Effects of a Downstream Disturbance on the Structure of a Turbulent Plane Mixing Layer

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Using a two-dimensional airfoil, a disturbance was introduced into a plane mixing layer some distance downstream of the splitter plate trailing edge. Results indicate that it is possible to induce very large changes in the layer growth rate downstream of the disturbance location, while leaving the portion of the shear layer between the splitter plate and the disturbance source essentially unaffected. Furthermore, the use of forcing for modification of the mixing layer in the region upstream of the disturbance is demonstrated. It is shown that two different mechanisms are responsible for coupling such disturbances to the flow in the present forcing of upstream and downstream regions.

Introduction

IT is known that the evolution of plane mixing layers can be strongly affected by low-amplitude disturbances. As a result of the sensitivity of shear layers to initial conditions, most of the effort has been concentrated on modifying the initial shedding of vorticity through artificial excitation. These and other related phenomena have been reviewed by Ho and Huerre.[1] Forcing is usually achieved by introducing disturbances acoustically,[2,3] mechanically by oscillating a trailing-edge flap,[4] or oscillating one or both freestream velocities.[5-7] Other methods such as the strip-heater technique have also been used.[8]

The common feature of forcing studies to date is that the disturbances are effectively introduced at the tip of the splitter plate. As a result of this, the entire region of the flow downstream of the splitter plate is modified. Experimental results[4,5] show that the forced shear layer exhibits three distinct response regions (see also Refs. 1 and 9). In region 1, the layer growth rate is enhanced by up to a factor of about two[9] compared to the unforced case. The mixing layer spreading rate remains virtually constant in region 2. This region is characterized by a single array of equally spaced large vortical structures that do not interact with one another. And finally, region 3 marks the gradual relaxation to the growth rate characteristics of the unforced mixing layer.

In the work described in this paper, we consider the case where a two-dimensional disturbance is introduced into a turbulent mixing layer at some distance downstream of the trailing edge of the splitter plate. The response of the mixing layer in the regions both upstream and downstream of the location of the disturbance source is investigated using flow visualization and laser Doppler velocimetry.

Experimental Facility and Instrumentation

This work was carried out in a low-speed, free-surface water channel. The test section was 45.72 cm wide and 42 cm high (dictated by the height of the water in the channel). In the present study, the first 210 cm of the over 300-cm-long test section was utilized. The water channel was modified to generate a high-aspect-ratio two-dimensional shear layer, as indicated in Fig. 1. The special insert used for this purpose followed the design of Dimotakis and Brown[10] and produced a shear layer with a velocity ratio, $r = U_2/U_1$, of approximately 0.44. In this design, the insert accelerated the flow below it and decelerated the flow above it. A perforated plate and a screen placed in the upper part of the insert were responsible for a head loss that matched the Bernoulli pressure drop in the lower part of the flow. This matching was necessary in order to avoid separation at the leading edge of the insert. For further details of the design, the reader is referred to Ref. 10. The details of the perforated plate and screen that were selected and the resulting flow characteristics are described by Lang.[11]

The velocity of the high-speed stream was set to $U_1 \approx 20.6$ cm/s, resulting in a Reynolds number, based on $\Delta U = U_1 - U_2$, of about 1150/cm. The boundary layer on the high-speed side at the splitter plate tip was found to be laminar with a momentum thickness of $\theta_0 = 0.76$ mm. The natural vortex formation frequency f_0, under these operating conditions, was about 6 Hz. This was determined from the peak of the spectrum of the streamwise velocity fluctuations close to the splitter plate tip. Throughout this paper, x refers to the streamwise coordinate measured from the splitter plate tip and y to the cross-stream direction (see Fig. 1).

Disburbances were generated by a pitching NACA 0012 airfoil that extended across the span of the water channel test section. The pitch axis was at the quarter-chord point and the airfoil chord was $C = 8$ cm. The driving mechanism was designed such that the airfoil could execute any arbitrary waveform shape.[12] For the results presented here, however, only sinusoidal oscillations were considered. The mean angle of attack relative to the shear layer freestream velocity vector was set to approximately zero. As an indication of the disturbance amplitude, we use the airfoil angle-of-attack amplitude A in degrees (i.e., airfoil angle of attack varies between $-A$ and A). For the range of values of A used here, the amplitude of the trailing-edge excursion in millimeters turns out to match the A values to within 5%.

