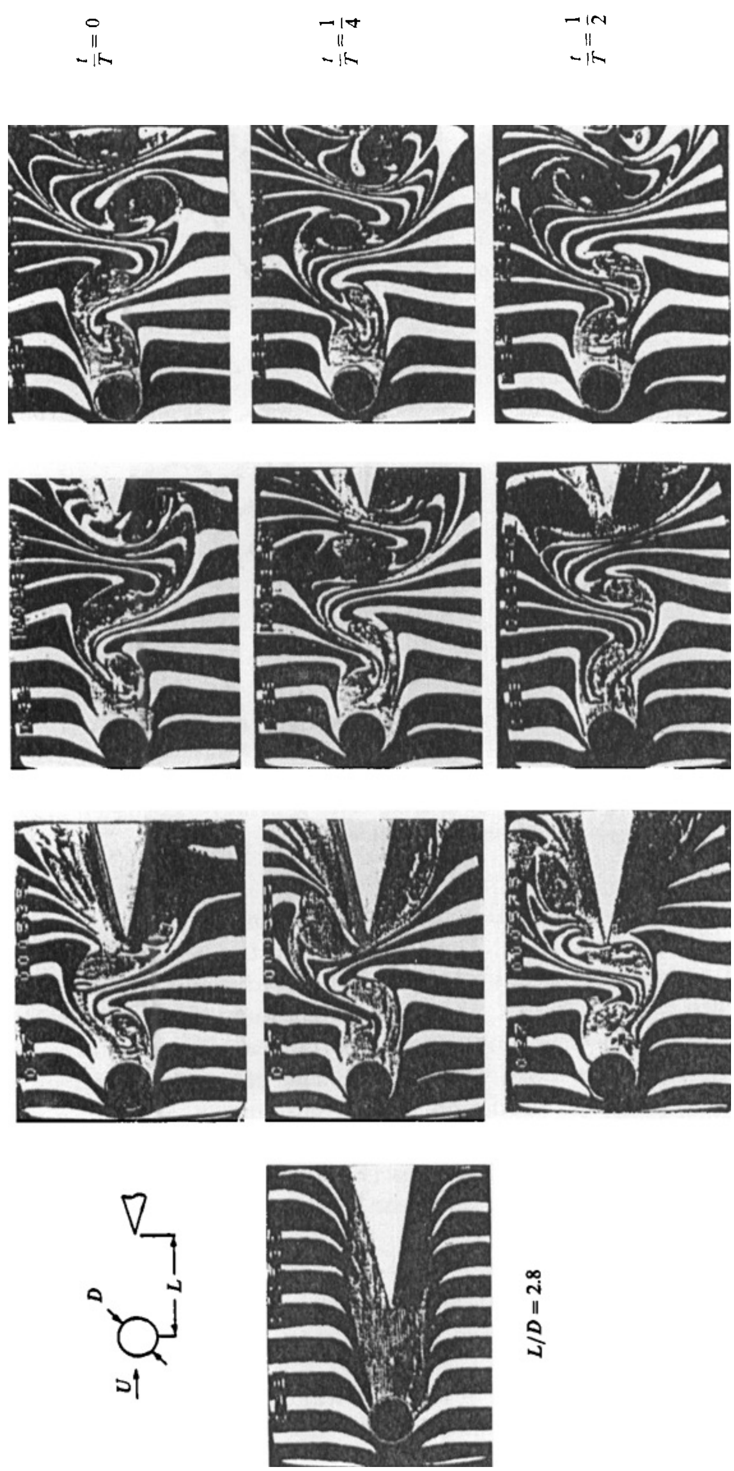

FIGURE 3. Visualization of wake–edge interaction at low Reynolds number, $Re = 142$ for increasing streamwise lengthscale. At each dimensionless streamwise lengthscale, L/D, photos are shown at three instants during oscillation cycle, $t/T = 0, \frac{1}{4}$, and $\frac{1}{2}$ where T equals period of oscillation.

scale instability in the region of the leading edge of the plate. At $L/D = 5.5$, the initial stage of vortex formation occurs, accompanied by closure of the near-wake region. As L/D increases from 5.5 to 6.5, there is decrease of the vortex formation length; it reaches its minimum value of $L/D = 6.5$. Beyond this value, there is again an increase in vortex formation length with a maximum occurring at $L/D = 7.5$. At still higher values of impingement length, the vortex formation length decreases, reaching another minimum at $L/D = 8.5$. Inspection of subsequent photographs shows that there are successive increases and decreases in vortex formation length with maximum and minimum values of formation length occurring at $L/D = 10.5$ and 13.5.

For the case of a higher Reynolds number, $Re = 3645$, there are similar qualitative trends of increase and decease in vortex formation length (Unal 1985). At this higher value of Re, the initial stage of vortex formation occurs at $L/D = 4$. At smaller values of L/D, however, the presence of small-scale instabilities in the separating shear layers is clearly present (see figure 5). In fact, these instabilities persist at least down to $L/D = 0.5$ (Unal 1985). In the corresponding free wake, they are referred to as 'transition waves' or 'Bloor–Gerrard' vortices. Their occurrence is well-documented for the wake from the cylinder in the absence of the plate (Bloor 1964; Wei & Smith 1986; Unal & Rockwell 1988). Since they occur at $L/D \ll 1$, it follows that their formation is not dependent on development of the large-scale vortices.

