Control of Coherent Structures in Reattaching Laminar and Turbulent Shear Layers

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The development of large-scale vortical structures in reattaching shear layers has been studied experimentally with the flow over a two-dimensional, backward-facing step. Flow visualization has shown the formation and merging of vortical structures, the increasing irregularity of these structures with increasing shear-layer turbulence, and the persistence of the structures far downstream of reattachment. Gentle excitation of the shear layer by an oscillating flap enhances the formation of vortical structures, especially for turbulent separation. Laser Doppler velocimeter measurements show that the excitation significantly intensifies the turbulence activity in the shear layer, but only moderately affects mean velocity profiles; excitation substantially reduces reattachment length, particularly when separation is turbulent.

Nomenclature

C_p' = fluctuating pressure coefficient, $C_p' = p'/q_0$
f = frequency
h = step height
p' = root mean square fluctuating pressure
q_0 = freestream dynamic pressure at separation, $q_0 = 1/2\rho U_0^2$
Re_h = Reynolds number based on step height, $Re_h = (\rho U_0 h)/(\mu)$
St = Strouhal number based on step height, $St = fh/U_0$
u = fluctuating velocity component in x direction
u' = root mean square value of u
U = mean velocity component in x direction
U_0 = freestream value of U at separation
v = fluctuating velocity component in y direction
x = streamwise coordinate, downstream from step face
x_r = reattachment length
y = cross-stream coordinate, upward from reattachment wall
δ_0 = boundary-layer thickness at separation
μ = viscosity
ρ = density

Introduction

THE process of shear-layer separation and reattachment is a key feature of many aerodynamic flow problems. In general, these flows involve free separation and reattachment, but there exist a number of significant flows in which the separation point is effectively fixed, such as leading-edge flow separation on a thin airfoil or flow entering a ramjet dump combustor. Despite the simplification associated with the immobility of the point or line of separation, such flows retain a number of fluid-dynamic complexities that must be properly considered if computational techniques are to be developed to correctly and completely predict these flows. These complexities are the following: 1) development of large-scale vortical structures in the free shear layer; 2) substantial unsteadiness of the entire separated flow, especially near reattachment and particularly at low frequencies; 3) slow relaxation to equilibrium of the reattached shear layer. Because 2 and 3 are related to 1, it is evident that the large-scale vortical structures are of essential importance in reattaching shear flows.

Since their discovery in the two-dimensional turbulent mixing layer about a decade ago,[1,2] the existence of large-scale vortical structures in such layers has become well recognized; Roshko[3] has provided a lucid introduction to the subject. Because the scale of fluid motions within large-scale vortices is comparable to the overall shear-layer thickness, the vortices dominate the transverse momentum transfer process when they are present in a shear layer. Although the process of large-scale vortex development has been investigated extensively through experimental, theoretical, and computational research in unbounded flows, such as mixing layers, jets, and wakes, little information is available for bounded flows, such as reattaching shear layers. Bounded flows, which arise in many situations of practical interest, differ from unbounded flows in several respects: 1) because of reattachment, the free shear layer has a finite length, which limits large-scale vortex development; 2) the shear layer supports a pressure gradient and is curved; 3) the strong interaction between the unsteady shear layer and the reattachment wall generates substantial acoustic and convective disturbances that feed back through the separation bubble to influence the shear layer at separation.

Among reattaching, separated flows, the two-dimensional, backward-facing step flow is the simplest configuration; nevertheless, it includes all the significant features. As a consequence, numerous studies of this basic flow have been conducted[4-11]; Eaton and Johnston recently provided a good review.[6] However, only recently have any of these studies begun to concentrate on the dynamics of the coherent vortical structures that develop and evolve in the reattaching shear layer.[8,9] The role of these structures needs to be defined because large-scale vortical structures affect flow features such as reattachment length, wall pressure distribution, and wall pressure fluctuation intensity and periodicity. The questions of vortical structure dynamics and their appropriate modeling are of prime importance in developing satisfactory computational tools for predicting reattaching flows.

A further rationale for studying the flow over a backward-facing step involves the possibility of altering the major flow features by modifying and controlling the dynamics of vortical structures in the reattaching flow. The ability to affect the large-scale vortical structure of a plane turbulent mixing layer through excitation of the free shear layer has already

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been demonstrated.[12] One of the objectives defined for the present set of experiments was to investigate the influence of shear-layer excitation on the structure and characteristics of reattaching shear layers.

Experimental Equipment and Procedures

An experimental investigation of large-scale vortical structure development in reattaching two-dimensional shear layers is being conducted in the McDonnell Douglas Research Laboratories (MDRL) Shear Flow Facility. This facility (Fig. 1) is a low-speed (0–78 m/s), closed-circuit wind tunnel developed especially for studies of two-dimensional bounded and free shear layers. The Shear Flow Facility test channel (Fig. 2) has glass windows along its full 5.5-m length for complete optical access to the flow; it also has a continuous, flexible, transparent top wall that can be adjusted through its screw-jack supports to provide streamwise pressure gradient control. For these experiments, the test channel roof was adjusted to eliminate pressure gradients up- and downstream of the reattaching flow. A large contraction ratio, smooth contraction fairing, and flow conditioning elements (honeycomb and four screens) in the settling chamber ensure high-quality flow in the test channel: mean flow velocity is uniform to within ± 0.5% in magnitude and 0.25 deg in direction over any cross section; the free-stream turbulence intensity is <0.05% for the flow speed range of these experiments (0–10 m/s).