The flow was visualized using food coloring issued from an injection port imbedded in the high-speed side of the shear layer insert and was subsequently recorded on photographic film by a 35 mm camera. The streamwise component of the velocity vector was measured by a single-channel, frequency-shifted laser Doppler velocimeter (LDV) in the dual scatter mode. The Doppler burst was processed by a tracking phase-locked loop (in-house design by P. E. Dimotakis) whose output frequency was measured by a real-time clock card interfaced to a data acquisition system based on a PDP 11/73 CPU.

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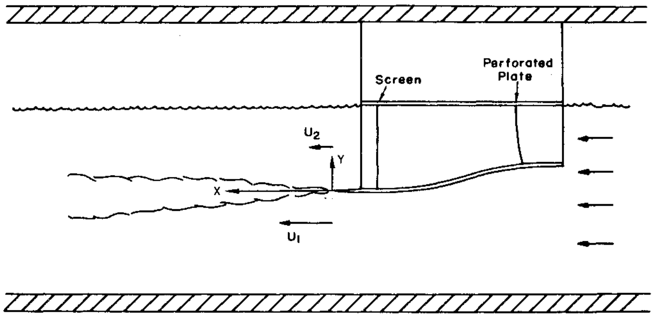


Fig. 1 Schematic of the shear layer insert.

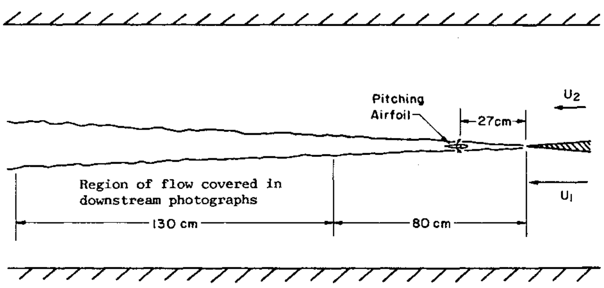


Fig. 2 Flow geometry in forcing experiments.

Results and Discussion

For the results described here, the airfoil was placed roughly in the middle of the shear layer at a downstream distance of 27 cm as measured by the distance between the airfoil pitch axis (quarter chord) and the trailing edge of the shear layer splitter plate; see Fig. 2. At this separation distance, the presence of the airfoil did not affect the characteristics of the otherwise natural layer in the region between the splitter plate and the airfoil. The initial instability frequency f_0 and the mean and rms profiles of the streamwise velocity component remained unchanged in this region, with or without the airfoil.

Throughout this paper, we use an integral thickness as a measure of the shear layer local thickness, defined by

$$\theta = \int_{-\infty}^{y_m} \left[\frac{U_1 - U(y)}{U_1 - U_m} \right] \left[\frac{U(y) - U_m}{U_1 - U_m} \right] \mathrm{d}y$$

where $U(y)$ is the mean streamwise velocity profile, U_m the minimum velocity in the profile, and y_m the y location where $U = U_m$. This definition was suggested by Lang[11] to accommodate mean profiles with a wake component. Note that when the wake component goes to zero, resulting in $U_m \to U_2$ and $y_m \to +\infty$, the usual definition of the integral thickness is recovered.

Downstream Influence

The general effect of the pitching airfoil on the shear layer in the region downstream of the airfoil is illustrated in Fig. 3. The right and left edges of each photograph correspond to a range of downstream stations of $80 < x < 210$ cm measured from the splitter plate trailing edge. This range is equivalent to $1053 < x/\theta_0 < 2763$, where θ_0 is the initial momentum thickness of the boundary layer on the high-speed side at the splitter plate tip. The width of each photograph in the cross-stream direction corresponds to the height of the water in the channel, approximately 42 cm in this case.

Figure 3 shows that large increases in the layer growth rate can be achieved at low forcing frequencies ($f/f_0 \ll 1$). Note that the mere presence of the nonoscillating airfoil in the layer (Fig. 3b, $f = 0$) appears to have reduced the layer growth rate.