From the alternate increase and decrease in vortex formation length visualized in figure 4, we expect a stage-like behaviour of the near-wake velocity field. To establish this connection, figure 5 shows the comparison of the near-wake fluctuation level $\tilde{u}_e/U$ (figure 2) and the inverse of observed vortex formation length D/l_f (from visualization of the sort shown in figure 4) versus the streamwise lengthscale L/D. An increase in near-wake fluctuation level corresponds to a decrease in vortex formation length and vice versa.

Figures 6 and 7 show the effect of streamwise lengthscale L/D on the spectral components of the near-wake instability, with f_v representing the frequency at which large-scale vortices are formed and nf_v where $n = 1, 2, \ldots$ corresponding to the higher harmonics of the vortex shedding frequency. Figure 6 shows that over the Reynolds-number range $Re = 70$ to 1100, there are two predominant spectral components present, f_v and $2f$. At relatively low values of Reynolds number, $Re =$ 70 to 395, there are only mild increases in Strouhal number for increasing streamwise lengthscale L/D. As Re increases, there is a decrease in the value of L/D at which oscillations are detectable. As already indicated by the flow visualization at $Re = 142$ (see figure 3), there are no visible oscillations of the wake for $L/D \lesssim 3$, further substantiated by the corresponding plots of near-wake fluctuation level in figure 2. However, at higher values of Reynolds number, $Re = 627 \leqslant Re \leqslant 1100$, there are detectable fluctuations at the vortex shedding frequency f_v and its first harmonic $2f_v$ at very small L/D.

Figure 7 shows that at relatively high values of Reynolds number, $Re = 2031$ to 5040, the near-wake structure becomes more complex with a number of additional frequency components present, even at very small L/D. At $Re = 2031$, f_v, its first harmonic $2f_v$, and the Bloor–Gerrard frequency at which small–scale vortices are shed, f_{BG}, are present even for $L/D \ll 1$. At $Re = 3645$ and 5040, as many as ten well-defined spectral components are detectable; only the six largest are indicated on the plot $S \equiv fD/U$ *vs.* L/D in figure 7. All spectral amplitudes are characterized at the edge of the shear layer. Of central interest here is the underlying mechanism for existence of f_{BG} and $\frac{1}{2}f_{BG}$ components in relation to the component at f_v. Indeed, the

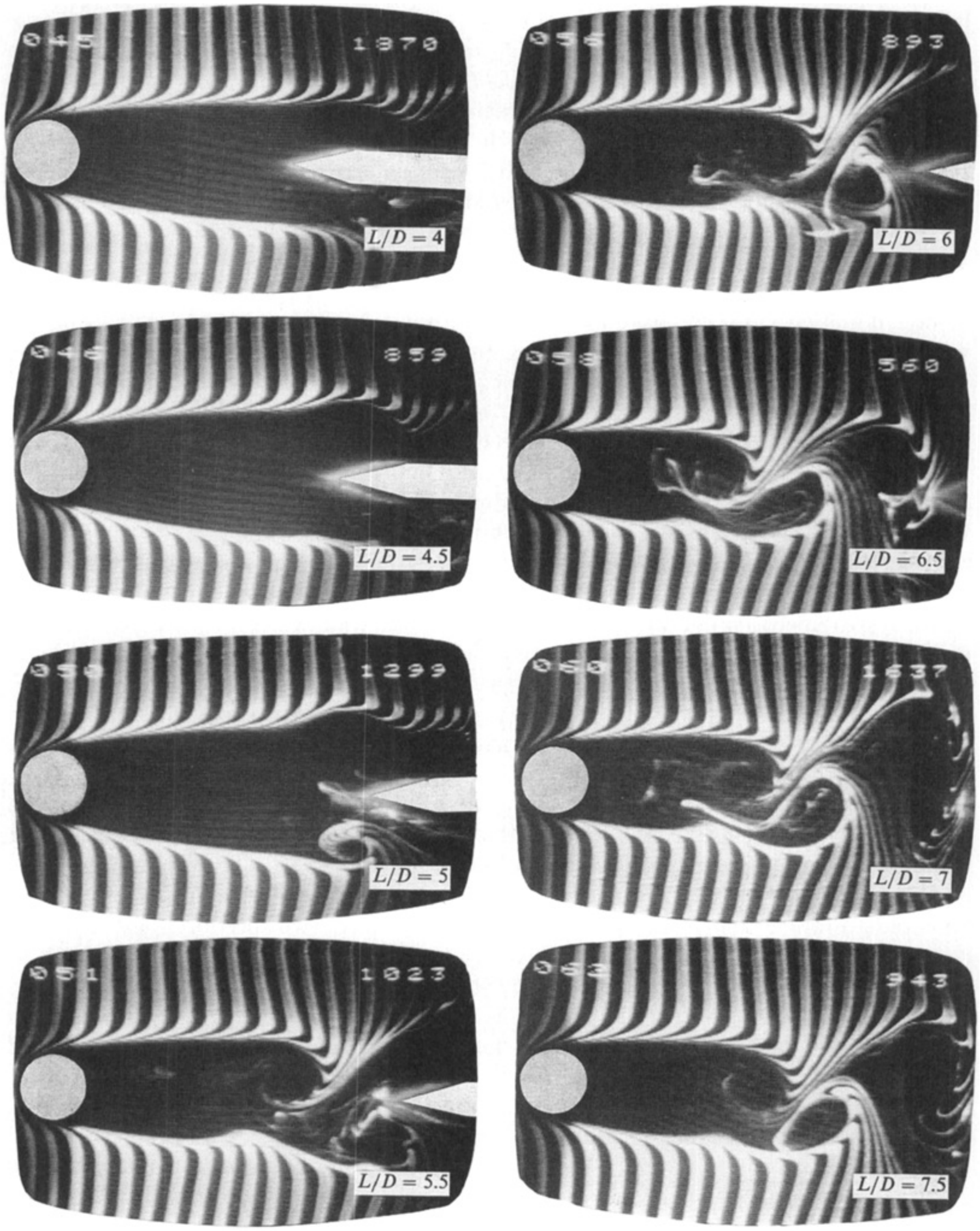

FIGURE 4. For caption see facing page.