For the flow reattachment studies, a backward-facing step insert was installed in the test channel (Fig. 3). The step height (h) is 8.9 cm; the aspect ratio is slightly greater than 10, satisfying the criterion established by de Brederode and Bradshaw[13] for two-dimensionality of the reattaching flow (i.e., independence of the mid-channel flow from sidewall interaction effects). The step assembly is equipped with extensive instrumentation, as detailed in Fig. 3. Static pressure orifices are distributed along the centerline of both the step wall and the top wall; pressures are measured by a high-precision transducer through a Scanivalve system. High-sensitivity semiconductor strain-gauge pressure transducers embedded in the reattachment wall downstream of the step are used to monitor wall pressure fluctuations beneath the reattaching shear layer. A computer-controlled, two-axis traversing unit positions hot-wire or pressure probes for surveys of the reattaching flows. The probe-traverse envelope, indicated in Fig. 3, includes the full height of the viscous flow and covers a streamwise range of $-2 \leq x/h \leq 12$.

Additional instrumentation includes a two-channel laser Doppler velocimeter (LDV) system to measure velocity components throughout the flow, particularly in regions of flow reversal. The LDV system is mounted on a computer-controlled, three-axis traversing unit that allows semi-automated, high-resolution measurement of velocity profiles.

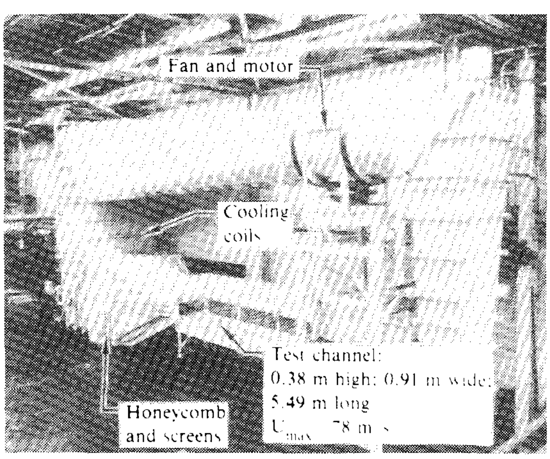

Fig. 1 The MDRL Shear Flow Facility.

Provisions for flow visualization include a porous panel upstream of the step (shown in Fig. 3) through which "smoke" (actually an aerosol of oil droplets) can be introduced into the separating boundary layer. Two different light sources are available to illuminate the smoke-filled shear layer. The first, a bank of incandescent lamps above the test-channel roof, is used for overall illumination of the top surface of the smoke layer; it is particularly useful for evaluating the spanwise regularity of large-scale vortical structure development.

The second smoke illumination system consists of a laser and several mirrors outside the test channel, plus another mirror within the channel at the downstream end. One of the mirrors is cylindrical, to spread the laser beam into a sheet that is directed upstream (as an x-y plane) through the reattaching shear flow. Both continuous and pulsed lasers are

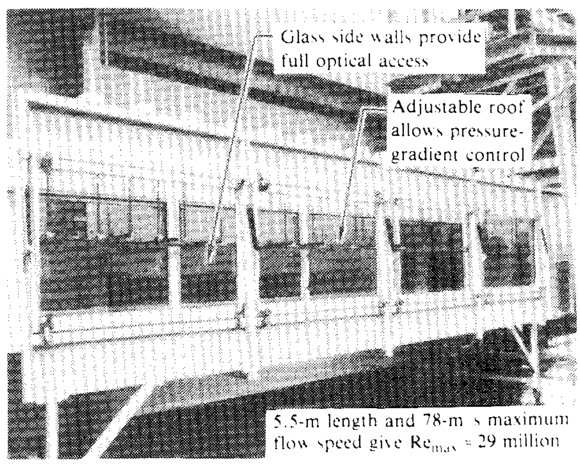

Fig. 2 Shear Flow Facility test channel.

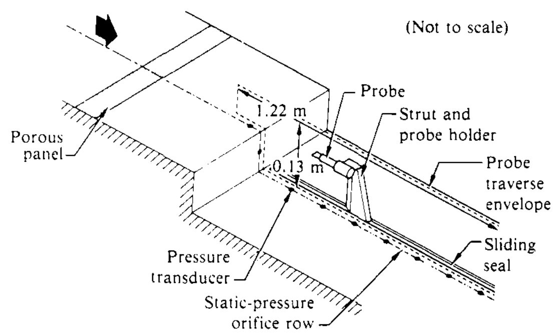

Fig. 3 Backward-facing step and instrumentation.

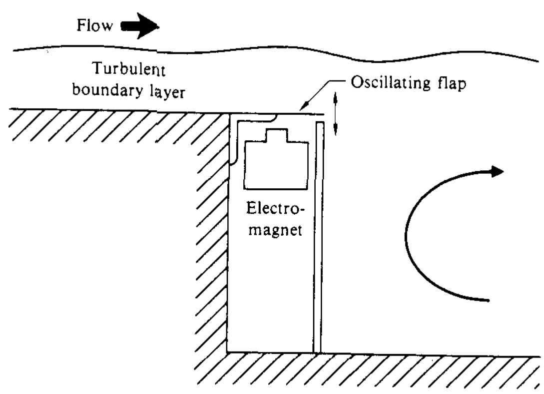

Fig. 4 Shear-layer excitation mechanism.

available; thus this light-sheet illumination can be used either for continuous observation or for sub-microsecond exposures that "freeze" the flow.

Excitation of the reattaching shear layer is accomplished at the point of shear-layer separation by an oscillating flap. The excitation mechanism, shown in Fig. 4, is a simple, electromagnetically driven, trailing-edge flap at the corner of the backward-facing step. The thin steel flap, which has a chord of 1.3 cm (the ratio of flap chord to step height = 0.14), is hinged to the step surface by a strip of thin plastic tape. Flap displacement is monitored by reflecting a laser beam off the flap surface onto a calibrated photodetector.