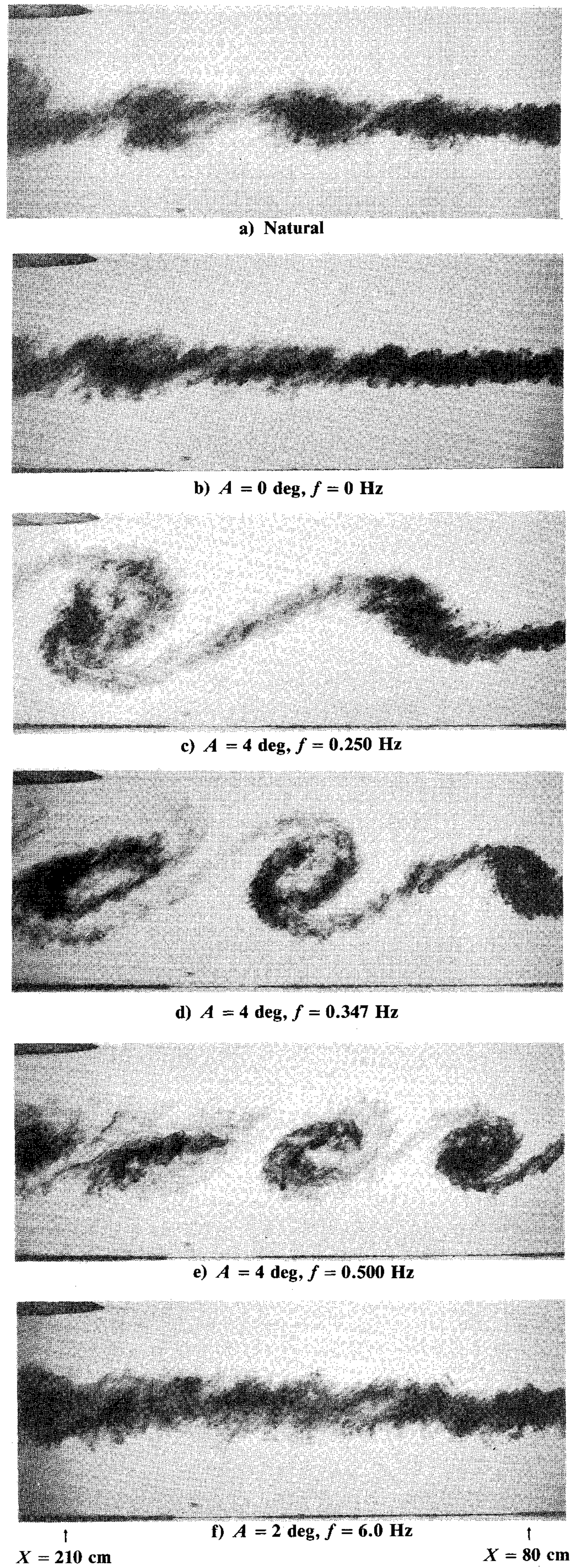


Fig. 3 Effect of the pitching airfoil on the shear layer structure and growth in the region downstream of the airfoil (flow is from right to left).

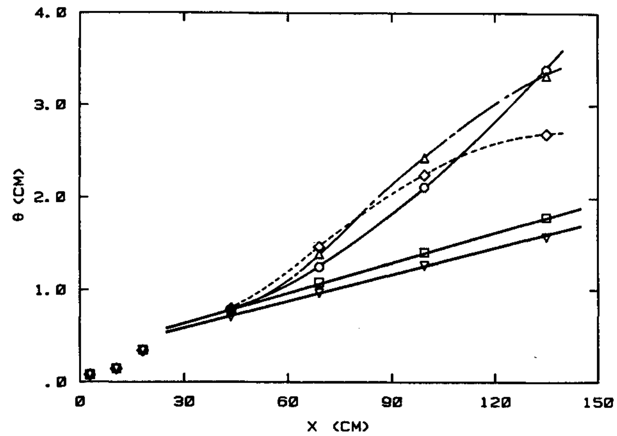


Fig. 4 Variation of the shear layer thickness for $A = 4$ deg (□ natural; ▽$f = 0$, $A = 0$; ○$f = 0.250$; △$f = 0.347$; ◇$f = 0.500$).