most striking feature of the spectra in figure 7 is the dominance of the large-scale shedding component f_v, and corresponding attenuation of the subharmonic of the small-scale vortex shedding $\frac{1}{2}f_{BG}$, when L/D becomes sufficiently large. This drastic change in spectral content is evident in comparing the spectra at $L/D = 3.5$ and 8.0 at the bottom of figure 7 for $Re = 5040$. Similar spectra were obtained at $Re = 3645$.

The near-wake structure associated with this change in the spectrum is described

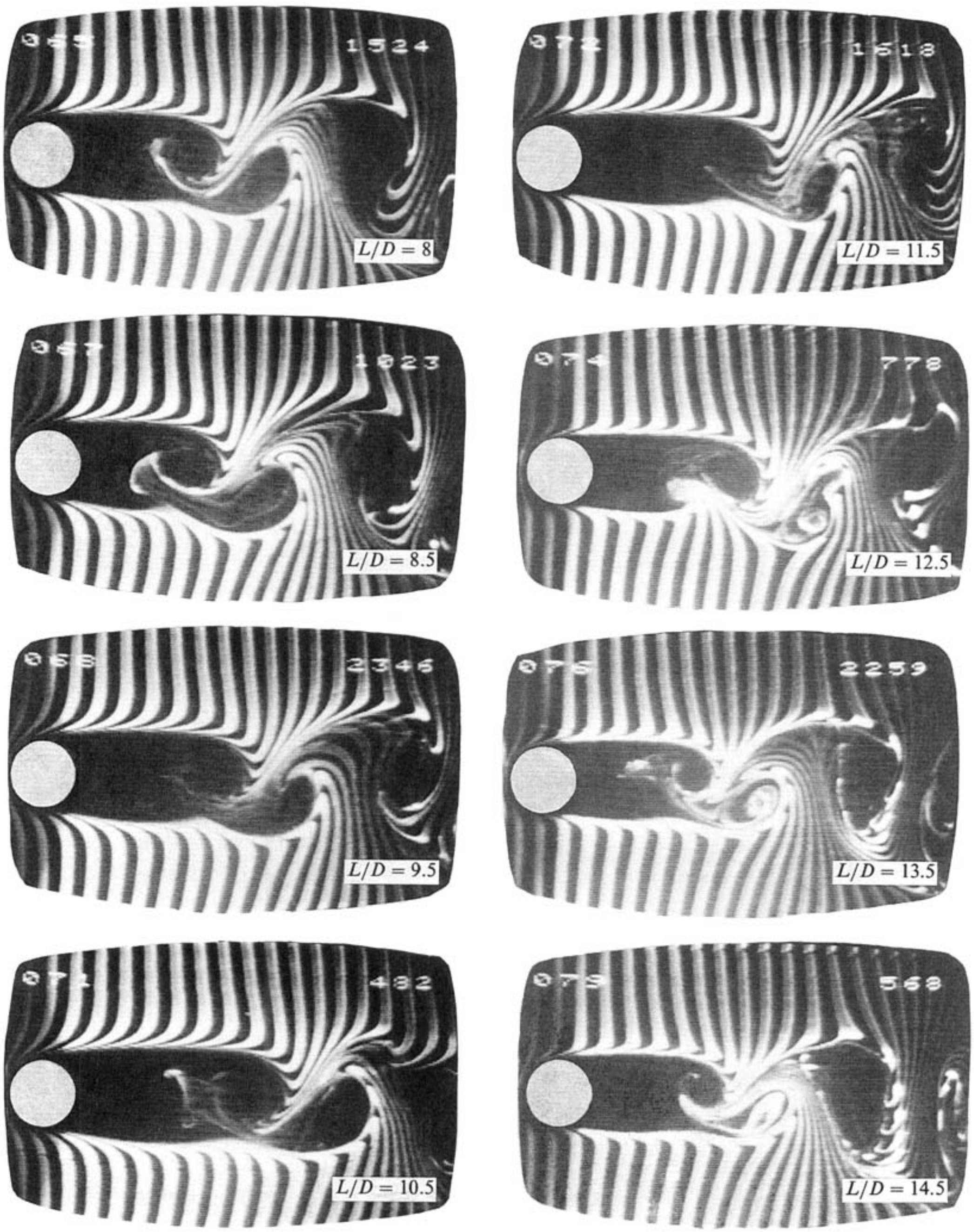

FIGURE 4. Visualization of near-wake structure for $Re = 785$ as a function of increasing streamwise lengthscale L/D.