Two-dimensionality of the reattaching flow was checked by evaluating spanwise agreement of velocity profiles measured at several streamwise stations. Tuft and oil flow visualization techniques also were employed in the reattachment region; an example of the latter is shown in Fig. 5. Drops of oil mixed with lampblack were placed at 1/4-step-height intervals in the vicinity of reattachment. The droplets moved immediately upon flow start-up, responding to starting transients and leaving a somewhat erratic track in the vicinity of reattachment. Nevertheless, it is evident that the mean reattachment line is essentially two-dimensional, except near the sidewall interactions. Based on these flow qualification studies, it was concluded that the time-averaged properties of the flowfield are satisfactorily two-dimensional between the regions affected by the sidewall boundary layers.

One of the primary parameters influencing development of reattaching shear-layer structure is the ratio of boundary-layer thickness at separation, δ_0, to the step height h. The significance of the δ_0/h ratio was addressed briefly by Eaton and Johnston[6] and has been further explored by Adams and Johnston.[14] On the basis of preliminary measurements with both hot-wire anemometers and the LDV system, δ_0/h was found to range from 0.21 (laminar separation) to 0.38 (turbulent separation) for the experiments described herein.

Results

Existence and Development of Coherent Structures

Flow visualization studies were conducted to characterize the developing large-scale vortical structures in the reattaching shear layer for laminar, transitional, and fully turbulent separation (as used here, these three terms refer to the state of the separating boundary layer). A sequence of smoke flow visualization photographs of an initially laminar shear layer appears in Fig. 6. Visualization was accomplished by overall illumination of the smoke sheet, produced by forced convection of vaporized oil from the surface of a heated wire ("smoke wire") placed parallel to the step edge; it is important to realize that the entire smoke layer, not just a thin sheet perpendicular to the wall, is visible. The mean reattachment line for this case is indicated by the dashed line at $x/h \approx 5.5$.

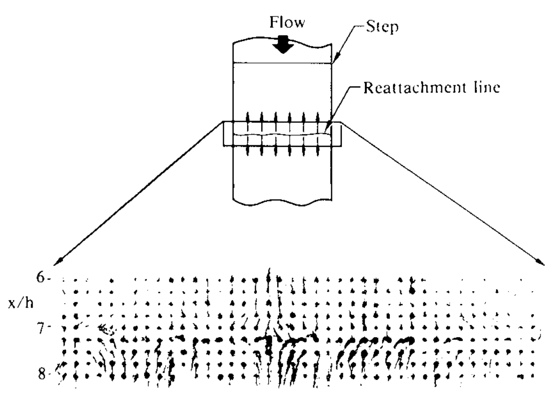

Fig. 5 Surface flow visualization in the vicinity of reattachment.

The time delay between successive photographs in Fig. 6 is essentially equal to one period of shear-layer oscillation, so that the sequence effectively represents five cycles of shear-layer vortex formation. In particular, the first two vortices that appear in the shear layer merge in the third photograph; similarly, the third and fourth vortices are merging in the fourth photograph, at a location somewhat upstream of the earlier merging (an indication of the variability of this nearly periodic process). In the fifth photograph, the merging of the third and fourth vortices is complete, while the fifth and sixth vortices show no signs of approaching a merger. The developing vortices clearly remain highly two-dimensional, at least up to the reattachment zone, where they interact violently with the wall.

The simple flow visualization sequence in Fig. 6 shows the irregular nature of shear-layer vortical structure development and merging, even in this laminar separation case. A more quantitative demonstration of vortex merging for a case of laminar separation is provided by the evolving frequency content of velocity fluctuations in the reattaching shear layer. Several velocity fluctuation power spectra, measured with a hot-wire probe at a constant height above the step ($y/h = 1.02$; $y/h = 1.0$ on the step), at several streamwise stations throughout the reattaching flow zone, are shown in Fig. 7. A prominent peak at $St \approx 0.40$ in the spectrum for $x/h = 2.0$ identifies the primary frequency of vortex formation. (The spectral bump at $St \approx 0.80$ may indicate an initial shear-layer instability at that frequency, although spectra taken closer to the step did not clearly show this.) With increasing streamwise distance, the $St \approx 0.40$ peak is replaced by smaller peaks at lower frequencies (initially the subharmonic, i.e., $St \approx 0.20$), suggesting one or even two stages of vortex merging; the broadening of the peak farther downstream indicates the increasing irregularity of vortical structure passage. Outer flow hot-wire spectra presented by Eaton and Johnston[10] for a case of laminar separation similarly show a large peak for $1 \leq x/h \leq 2$ that becomes smaller and shifts to lower frequencies with increasing x/h.

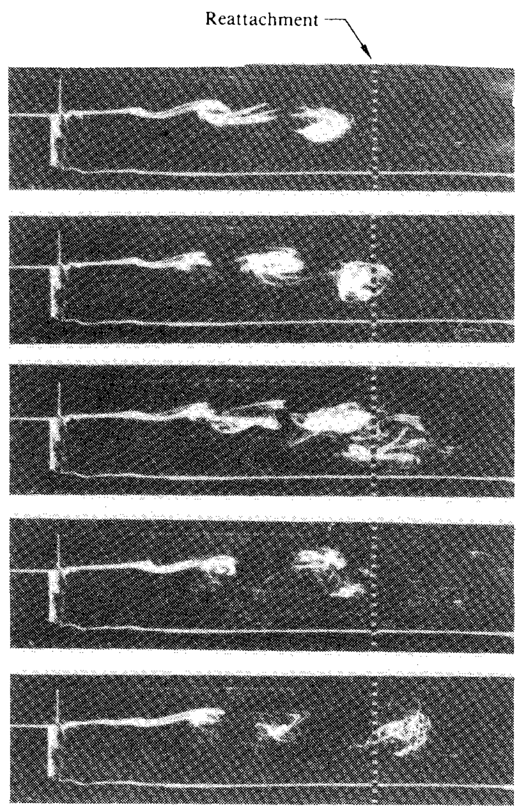

Fig. 6 Vortex rollup and merging in a reattaching laminar shear layer.

