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A CANCELLATION EXPERIMENT IN A FORCED TURBULENT SHEAR LAYER

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Abstract

Results are presented which demonstrate that it is possible to cancel, using feedback control techniques, the effects of an externally generated disturbance in a fully-developed turbulent two-dimensional shear layer.

Introduction

The evolution of plane mixing layers can be strongly affected by low-amplitude disturbances. The growth rate of a turbulent shear layer, for example, is effectively manipulated using controlled periodic excitation or forcing. These effects and other related phenomena have been recently reviewed by Ho & Huerre [1]. Forcing is usually achieved by introducing disturbances acoustically [2,3], mechanically by an oscillating flap [4-5], or oscillating one or both free-stream velocities [6-7].

Practically all of the turbulent mixing layer forcing studies to date may be classified as open-loop forcing of the turbulent layer. Successful manipulation of fully-developed turbulent flows through active, closed-loop, feedback control techniques has, to our knowledge, not yet been demonstrated. The possibility of active feedback control of turbulent flow would suggest new prospects of potentially significant applications such as turbulent mixing control and throttling combustion processes, drag reduction, pollution control, noise reduction, etc. It is further noted that discovering what is required to actively control a turbulent flow would be expected to reveal a great deal about the underlying dynamical processes at work within the flow. It should be mentioned that recent research in feedback control in fluid mechanics has demonstrated the potential of manipulating turbulence *transition* phenomena [8-12]. We believe that the possibility of feedback control of *fully-developed* turbulent flow has yet to be demonstrated and exploited.

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In the work described in this paper, we present a "proof of concept" experiment. We address the question of whether it is possible to cancel the effects of a controlled external disturbance which has been allowed to develop in a high Reynolds number, fully-developed turbulent shear layer. Exercising control over a turbulent flow that is forced in a known manner is an important first step before the control of a "natural" fully-developed turbulent flow can be attempted.

Experimental Facility & Instrumentation

The experiments were performed in the Low Speed Water Channel of the Graduate Aeronautical Laboratories of California Institute of Technology (GALCIT). The water channel was modified to generate a high aspect ratio 2-D shear layer, as indicated in Figure 1. The special insert used for this purpose followed the design of Dimotakis & Brown [13] and produced a shear layer with a velocity ratio, $r = U_2 / U_1$, of about 0.44 . The high-speed stream was set to a velocity of $U_1 = 20.6$ *cm/sec*, resulting in a Reynolds number, based on $(U_1 - U_2)$, of about 1150 per centimeter.

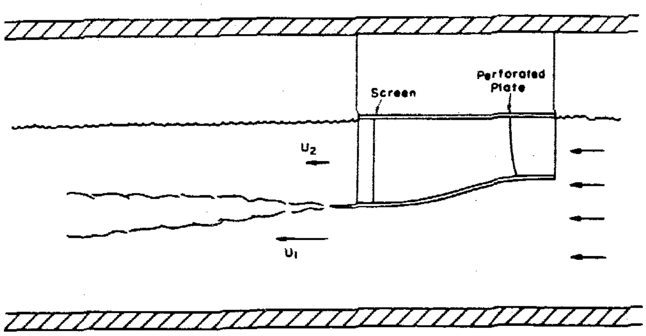


Figure 1. Schematic of the shear layer insert.

Disturbances were generated by two pitching airfoils that extended across the span (45 *cm*) of the water channel test section. The geometry of airfoil placement is shown in Figure 2. The first airfoil, a *NACA*–4415 with a chord of 4 *cm*, oscillated nearly sinusoidally about the 1/4-chord point with a prescribed amplitude and frequency. The drive mechanism was based on a DC motor and a linkage system and the angular position of the airfoil was monitored using a potentiometer. This assembly was used to launch a disturbance into the layer. Effects of this type of forcing on the turbulent shear layer have been described previously [5].

The second airfoil, a *NACA*–0012 with an 8–*cm* chord, was placed some distance downstream of the first airfoil. The driving system was designed such that this airfoil could execute arbitrary pitching motion [14]. A PDP-11/73 based computer monitored the motion of the first airfoil and computed a command signal which, through a D/A channel, drove the second airfoil.

The flow was visualized using food-coloring issuing from an injection port imbedded in the high-speed side of the shear layer insert and was subsequently recorded photographically using 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. We took advantage of frequency shifting for efficient band-limited filtering of the Doppler burst and also for lowering the signal dynamic range so that it could be measured by a Tracking Phase-Locked Loop. The output frequency of the phase-locked loop was measured by a Real Time Clock card interfaced to the same PDP-11/73 computer responsible for controlling the motion of the second airfoil. Other measurements using this LDV setup have been reported previously [5,14].