by Unal (1985). At small L/D, attenuation of large-scale (f_v), antisymmetrical vortex formation allows coalescence of small-scale (f_{BG}) vortices on either side of the wake, producing a component at $\frac{1}{2}f_{BG}$. Correspondingly, the spectrum shows pronounced components at f_v, f_{BG}, and $\frac{1}{2}f_{BG}$. On the other hand, at sufficiently large L/D, large-scale (f_v) vortex formation does occur; the small-scale (f_{BG}) vortices form a frill upon

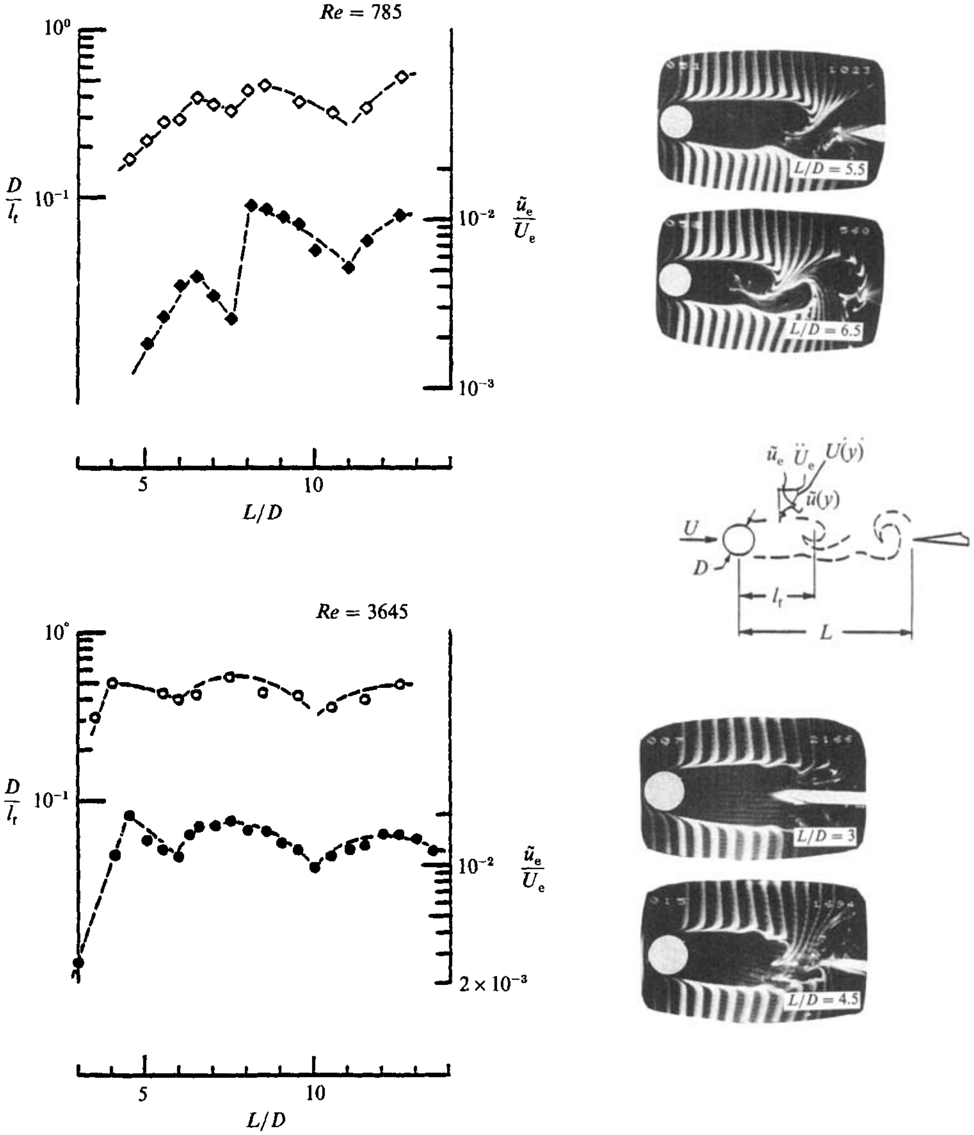

FIGURE 5. Comparison between fluctuation level at edge of shear layer in near-wake region $\tilde{u}_e/U_e$ with inverse of vortex formation length D/l_f as streamwise lengthscale L/D is varied.

them without undergoing successive coalescence. As a result, the spectrum is dominated by the f_v component. Taken together, the foregoing observations suggest that when large-scale (f_v), antisymmetrical vortex formation occurs, the large-amplitude fluctuations induced by upstream influence preclude successive coalescence of small-scale (f_{BG}) vortices and thereby lack of significant energy at $\frac{1}{2}f_{BG}$. There is a similarity between this mechanism and that due to large-amplitude forcing of free mixing-layers (Ho & Huang 1982) as discussed by Unal & Rockwell (1988).