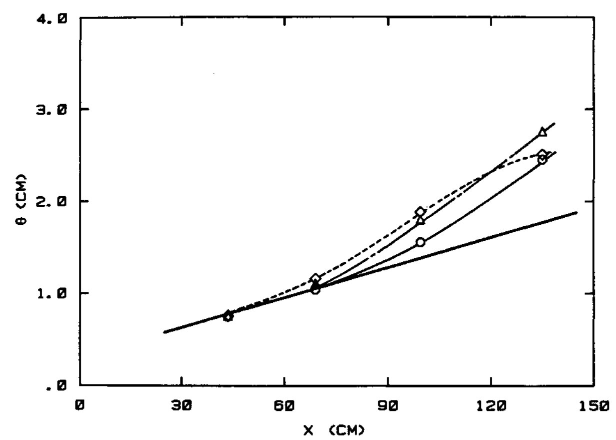


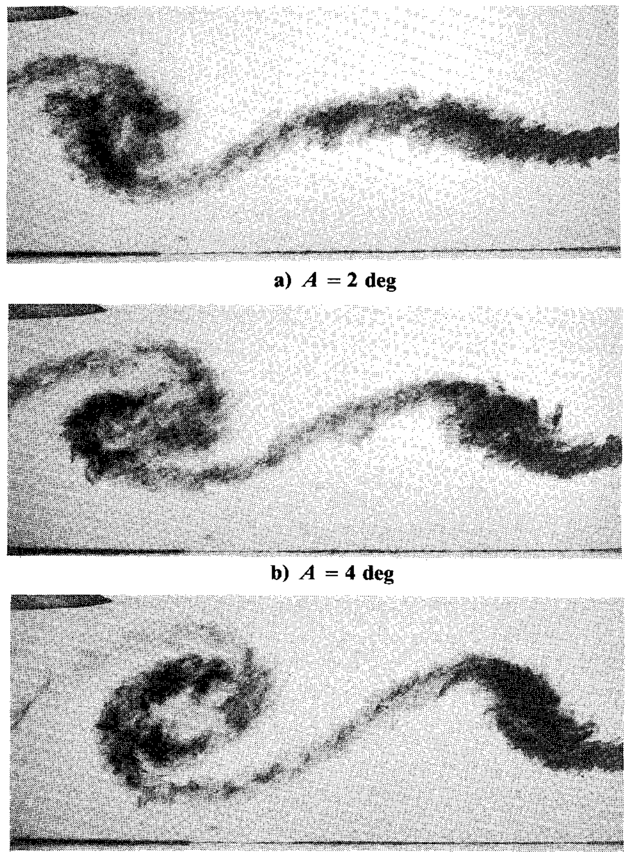
Fig. 5 Variation of the shear layer thickness for $A = 2$ deg (—— natural, ○$f = 0.250$, △$f = 0.347$, ◇$f = 0.500$).

Similarly, in the case of a high oscillation frequency ($f = 6$), the shear layer seems to grow more slowly than the natural case. It should be mentioned that, for high-frequency cases, the airfoil oscillation amplitude was lowered in order to keep the acceleration at these high frequencies manageable, particularly during long periods of time required for data acquisition. No discernible difference was observed upon increasing the amplitude from 2 to 4 deg in the case of high-frequency forcing.

These qualitative results are further substantiated by velocity profile measurements. See the θ vs x plots in Fig. 4, which were computed from these profiles (Figs. 8, 12, and 14 represent typical profiles). This figure includes only low-frequency forcing results, since that is when the largest effects were observed. When the stationary airfoil is in the layer, the downstream growth rate is reduced by approximately 15% relative to that of the natural layer. At this point, it may be interesting to note the qualitatively similar behavior of turbulent boundary layers resulting from the insertion of large-eddy breakup devices.[13] Whether the reduction of the shear layer growth rate can be explained by similar mechanisms and whether this reduction persists at large downstream distances requires further study. We also note that the downstream growth rate of the layer at high forcing frequencies (results not shown here) tends to be lower than the natural case and is bracketed between the growth rates of the natural layer and the layer with the stationary airfoil.

Results obtained at forcing frequencies of $f = 0.25$, 0.347, and 0.50 indicate that low-frequency forcing is characterized by an increase of the shear layer spreading rate culminating in the formation of large vortices. The enhanced growth is not linear in x and its magnitude depends on the forcing frequency (e.g., see Fig. 4). As the frequency decreases, the region of flow showing increased growth moves downstream and the final vortex formed has a larger size. It appears that the growth of the forced layer becomes very small once the associated large vortices are formed. This can be seen in the photographic data (Fig. 3) and the trend in the θ vs x plot (Fig. 4) as x increases.

The forcing amplitude affects the features described above in the following way. An increase (decrease) of the airfoil pitch amplitude increases (decreases) the layer spreading rate and causes the final large vortex to be formed somewhat earlier (later). These effects are shown in Fig. 5 (to compare with Fig. 4) and Fig. 6. One consequence of these events is that, as the forcing amplitude is raised, the shear layer thickness, at a fixed downstream location, increases and ultimately reaches a "saturation" value; see Fig. 7. It is not clear, at this



a) $A = 2$ deg

b) $A = 4$ deg

c) $A = 6$ deg

$X = 210$ cm ↑ ↑ $X = 80$ cm

Fig. 6 Effect of the forcing amplitude on the shear layer structure and growth for $f = 0.250$ Hz.