Temporal and spatial irregularity of vortical structure formation and merging, apparent even with laminar separation (Fig. 6), become increasingly pronounced as the flow within the shear layer becomes more and more turbulent (e.g., with increasing Reynolds number). Visually, the large-scale regularity of structure within the reattaching shear layer is no longer evident when transition to turbulence occurs upstream of separation.

Gentle excitation of the free shear layer at the point of separation provides a strong regularizing influence on the process of vortical structure development. This extremely useful effect not only facilitates the study of shear-layer vortical structure development, per se (by sharply reducing the cycle-to-cycle "jitter" in vortex evolution), but also provides a potential mechanism for altering major characteristics of reattaching shear flows.

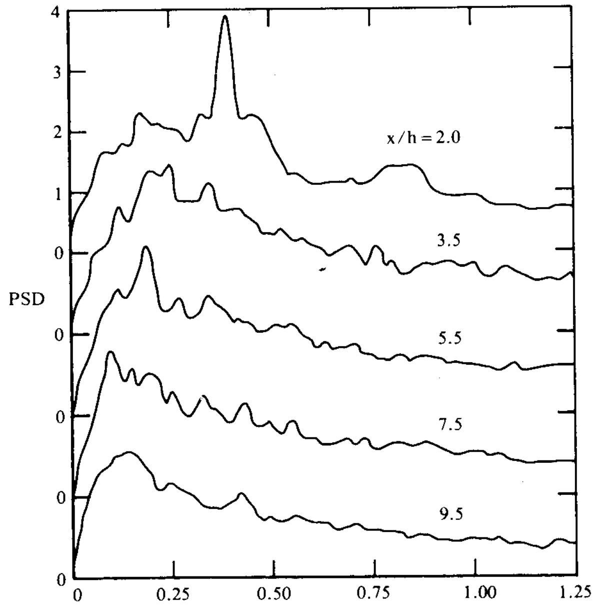

Fig. 7 Power spectra of streamwise velocity fluctuations measured at $y/h = 1.02$ for a laminar separation ($Re_h = 7500$).

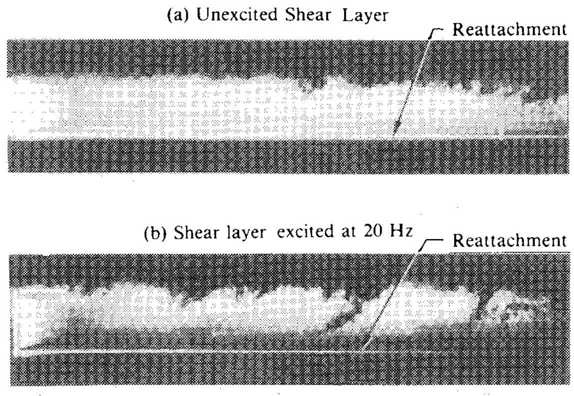

Fig. 8 Laser sheet illumination of entrained smoke in reattaching flow following turbulent separation ($Re_h = 39{,}000$).

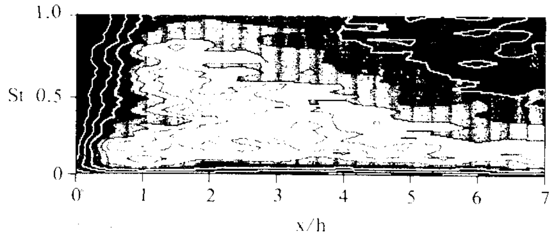

Fig. 9 Shear-layer velocity fluctuation spectral map for unexcited laminar separation ($Re_h = 9500$).

The influence of very slight excitation is particularly strong when the separating boundary layer is turbulent, as the flow visualization photographs in Fig. 8 show. These photographs were made using pulsed-laser light-sheet illumination of oil-vapor "smoke" bled into the boundary layer upstream of separation. Figure 8a shows the reattaching turbulent shear layer in its natural state; Fig. 8b shows the same flow being excited at 20 Hz ($St = 0.22$) by the oscillating flap shown in Fig. 4. The excitation is slight: amplitude of the flap trailing-edge displacement is less than 1% of δ_0, the thickness of the separating boundary layer. This slight excitation considerably alters the visible large-scale structure of the reattaching turbulent shear layer; structures with a wavelength of roughly two step heights are clearly evident in the excited flow. The reattachment length is also appreciably affected by the excitation; this will be discussed in the next section.

Figures 9–13 dramatically show the regularizing influence of shear-layer excitation. These figures present the power spectral densities of extensive hot-wire anemometer surveys of reattaching shear-layer velocity fluctuations for various flow conditions. To emphasize the changing frequency content with streamwise development of the shear layer, the spectral data are presented in the form of spectral maps of the reattaching flows. For each flow condition, spectra were evaluated at intervals of 0.5 over $0.5 \leq x/h \leq 10.0$, with the hot-wire probe positioned at a constant height ($y/h = 1.02$) above the reattachment wall. In each figure, the abscissa represents streamwise position downstream of separation; Strouhal number ($St = fh/U_0$) is plotted along the ordinate. The spectral density of the hot-wire signal is represented by the gray level, with lighter shading indicating more intense fluctuations. Spectral densities are not plotted to a common scale for all maps; each map was normalized in the sense that the lightest shading represents the highest spectral density for that map. The emphasis here is on frequency content and not absolute energy levels.