Results & Discussion

For the results described here, both airfoils extended across the shear layer span and were placed roughly in the middle of the layer, see Figure 2. We refer to the case when both airfoils are off (namely not oscillating) as the reference or unforced state. The flow, in this case, is not exactly the same as the "natural" layer without the two airfoils. Previous results have shown that the presence of such blades in the flow reduces the shear layer growth rate somewhat [5]. A photograph of the flow in the unforced case is illustrated in Figure 3a. The right and left edges of the photograph correspond to a range of downstream stations of $80\ cm < X < 210\ cm$ 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 the photograph in the cross-stream direction corresponds to the height of the water in the channel, roughly 42 *cm* in this case. All of the photographs shown in this paper have the same geometric arrangement as described above.

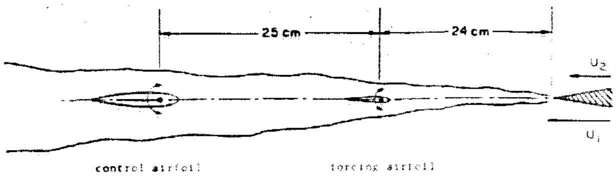
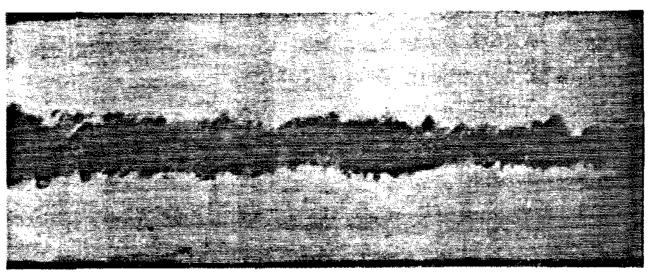


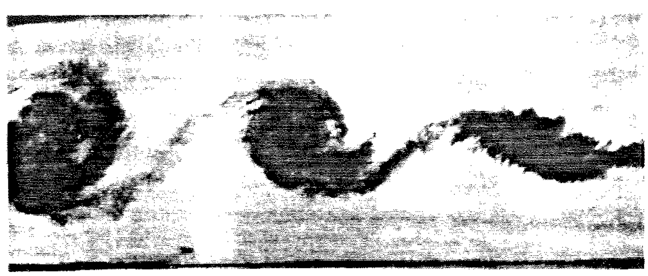
Figure 2. Flow geometry in the cancellation experiment.

The first airfoil, termed the forcing airfoil, was activated to pitch at a frequency of $f = 0.346\ Hz$ with an amplitude of about 3.6 degrees (i.e. peak-to-peak amplitude of 7.2 deg.). A photograph of the resulting forced turbulent shear layer is shown in Figure 3b. The selection of the frequency and amplitude values were based on previous work describing the response of a turbulent mixing layer forced by the technique used here [5]. Results are similar to those observed using other forcing techniques [2,4,6,7] and are briefly described below.

Earlier results [5] suggest that the airfoil oscillation frequency for which the largest effects are observed, at a given downstream station, appears to roughly correspond to the predominant local vortex passage frequency of the natural layer at that station. Forcing results in an increase of the shear layer spreading rate culminating in the formation of large vortices (e.g. see Figure 3b). As the frequency decreases/increases, the region of flow showing increased growth moves downstream/upstream. The passage frequency of the vortices that are finally formed is



(a) Unforced



(b) Forced

Figure 3. Turbulent shear layer in the reference (unforced) state and its response to forcing.

the same as the forcing frequency. In other words, if L is the vortex spacing, $U_c \approx (U_1 + U_2) / 2$ the convection speed and f the forcing frequency, then $f L / U_c = 1$.

The value of forcing frequency was selected such that the region of the layer that was most affected occured downstream of the forcing airfoil. For the operating conditions in this experiment, that would correspond to frequencies below approximately 2 Hz. Furthermore, the final vortex spacing L was chosen to be comparable or greater than the spacing between the two airfoils (25 cm). This reduced the forcing frequency to values below 0.6 Hz. The actual frequency of 0.346 Hz was finally selected to allow comparison with previous velocity measurements of the shear layer forced at this frequency (see Ref. 5). For comparison, we mention that the natural vortex shedding (instability) frequency at the splitter plate tip was about 6 Hz [5]. It should also be mentioned that the chord of the second airfoil becomes small relative to the forced vortex spacing, L, for the frequency selected here. This is believed to be a necessary requirement for effective cancellation.