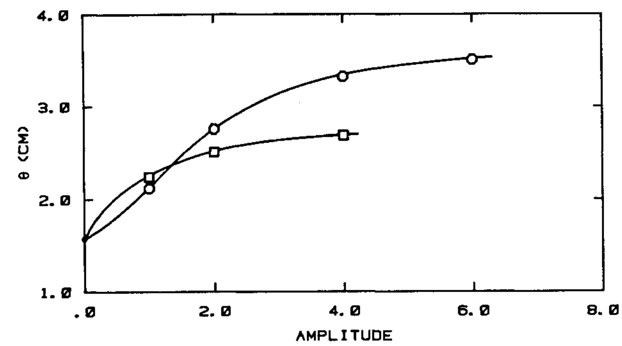


Fig. 7 Variation of the shear layer thickness with forcing amplitude at $X = 135$ cm (○$f = 0.347$, □$f = 0.500$).

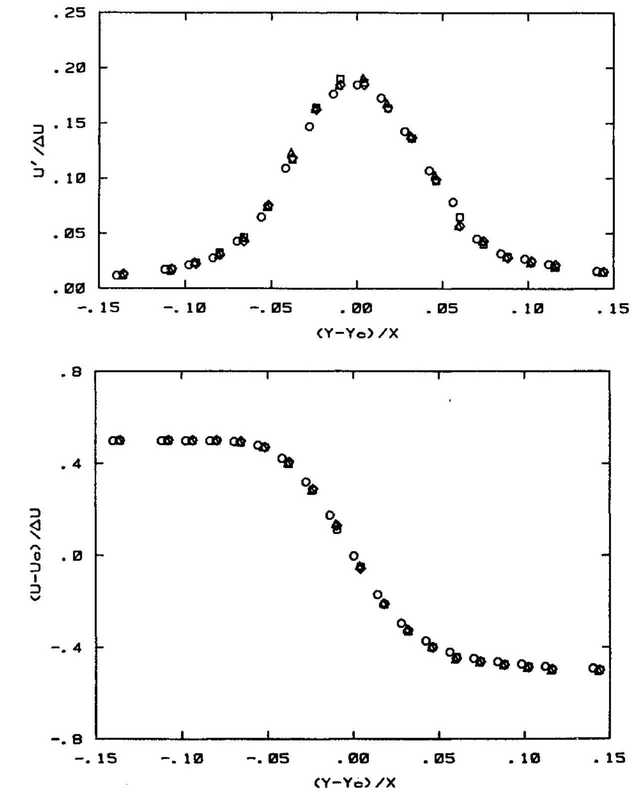


Fig. 8 Mean and rms velocity profiles at $X = 18$ cm (○ natural; □ $A = 0, f = 0$; ◇ $A = 4, f = 0.250$; △ $A = 4, f = 0.500$).

point, whether this saturation is due to the layer growth rate having reached a limiting value or the moving upstream of the location of vortex formation.

Results from Fig. 3 ($f = 0.25$, 0.347, 0.5) and also Fig. 9 (discussed in the next section) suggest that, for a given airfoil oscillation frequency, the shear layer thickness reaches a maximum at a downstream station x where the final large vortices are fully formed. This station seems to be the location where the mean vortex passage frequency of the natural layer roughly matches the forcing frequency. If $\overline{l_n}$ denotes the mean vortex spacing at downstream station x in the natural layer, the mean vortex passage frequency $\overline{f_n}$ can be calculated from $\overline{f_n} = U_c/\overline{l_n}$. The convection speed U_c, in the present case of uniform density, is approximately[14,15] $U_c \approx (U_1 + U_2)/2$. The mean vortex spacing can be estimated using the relation,[15]

$$\frac{\overline{l_n}}{x} = 0.68 \frac{1-r}{1+r}$$

where $r = U_2/U_1$ is the velocity ratio. The mean vortex passage frequency can now be estimated according to

$$\overline{f_n} = \frac{U_c}{0.68 x \lambda}$$

where $\lambda = (1-r)/(1+r)$. Matching of the forcing frequency f and the mean vortex passage frequency $\overline{f_n}$ leads to the relation $\lambda x f / U_c \approx 1.47$ as an estimate of the downstream location where the layer thickness reaches a maximum and the large vortices are fully formed. This estimate agrees with the findings of Oster and Wygnanski[4] that the center of "region 2" (see the introduction) occurs at $\lambda x f / U_c \approx 1.5$.