The spectral map in Fig. 9 represents the unexcited shear layer following laminar separation, showing features similar to those seen in Fig. 7. A spectral peak appears at approximately $St = 0.41$ in the neighborhood of $x/h = 1.5$–2.5, suggesting that this is the natural instability frequency of the layer (although the spectral map appears somewhat spotty); a peak in the vicinity of $St = 0.20$–0.23, stretching from $x/h = 1.5$–4, indicates a transfer of fluctuation energy to a lower frequency (i.e., greater wavelength) through the vortex coalescence mechanism. The same flow excited by the oscillating flap at the apparent shear-layer natural frequency ($St = 0.41$) produced the spectral map of Fig. 10. The low amplitude excitation has concentrated the shear-layer velocity fluctuation energy into a strong spectral peak at the fundamental frequency; a moderate-intensity peak at the first subharmonic in the reattachment region ($x/h \approx 5$) results from vortex coalescence. (The minor peak at $St = 0.83$ probably arises from harmonic content in the flap oscillation.)

An even more impressive example of the influence of excitation concerns the case of a turbulent separating layer, represented by Figs. 11–13. Figure 11 shows the spectral map of the unexcited layer, indicating a spread of fluctuation energy over a rather broad range of frequencies and roughly suggesting a gradual flow of energy from Strouhal numbers in the 0.15–0.30 range at $x/h = 2$ down to about $St = 0.07$ at and beyond reattachment ($x/h \geq 7$). The clear spectral peak following laminar separation (Figs. 7 and 9) is not evident here. Eaton and Johnston[10] attributed this absence of a definite spectral peak to irregularity in the temporal and spatial scales of the large-scale vortical structures that form in a turbulent shear layer. Eaton and Johnston's[10] hot-wire spectra for the turbulent separation case showed the bulk of the turbulence energy gradually shifting to lower frequencies with increasing downstream distance; this behavior was also noted by Bhattacharjee, Scheelke, and Troutt.[15]

Excitation of the separating turbulent layer by the oscillating flap at $St = 0.29$ produced the spectral map in Fig. 12, where a strong concentration of energy at the excitation frequency evolves into a peak at half that frequency (i.e., twice the wavelength) farther downstream. (Note that the wavelength corresponding to $St = 0.29$ is roughly $2h$, which is approximately the scale of the large structures visible in Fig. 8b.) Comparison of Fig. 12 with the corresponding unexcited case in Fig. 11 reveals the remarkable organizing influence of the low amplitude flap oscillations.

Bhattacharjee, Scheelke, and Trout also excited the turbulent shear layer separating from a backward-facing step, similarly observing a strong peak at the excitation frequency in their hot-wire spectra.[15] However, because their acoustic excitation technique had a global influence (in contrast to the highly localized effect of the oscillating flap), they did not observe the frequency halving (Fig. 12).

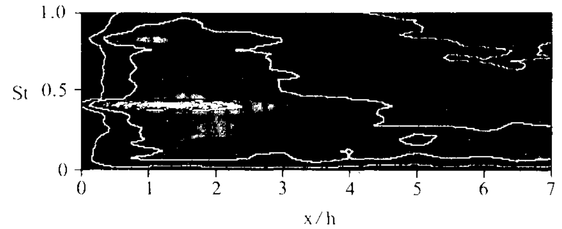

Fig. 10 Shear-layer velocity fluctuation spectral map for laminar separation, excited at $St = 0.41$ ($Re_h = 9500$).

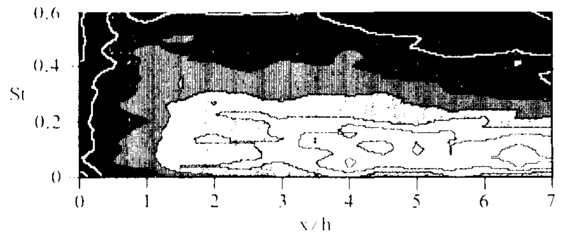

Fig. 11 Shear-layer velocity fluctuation spectral map for unexcited turbulent separation ($Re_h = 39{,}000$).

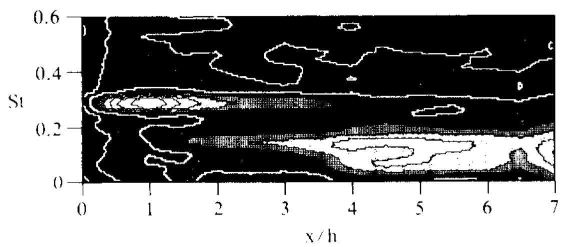

Fig. 12 Shear-layer velocity fluctuation spectral map for turbulent separation, excited at $St = 0.29$ ($Re_h = 39{,}000$).

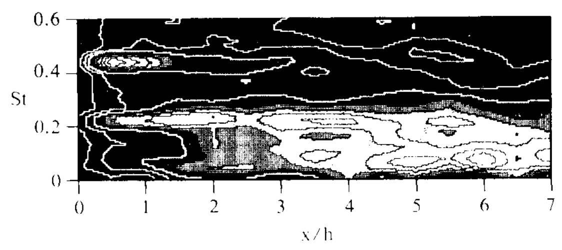

Fig. 13 Shear-layer velocity fluctuation spectral map for turbulent separation, excited at $St = 0.22$ ($Re_h = 39{,}000$).

A strikingly different response was obtained when the turbulent shear layer was excited at $St = 0.22$, resulting in the spectral map of Fig. 13. In this case, the initial energy concentration in the shear layer does not occur at the excitation frequency, but at the first harmonic ($St = 0.44$), transferring to the $St = 0.22$ mode somewhat downstream, and dropping again at, and beyond, reattachment. The harmonic content of the oscillating flap displacement is less than 2% of the fundamental; while this does not eliminate the possibility that the shear layer was responding to the small harmonic component of the excitation rather than the fundamental, it does indicate the complexity and frequency sensitivity of the turbulent shear-layer response to excitation. Further work is needed to establish the variation of shear-layer receptivity with frequency and amplitude of the excitation for the reattaching turbulent shear layer.