The actual amplitude of the forcing airfoil does not affect the outcome of the cancellation experiment. It is only required that the amplitude be sufficient in order to force the layer. We point out, for completeness however, that according to previous work [5] the overall qualitative features of the forced layer, Figure 3b, are not expected to change if a different airfoil amplitude is used.

In an attempt to cancel the effects produced by the forcing airfoil a simple feedback scheme was tried. The motion of the second airfoil, or the control airfoil, was phase locked, under program control, to the motion of the first. A sinusoidal shape for the oscillation was selected and the amplitude and the phase difference between the two airfoils could be independently adjusted. Motion of the control airfoil was selected to be 180 degrees out of phase with the motion of the forcing airfoil, taking account also of the time delay required for the flow to convect the separation distance between the airfoils at a convection speed of $U_c \approx (U_1 + U_2) / 2$. The sequence of photographs in Figure 4a-c shows the results as the control airfoil is activated. Note that the layer immediately responds to the action of the control airfoil and resumes a growth rate comparable to the unforced case (compare Figures 3a and 4c).

These qualitative results are corroborated and quantified by LDV measurements of the streamwise component of velocity, see Figure 5. The measurements were carried out at a downstream station of X = 135 cm which corresponds to a location roughly half-way between the right and left edges of the photographs shown earlier.

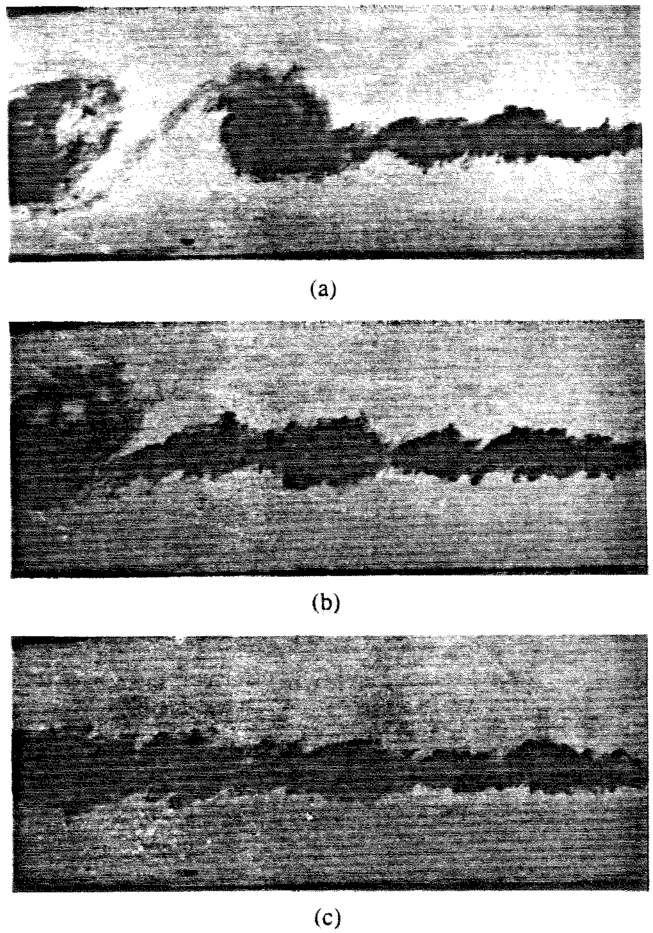


Figure 4. Response of the shear layer as the control airfoil is activated.

Note, in Figure 5, that both the mean velocity profile and the mean rms velocity fluctuation profile approach the "unforced" profiles upon activating the control airfoil.

It should be mentioned that success of the cancellation depends strongly on the proper choice of the amplitude and phase of the control airfoil. For example, insufficient amplitude results in partial cancellation. On the other hand, too large an amplitude turns the "control" airfoil into a new "forcing" airfoil. While one could employ automated parameter search and performance optimization algorithms, the optimum amplitude of the control airfoil, which was approximately 3.4 degrees for the results presented, was determined here by trial and error. Once the proper amplitude and phase were determined, the cancellation could be maintained for long periods of time. Data of Figure 5, as an example, were acquired over a period of about one hour.