Furthermore, the plots of figure 7, in conjunction with flow visualization of figures 3 and 4, show that the shedding frequency of the large-scale vortices at f_v is detectable at very small L/D, even though large-scale vortex formation does not

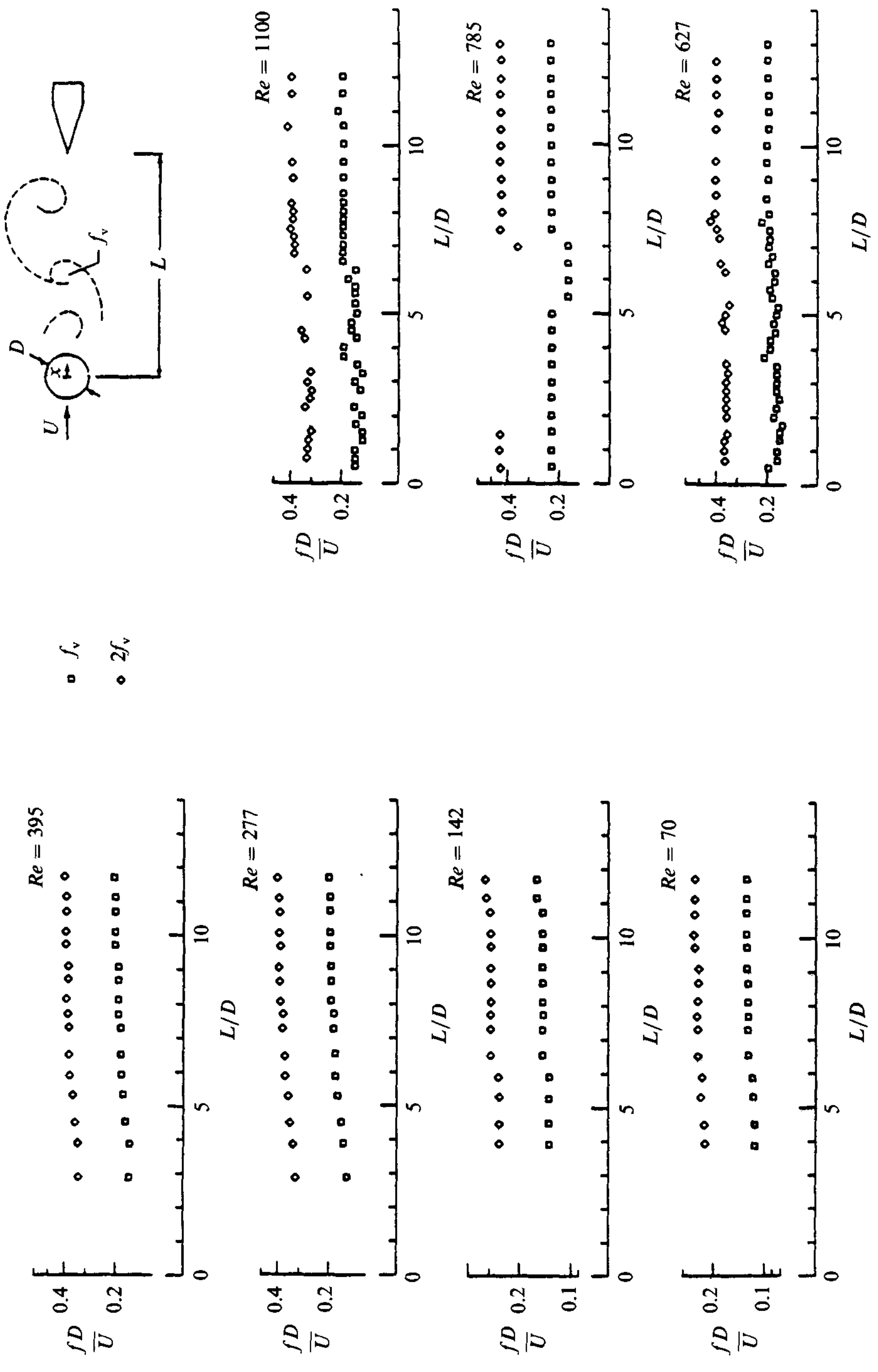

FIGURE 6. Variation of predominant spectral components of near-wake region at $x/D = 2$ as a function of streamwise lengthscale L/D.