Although the unexcited reattaching turbulent shear layer does not show visible evidence of large, well organized vortical structures (recall Fig. 8a), such structures are, in fact, developed within the turbulent layer. This development is revealed through flow visualization of the region at, and downstream of, reattachment where an irregular pattern of large structures appears and is convected downstream in the redeveloping turbulent boundary layer. This phenomenon of persistent large-scale structures in the reattached shear layer seems to be qualitatively similar for laminar and turbulent separating boundary layers, as shown in Fig. 14, which represents oblique views of streamwise "slices" of the reattaching shear layer illuminated by the pulsed-laser light sheet. The sketch (Fig. 14a) indicates the angle of view in the flow visualization photographs below, which cover the flowfield at least 25 step heights downstream of the step. The structures in the flow with turbulent separation (Fig. 14c) are remarkably similar to the structures in the laminar separation case (Fig. 14b), a result that is understandable when one considers that it is the basic inviscid instability of the free shear layer that leads to the large structure development. The final flow visualization photograph (Fig. 14d) shows a case of turbulent separation with the shear layer excited at 13.8 Hz ($St = 0.20$) by the oscillating flap. Once again, the organizing influence of the gentle excitation is markedly evident in the regular pattern of large-scale structures in the turbulent shear layer both up- and downstream of reattachment. In all cases, these large-scale structures persist for an appreciable distance downstream and hence are likely to be associated with the redeveloping boundary layer's slow approach to equilibrium as documented by Bradshaw and Wong.[4]

Mean Flow and Turbulence Measurements

The most important, as well as the most obvious, single characteristic of reattaching shear flows is the length to reattachment. Figure 15 shows some results of the influence of shear-layer excitation on reattachment length (x_r) for a range of Reynolds numbers covering laminar and turbulent separations. Reattachment length was identified as the point where $U = 0$ in a streamwise LDV scan of the reattachment zone made at a distance $y = 0.015h$ above the reattachment wall. The bars on the data symbols represent uncertainty in interpreting the data used to determine x_r. The preliminary results in Fig. 15 were obtained with constant oscillating flap amplitude (approximately 1% of δ_0 at the flap trailing edge) and a constant Strouhal number of 0.29, with no attempt to tune the excitation for best response; nevertheless, these results show that gentle excitation of the separating shear layer was effective in reducing the reattachment length, typically by at least one step height. For fully turbulent separation ($Re_h \approx 56{,}000$), the reduction was fully two step heights.

Note that when excitation is effective in organizing and regularizing development of the large-scale vortical structure in the reattaching shear layer, x_r/h is almost the same for fully laminar and fully turbulent separations. This observation leads to the hypothesis that when well organized vortical structures exist in the layer, they provide the dominant momentum transfer mechanism, over-riding the natural (i.e., unexcited) differences in laminar and turbulent shear-layer development. Hence, in such cases, the overall characteristics of the excited reattaching flow do not depend on the state of the separating boundary layer (at least for $\delta_0/h<1$). Unfortunately, the experimental apparatus was incapable of measurements at $Re_h>56{,}000$ during the experiments discussed here. A simple modification to the experimental facility will permit substantially higher values of Re_h to be reached in future tests so that the hypothesis presented here may be tested.

One other significant feature of the reattachment length data in Fig. 15 is the reduced effectiveness of shear-layer excitation in the transition range. The flow in this Re_h range actually consists of alternating periods of laminar and turbulent separation. Since the laminar and turbulent shear layers have different instability frequencies at a given flow speed (i.e., Re_h), the single frequency excitation does not couple equally well with both the laminar and turbulent layers. The result is that the excitation is less effective in regularizing the development of large-scale vortical structures during transition than it is when the separation is fully laminar or fully turbulent.

The mean flow in the reattachment region was documented by measuring a series of velocity profiles with the LDV system. Pitot and hot-wire anemometer probes also were used to measure mean velocity in the outer (i.e., nonreversing) flow, where excellent agreement existed among the three measuring systems. A comparison of LDV measured profiles of U/U_0 for unexcited and excited laminar separation is shown in Fig. 16, while Fig. 17 presents a similar comparison of profiles for turbulent separation. Each profile represents at least 30 data points, which were omitted in favor of curves for clarity in these comparisons. These profiles are in good qualitative agreement with other recent results for backward-facing step flows,[7-10] although differences in δ_0/h and channel expansion ratio preclude direct comparison. For both the laminar and turbulent cases, the excitation frequency used was the apparent natural instability frequency determined from hot-wire measurements of the unexcited flows (recall Figs. 9 and 11).

The principal differences between the unexcited and excited mean velocity profiles are associated with the reduction in reattachment length that results from shear-layer excitation. When the profile comparison is made in terms of x/x_r to compensate for the reattachment length variation produced by excitation, as has been done here, in each case the unexcited and excited profiles are nearly identical. The only significant difference is that the excited turbulent layer is somewhat thicker than the unexcited turbulent layer at reattachment (Fig. 17), a result also indicated by the data of Bhattacharjee et al.[15] The point to be emphasized is that, despite the profound effects of shear-layer excitation on the several qualitative and quantitative aspects of the flow that have already been described, the enhanced, regularized large-scale vortical structures resulting from excitation produce lit-