In both cases of forcing the downstream region and the upstream region (see the next section), the passage frequency of the large vortices that are formed is the same as the forcing frequency. In other words, if l is the vortex spacing and f the forcing frequency, we obtain $fl/U_c = 1$. The vortex spacing can be readily obtained by measuring the separation distance between the vortices in Fig. 3. While there are general similarities between our results and the previous work on shear layer low-frequency forcing,[4,5] the growth rates observed here appear to be larger. Under low-frequency excitation, shear layer growth rate increases of up to a factor of two over the unforced layer have been reported.[9] In our data of Fig. 4, maximum spreading rates as high as three times the natural layer are indicated. Note also that, in most high-growth cases, the size of the structures has become comparable to the channel height. It is quite possible that the finite height of the channel may be restricting the growth of structures that might otherwise have grown to even larger sizes.

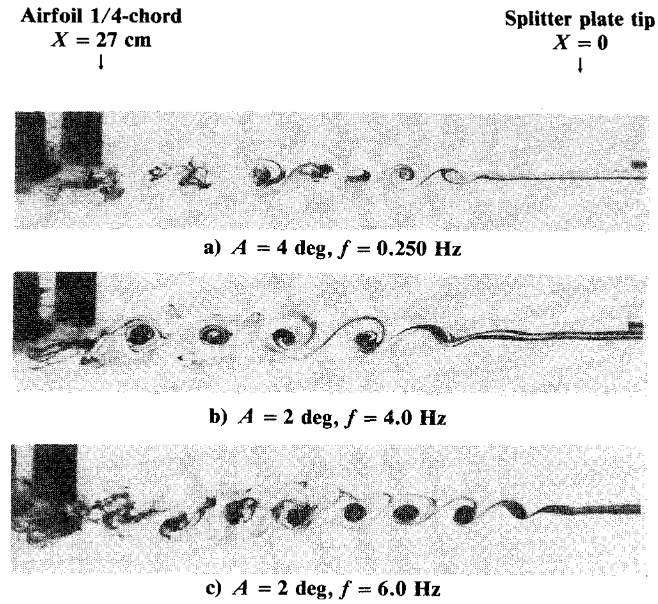


Fig. 9 Effect of the pitching airfoil on the shear layer structure and growth in the region upstream of the airfoil.

Upstream Influence

The growth of the shear layer in the region *upstream* of the airfoil is not affected by either the presence of the stationary airfoil or its oscillation at low frequencies; see Fig. 4. Measurements of the streamwise velocity at three stations in the upstream region show that the mean and rms profiles also remain unchanged when compared to the natural layer. Figure 8 shows one such comparison at a distance about one chord length upstream of the airfoil. For these low frequencies, the shear layer is divided into two regions: one upstream of the airfoil where the layer grows as in the natural case and the other downstream of the airfoil where the growth rate is substantially increased. The large mismatch of the airfoil oscillation frequency with the predominant natural frequencies in the shear layer in the upstream region of the airfoil is most likely the reason this portion of the layer remains unaffected.

Control over the structure and growth rate in the upstream part of the layer *can* be exercised if the forcing frequency is raised. Examples of forcing the upstream region are provided in Fig. 9. The photograph in this figure, corresponding to low-frequency forcing, also represents the flow patterns in cases of the natural layer and stationary airfoil, due to the insensitivity of this region to low-frequency excitation, as discussed previously. Figure 9 shows that forcing close to the natural frequency leads to the formation of a periodic, noninteracting array of vortices. These effects are similar to results obtained by previous excitation techniques where forcing was applied at the splitter plate trailing edge (e.g., see Refs. 5–7). In fact, using the present technique of forcing the upstream region, we have been able to observe many of the features documented in mixing layers that were forced by other means.[1]

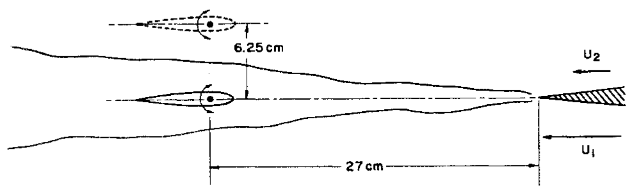
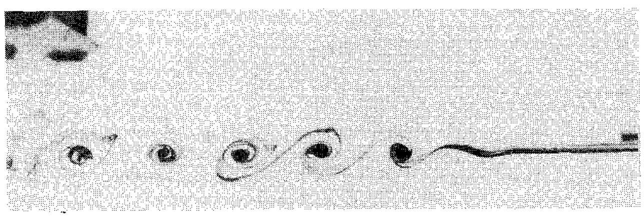
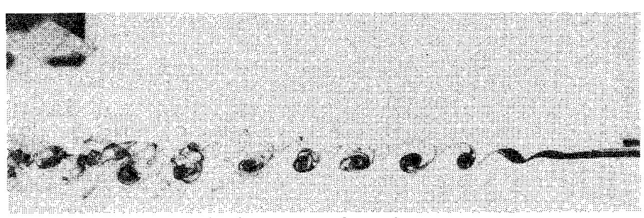


Fig. 10 Flow geometry with the airfoil inside and outside the shear layer.