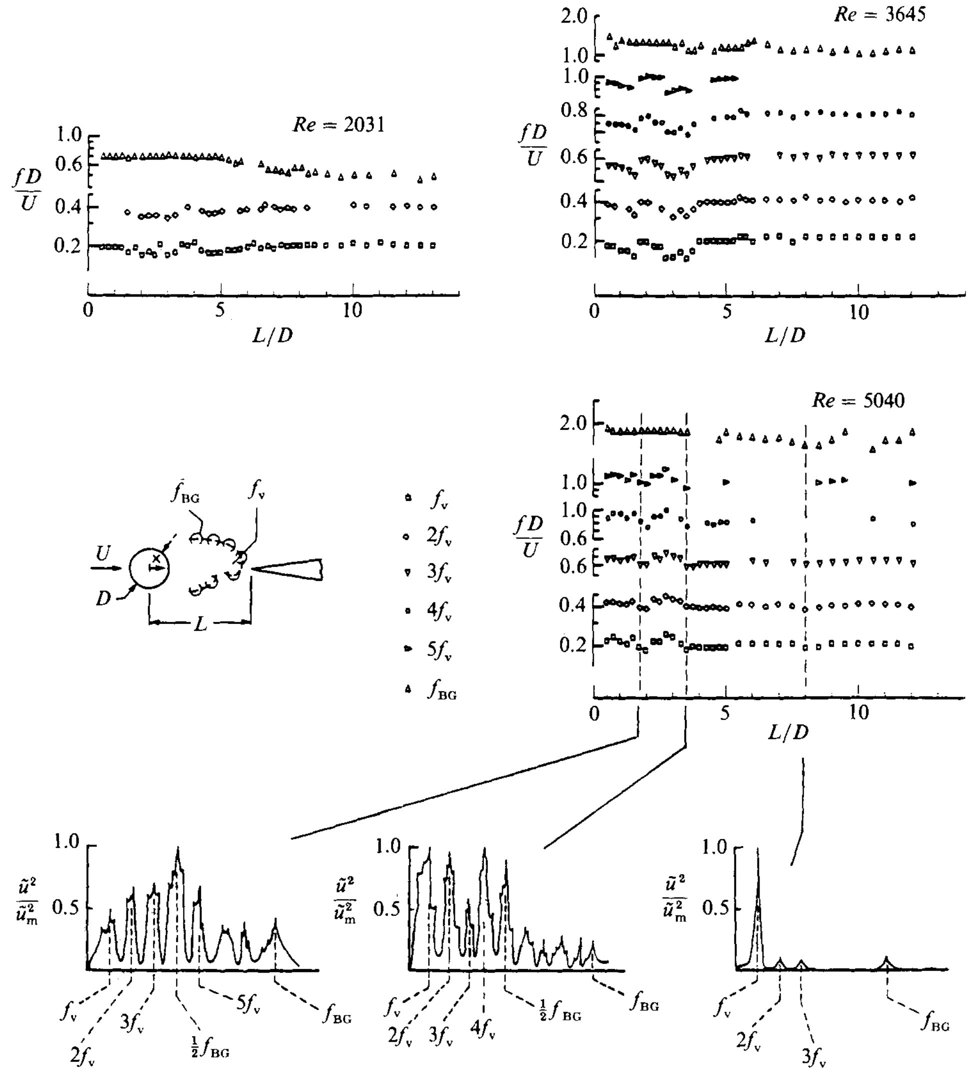

FIGURE 7. Variation of discrete components of near-wake region at $x/D = 2$ as a function of streamwise lengthscale L/D.

occur. This means that the mechanism leading to large-scale vortex formation is associated with an instability of the separating shear layer.

Regarding the pressure induced at the surface of the leading edge of the plate, figure 8 shows the pressure amplitude $\tilde{p}(f_V)$ at the frequency of large-scale vortex formation f_V. It corresponds to the peak amplitude in the pressure spectrum. Pressure $\tilde{p}_m$ represents the maximum peak amplitude measured over the range of L/D. The amplitude of $\tilde{p}(f_V)$ increases by roughly one and a half orders of magnitude at $L/D \approx 4$, corresponding to the onset of large-scale vortex formation immediately upstream of the leading edge (compare with figure 2). As L/D approaches a value of 4, the pressure rises rapidly, in accord with the initial phase of large-scale vortex formation. Comparing with the data of figure 2, there is an exponential increase in the near-wake fluctuation level $\tilde{u}_e$ over this range of L/D.

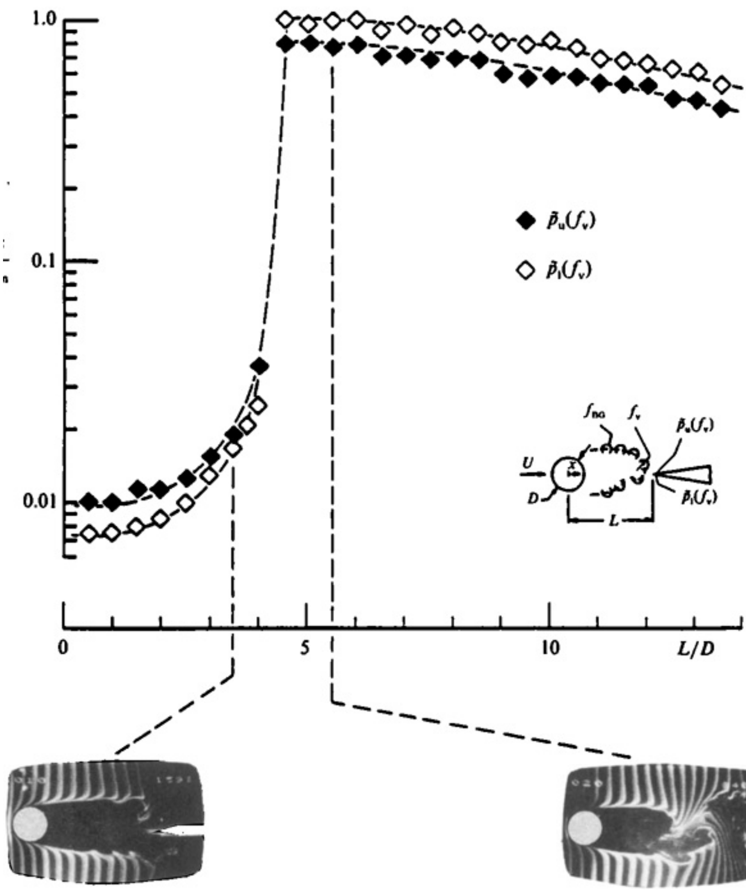

FIGURE 8. Dependence of pressure fluctuation amplitudes on upper $\tilde{p}_u$ and lower $\tilde{p}_l$ surfaces of leading-edge as a function of streamwise lengthscale L/D. All pressure amplitudes represent the spectral peak at the predominant frequency f_v of large-scale vortex shedding. $Re = 3645$.