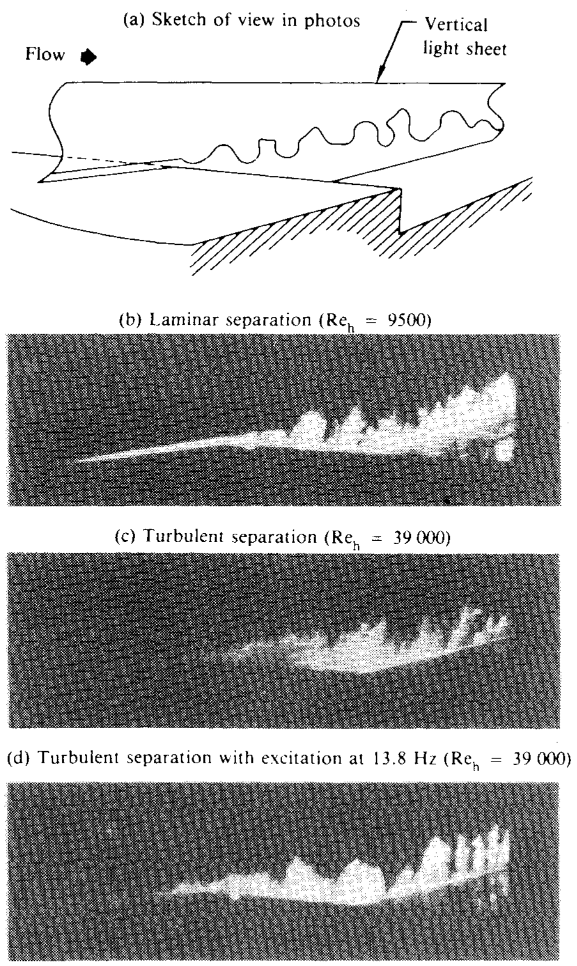

Fig. 14 Persistence of large-scale structures downstream of reattachment.

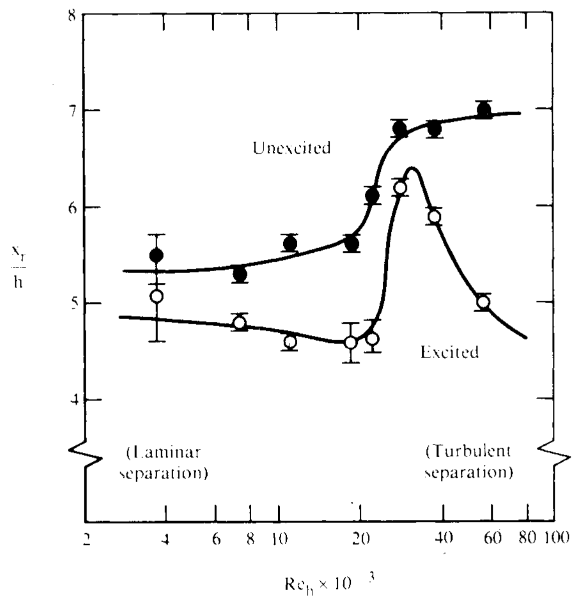

Fig. 15 Influence of shear-layer excitation on reattachment length (x_r).

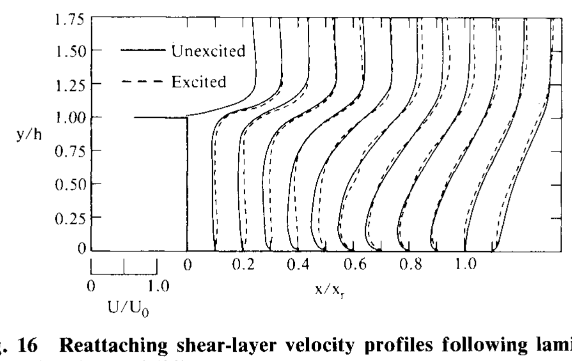

Fig. 16 Reattaching shear-layer velocity profiles following laminar separation ($Re_h=9500$).

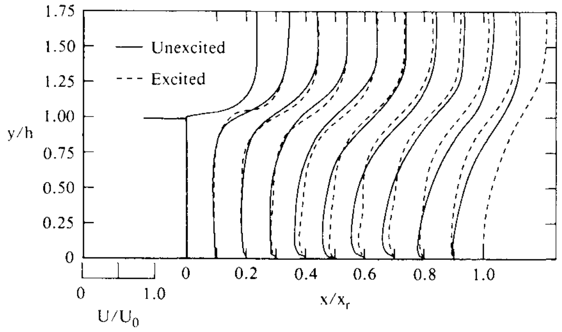

Fig. 17 Reattaching shear-layer velocity profiles following turbulent separation ($Re_h = 39{,}000$).

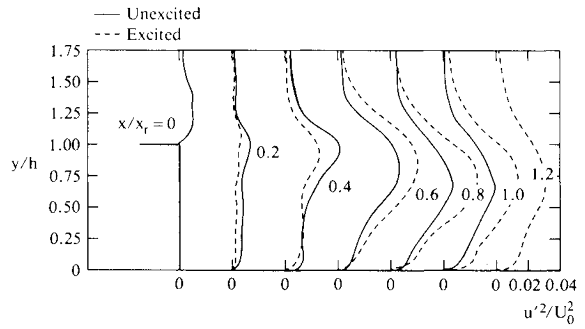

Fig. 18 Streamwise velocity fluctuation intensity in reattaching laminar shear layers ($Re_h = 9500$).

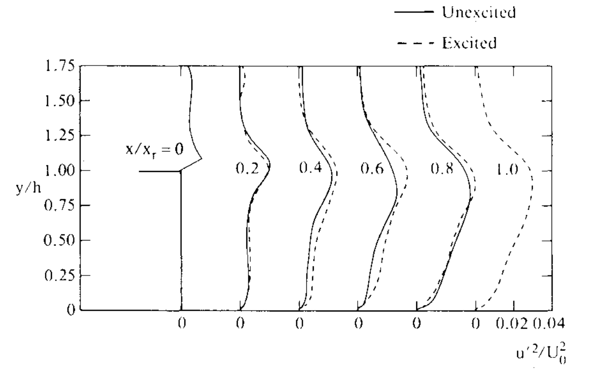

Fig. 19 Streamwise velocity fluctuation intensity in reattaching turbulent shear layers ($Re_h = 39{,}000$).

tle change in the mean-velocity profiles. In other words, the mean-velocity profile is an insensitive indicator of the details of time-dependent shear-layer structure.