Airfoil 1/4-chord $X = 27$ cm ↓ Splitter plate tip $X = 0$ ↓



a) $A = 2$ deg, $f = 4.0$ Hz



b) $A = 2$ deg, $f = 6.0$ Hz

Fig. 11 Upstream forcing with the airfoil outside the shear layer.

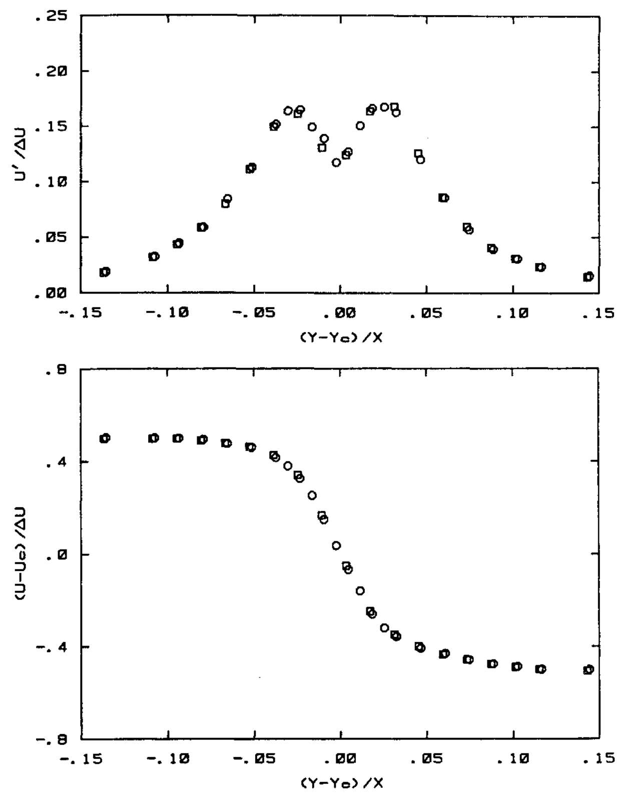
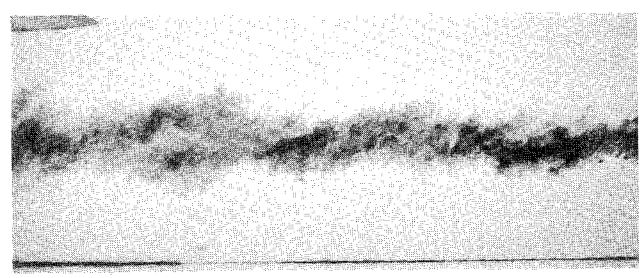
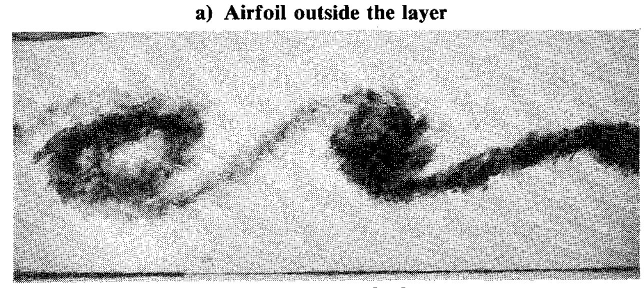


Fig. 12 Mean and rms velocity profiles at $X = 18$ cm, $A = 2$ deg, and $f = 4.0$ Hz (○ airfoil inside the layer, □ airfoil outside the layer).



a) Airfoil outside the layer



b) Airfoil inside the layer

Fig. 13 Effect of the airfoil position on downstream forcing ($A = 2$ deg, $f = 0.347$ Hz).

Coupling Mechanism

The oscillating airfoil can disturb the shear layer by at least two mechanisms. First, there is the "potential" disturbance generated by the motion of the airfoil. This is the disturbance that would be present even in the absence of the shear layer (i.e., an oscillating airfoil in the freestream) and is due to the oscillating bound circulation on the airfoil and the circulation of the resulting free vortices shed into the wake. The potential disturbance is transmitted everywhere in the flow, both upstream and downstream, instantaneously for the (present) case of an incompressible flow. Second is the disturbance caused by the interaction between the vorticity shed by the airfoil and that already present in the shear layer. This disturbance is convected only in the downstream direction. At low airfoil oscillation frequencies, the disturbance could take the form of a transverse oscillation imposed on the shear layer at the airfoil trailing edge. At higher frequencies, the airfoil-shed vorticity that concentrates into vortical structures[12,16] can interact with the shear layer large-scale vortices. Note that this discussion does not presume a linear interaction process. It should be stated that the vortex interaction mentioned above has, in principle, an upstream influence also. The influence is believed to be limited to the near vicinity of the airfoil, since the main contribution comes from high-order moments (poles) of the vorticity distribution whose induced velocity drops sharply with separation distance.