The phasing of these pressure fluctuations on the surface of the leading edge is correlated with the near-wake structure in figure 9. Each photograph corresponds to a different value of L/D as indicated. At each value of L/D, it is necessary to have a consistent means of selecting a representative photo of the wake during its oscillation cycle. It was decided to employ the following criterion: formation of the first large-scale vortex on the lower right-hand side of the wake, indicated by the lower right-hand (black) protruding area of the wake separation zone. In accord with the series of photographs in Unal (1985), an increase in L/D produces successive increases and decreases in vortex formation length; in effect, they alter the effective origin of the vortex street and thereby the phasing of the pressure fluctuations on the (lower) surface of the leading edge. The instantaneous pressure trace corresponding to each photo (see inset of figure 9) provides the link between the phase of the (lower) surface pressure and visualized vortex formation in the near-wake region. For $L/D = 5$ and 6, the major share of the large-scale vortex passes along the upper side of the leading-edge of the plates. Correspondingly, the pressure will be maximum negative on the upper side of the leading edge and maximum positive

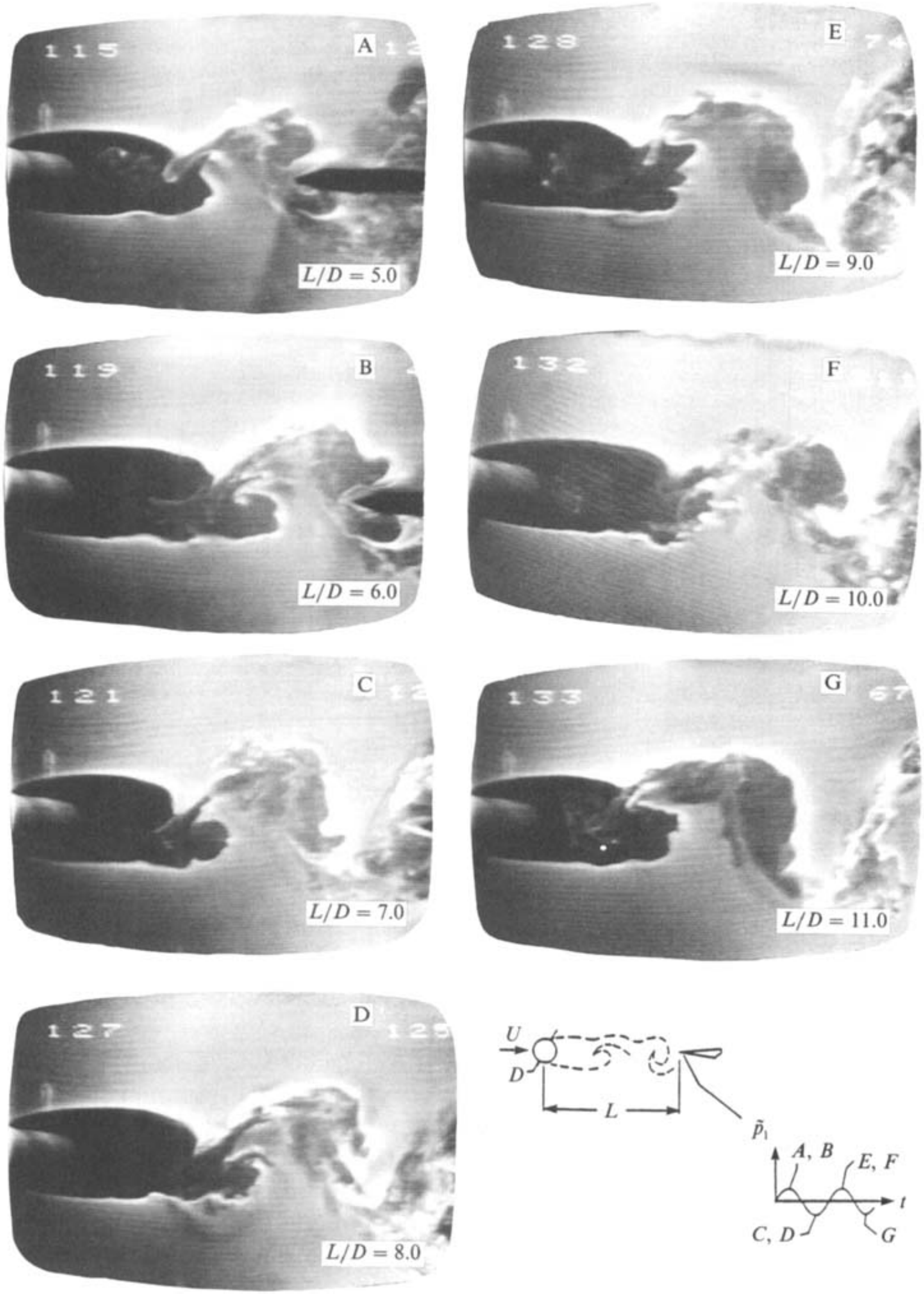

FIGURE 9. Simultaneous visualization of near-wake region and instantaneous pressure at lower surface of leading edge for varying streamwise lengthscales L/D. All photographs are phase-locked to completion of vortex formation of the initial vortex of the lower side. $Re = 3645$.

on the lower side, in accord with the indicated pressure trace. This relation between phasing of the large-scale vortex and the local pressure fluctuation has been verified for a single vortex–edge interaction by Kaykayoglu & Rockwell (1985). As the plate is displaced to successively larger L/D, the phasing of the edge pressure fluctuation switches between maximum-negative and maximum-positive.