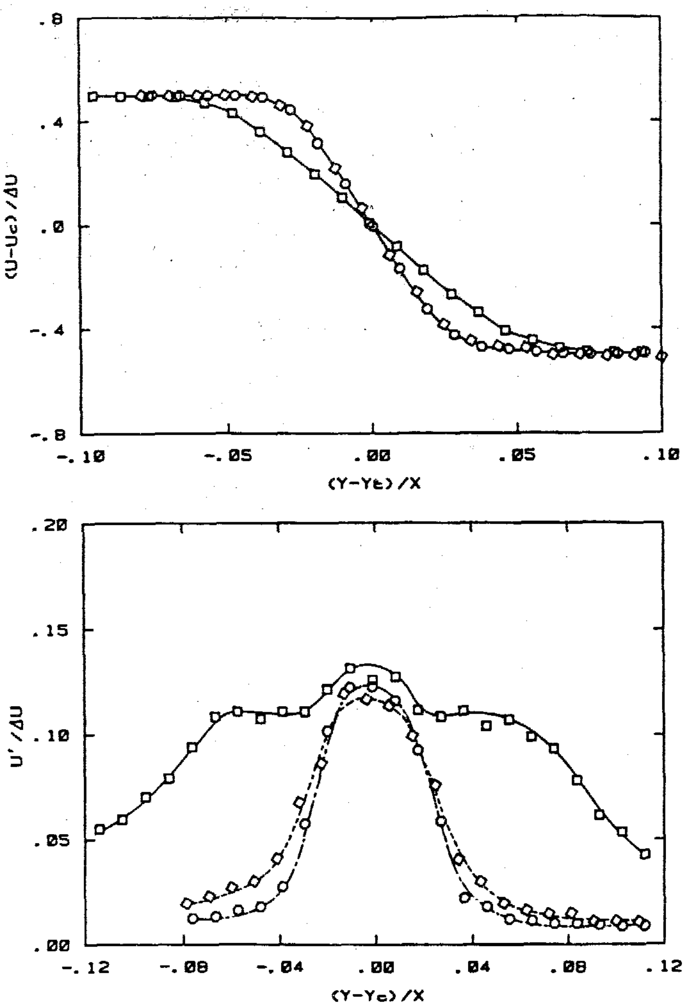


Figure 5. Mean and rms velocity profiles in the cancellation experiment; X = 135 *cm*.

○ both airfoils off,

□ forcing airfoil on, control airfoil off,

◇ control airfoil activated.

Moving the control airfoil in phase with the forcing airfoil was observed to result in an increase of the layer growth rate. The increase was, however, modest. This, we believe, is due to the finite height of the channel which may be restricting the growth of the layer. In Figure 3b, the size of the structure has become comparable to the channel height (visible at the left edge of the picture).

It seems tempting to argue for the success of the cancellation exepriment in terms of linear wave-cancellation ideas. It has been suggested [2,4,15] that the large-scale structure behavior in the forced turbulent mixing layer may be described in part by the linear inviscid stability theory. We emphasize, however, that the linear wave analysis, though *sufficient* to explain the present results, at least qualitatively, is probably not *necessary*. A numerical simulation of the cancellation experiment would help clarify the nonlinear vortex interaction between the vorticity shed by the oscillating control airfoil and that already present in the forced shear layer. The numerical simulation can take advantage of vortex tracing methods such as that used by Spalart & Leonard [16] in the case of oscillating airfoils in uniform free-stream. It should be noted that, for the present experiment, the non-uniform free-stream imposed by the forced turbulent free shear layer would have to be taken into account in the calculations of the vorticity shed from the trailing adge of the oscillating control airfoil.

These results, we believe, represent the first cancellation experiment in the spirit of previous experiments in the transition region of flat plate boudary layers [8-11], performed here, however, on a fully-developed turbulent shear flow. A major difference is that in the boundary layer experiments the flow is transitional and one could argue for the justifiability of a linear wave analysis (and linear wave superposition) in rather more rigorous terms. In the present case, we have demonstrated the cancellation of a disturbance which was allowed to grow amidth other nonlinear processes in a fully-developed, turbulent shear layer.

Conclusions

It was shown that it is possible to cancel the effects of an artificially generated disturbance in a fully-developed turbulent shear layer. In the experiment, a pitching airfoil launched a disturbance into the layer which resulted in a large increase of the layer growth rate. In the cancellation experiment, a second airfoil was placed downstream of the first. Pitching the second airfoil at the proper phase relative to the first and also at the right amplitude effectively cancelled the disturbances introduced by the first airfoil.

This, we believe, is the first cancellation experiment in the spirit of previous experiments in the transition region of flat plate boundary layers, performed here, however, on a fully-developed turbulent shear flow.

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