Forcing the upstream region, described earlier, can be explained very simply as being the result of the coupling of the airfoil's "potential" disturbance to the flow in the vicinity of the splitter plate trailing edge. This behavior would then be similar to the case of acoustic excitation in that the effective coupling occurs near the trailing edge of the splitter plate.[17,18] Is the large downstream increase of the layer growth rate under low-frequency excitation the result of coupling of the disturbance to the flow at the splitter plate or the direct interaction at the airfoil location by the second mechanism?

We attempted to answer this question by taking away the second coupling mechanism. This is done by removing the airfoil from the middle of the layer and placing it on the low-speed side outside the shear layer, as indicated in Fig. 10. Except for a minor reduction in the effective amplitude, the first mechanism is believed to be mostly unaffected by the change of position of the airfoil. The effects of forcing on the upstream region, with the new geometry, are shown in Fig. 11. It can be seen that the shear layer can be forced just as easily

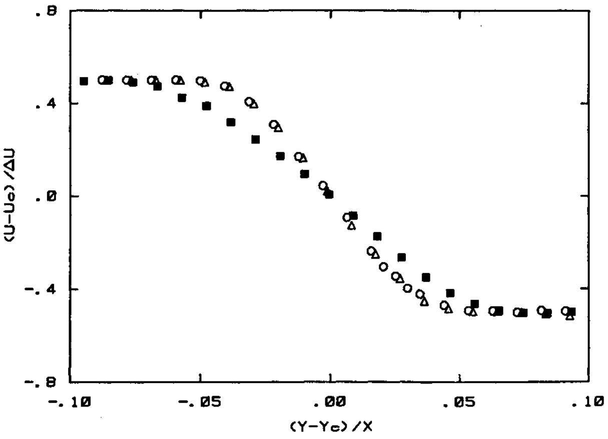


Fig. 14 Effect of the airfoil position on the mean velocity profile in the forced layer when $A = 2$ deg, $f = 0.347$ Hz, and $X = 135$ cm (○ natural, ■ airfoil inside the layer, △ airfoil outside the layer).

as before and the resulting flow, except for a region very near the airfoil, is the same as when the airfoil is in the middle of the layer. Measurements of the velocity at various locations in the upstream region show that the mean and rms profiles are identical, regardless of the airfoil position. One such comparison is shown in Fig. 12. On the other hand, the position of the airfoil is crucial in forcing the downstream region, as illustrated in Figs. 13 and 14. Moving the airfoil outside the shear layer appears to have also removed almost all the disturbances at the forcing frequency. With the airfoil in the new position, the shear layer does not grow into large sizes. The mean velocity profile is as in the natural case and the rms profile (not shown here) shows little change relative to the natural layer.

Based on the results described above, we conclude that forcing the upstream region can be thought of as being the result of the "potential" disturbances introduced by the oscillating airfoil. On the contrary, in the cases of forcing the downstream region, results show that the disturbances are coupled into the layer at the airfoil location and that the effect of the "potential" disturbances amplified throughout the layer is negligible.

Conclusions

The effects of a locally introduced disturbance on a turbulent plane mixing layer were investigated. Disturbances were generated by a two-dimensional pitching airfoil located downstream of the splitter plate trailing edge. Results show that the regions upstream and downstream of the airfoil can be selectively forced by the proper choice of the frequency. At low forcing frequencies, the region upstream is unaffected, while large increases in the shear layer spreading rate downstream of the disturbance source are observed. Forcing at high frequencies leaves the growth rate of the layer in the downstream region relatively unchanged (slight decrease compared to natural), whereas the flow structure in the upstream region is modified. Results suggest that forcing the upstream region is a consequence of the coupling of the airfoil's "potential" disturbance to the flow at the trailing edge of the splitter plate. This type of coupling is very weak in the case of low-frequency forcing of the downstream region. In this case, the direct transverse oscillations imposed on the shear layer locally at the airfoil trailing edge provide the coupling of the disturbance to the flow.

Acknowledgments

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