4. Concluding remarks

Over the range of Reynolds number $140 < Re < 5000$, insertion of a plate in the wake of a cylinder can inhibit the development of the large-scale instabilities leading to formation of the classical von Kármán vortex street. At sufficiently low values of Reynolds number representing the pure von Kármán regime of the corresponding free wake, e.g. $Re = 142$, the instability can be eliminated altogether when the plate is placed sufficiently close to the cylinder. In this case, the separating shear layer appears to remain laminar until it reattaches to the downstream edge. On the other hand, at higher values of Reynolds number, when large-scale vortex formation at f_v is precluded by the edge, there is still unstable disturbance growth at f_v in the shear layer separating from the cylinder. Therefore, it may be concluded that the effect of intrusion of the leading-edge of the plate in the near-wake region is to inhibit the full development of the large-scale wake vortices, rather than to preclude the onset of the initial instability immediately downstream of shear-layer separation (Unal & Rockwell 1988).

In addition to the large-scale instability at f_v, it is well known that at sufficiently high Reynolds number, there also occurs small-scale vortex shedding at f_{BG} (Bloor 1964; Wei & Smith 1986; Unal & Rockwell 1988). Similarly to the foregoing observation for the existence of a discrete component at f_v in the presence of the edge, the component f_{BG} also persists even in the limiting case as the streamwise lengthscale between the cylinder and the leading edge of the plate becomes very small. This suggests that the region of the shear layer immediately downstream of separation supports amplification of the disturbance leading to the small-scale shedding at f_{BG}.

It should also be noted that, in addition to components f_v and f_{BG}, there exist higher harmonics of f_v, i.e. nf_v, where $n = 1, 2, \ldots$ as well as a subharmonic of f_{BG} and a number of other discrete components. For sufficiently large distance between the cylinder and the leading edge of the plate, the nature of the velocity spectrum changes drastically. The frequency f_v of the large-scale vortex shedding dominates the other discrete components in the spectrum. In other words, once the large-scale vortex(ices) is allowed to form downstream of the body, there is predominance of fluctuation energy at the large-scale component f_v. This observation is consistent with existence of an absolute instability in the near-wake region (Koch 1985; Monkewitz & Nguyen 1986); the global resonance of this type of instability apparently overwhelms the multiple frequency characteristics of the purely convective shear layer.

Indeed, this observation is in contrast to that occurring in the corresponding mixing layer formed by unequal free-stream velocities from a streamlined trailing edge (Miksad 1972). In this case, the nonlinear evolution of the disturbance downstream of the trailing edge involves a number of spectral components associated with nonlinearity and nonlinear interactions. In essence, any comparison between mixing-layer and bluff-body wake instabilities must account for the distinctive nature of the mean flow past a bluff body: it is capable of supporting an absolute instability over a wide range of flow parameters. When resonant oscillations characteristic of the absolute instability do occur, they may alter the very nature of the shear-layer spectral content.

Control of the near wake by an edge can occur even if the edge is located downstream of one or more fully formed vortices. This control is evident in changes in formation length of the first vortex. Correspondingly, these changes are reflected in the amplitude of the fluctuation velocity near separation: shorter values of vortex formation length are associated with higher initial fluctuation levels. At larger distances between the cylinder and edge, where one or more large-scale vortices may develop prior to interaction with the leading edge of the plate, the upstream influence may, in general, take two forms: Biot-Savart induction and/or an upstream influence from a region of absolute instability (Koch 1985; Monkewitz & Nguyen 1986). This upstream influence may be, or even exceed, that from the vortex–edge interaction region. In fact, at the lowest value of Reynolds number examined herein, $Re = 142$, the near-wake, large-scale vortices are strongly coherent; once they develop upstream of the leading edge of the plate, variation in the streamwise lengthscale between the cylinder and the edge has no influence on the initial fluctuation level and thereby on the near-wake development. On the other hand, at higher values of Reynolds number, the near-wake region is highly sensitive to downstream vortex development and vortex–edge interaction. In future studies, these Reynolds-number effects should be assessed within the theoretical framework of an absolute instability (Monkewitz & Nguyen 1986). Important parameters are the thickness of the separating shear layer (relative to the body diameter) and the magnitude of the backflow along the centreline of the near wake (relative to the free stream). Both of these parameters may change with Reynolds number in such a manner as to alter the strength of the absolute instability of the near wake, or even to cause a transition to an initially convective one. In doing so, however, the nature of the three-dimensionality of the near wake must also be accounted for.

Finally, it should be noted that well-defined stages of oscillation frequency do not appear to exist for the bluff-body configuration. Such stages are a prevalent feature of jet– and mixing-layer–edge oscillations (Rockwell 1983); they are characterized by a streamwise phase difference of $2\,n\pi$ as well as key jumps in oscillation frequency as length L is varied. Although the length of the vortex formation region (i.e. length of base region) is clearly dependent on streamwise lengthscale between the cylinder and edge at higher values of Reynolds number, there appears to be no 'locking-on' of the overall oscillation frequency and occurrence of a $2\,n\pi$ streamwise phase difference between separation and impingement. (Detailed phase measurements are described by Unal 1985). As suggested in the previous paragraph, the degree of predominance of the upstream influence from the near-wake instability relative to that from the wake–edge interaction appears to change with Reynolds number. Indeed, step-like variations of dimensionless frequency with changes in length are indiscernible in the range of Reynolds number corresponding to the pure von Kármán region.

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