Turbulence measurements were made in the reattaching flows, initially with an x-wire probe but primarily with the LDV system. Figures 18 and 19 show sets of streamwise velocity fluctuation intensity profiles for the unexcited and excited laminar separation (Fig. 18) and turbulent separation (Fig. 19) cases. Here the effects of shear-layer excitation are more evident, especially for laminar separation. This seems contradictory, considering that excitation exerts a greater overall influence on the reattaching turbulent layer (Fig. 15). However, it must be remembered that essentially all of the velocity fluctuation energy in the laminar case results from the vortical-structure dynamics, whereas much of the fluctuation energy in the turbulent case resides in incoherent turbulent motion. Consequently, the large-scale-structure enhancement produced by excitation has a more pronounced effect on the intensity of velocity fluctuations when separation is laminar. Good qualitative agreement again exists between the unexcited profiles and other recent data.[7-10]

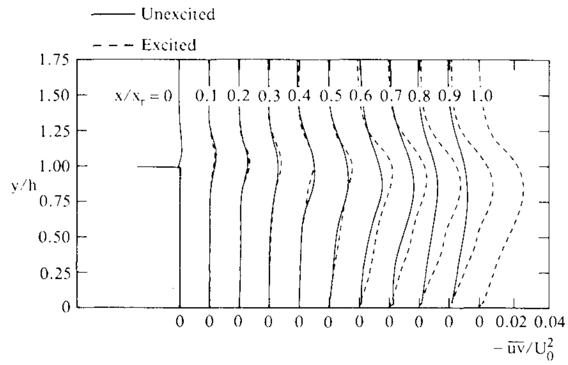

Fig. 20 Reynolds stress distributions in reattaching turbulent shear layers ($Re_h = 39{,}000$).

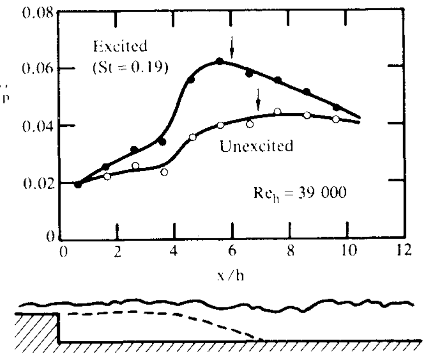

Fig. 21 Wall pressure fluctuation intensity beneath a reattaching turbulent shear layer.

Reynolds stress profiles were evaluated for both laminar and turbulent separations. Figure 20 shows a comparison of the Reynolds stress distributions for unexcited and excited turbulent separations. The enhanced vortical structure formation that follows from shear-layer excitation produces higher Reynolds stresses (particularly in the vicinity of reattachment), a measure of the more intense mixing and increased entrainment that result in more rapid reattachment of the shear layer.

Pressure fluctuation measurements beneath the reattaching shear layer not only further indicate the large-scale structures within the layer, but also provide another measure of the effect of shear-layer excitation on the properties of reattaching shear flows. Wall pressure fluctuation intensity data are presented in coefficient form in Fig. 21 for unexcited and excited reattaching turbulent shear layers. The arrows on the plot indicate the location of mean reattachment for the two cases. As might be expected, pressure fluctuations are most intense in the reattachment zone and decrease with distance in both the upstream and downstream directions. Fluctuation intensity beneath the excited shear layer shows a more rapid streamwise increase as reattachment is approached and rises to a considerably higher peak level. The greater localization of the peak pressure fluctuation intensity for the excited case can be explained as follows. Shear-layer excitation improves the regularity of large-scale vortical structure formation, thereby reducing the streamwise dispersion of "collisions" between individual vortical structures and the reattachment wall. The greater peak fluctuation intensity for the excited case arises because the large-scale vortical structures that interact with the reattachment wall are more regular and more intense.

Conclusions

In summary, the results of these experiments show that two-dimensional vortical structures form in the reattaching shear layer generated by flow over a backward-facing step and that these vortical structures merge in a manner similar to mixing layer vortices. The large-scale vortical structures become irregular with increasing shear-layer turbulence. In all cases, large-scale structures exist and persist far downstream of reattachment.

Gentle shear-layer excitation by an oscillating flap at the separation point has a strong regularizing influence on vortical structure formation, especially for turbulent separation. This influence produces intensified turbulence activity within and beneath the reattaching shear layer, but has little effect on mean velocity profiles. The greater mixing and entrainment of the excited shear layers result in substantially reduced reattachment lengths, especially when separation is turbulent.

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References

[1]Brown, G.L. and Roshko, A., "On Density Effects and Large Structure in a Turbulent Mixing Layer," *Journal of Fluid Mechanics,* Vol. 64, Part 4, 1974, pp. 775–816.

[2]Winant, C.D. and Browand, F.K., "Vortex Pairing: The Mechanism of Turbulent Mixing-Layer Growth at Moderate Reynolds Number," *Journal of Fluid Mechanics,* Vol. 63, Part 2, 1974, pp. 237–256.

[3]Roshko, A., "Structure of Turbulent Shear Flows: A New Look," *AIAA Journal,* Vol. 14, Oct. 1976, pp. 1349–1357.

[4]Bradshaw, P. and Wong, F.Y.F., "The Reattachment and Relaxation of a Turbulent Shear Layer," *Journal of Fluid Mechanics,* Vol. 52, Part 1, 1972, pp. 113–135.

[5]Kim, J., Kline, S.J., and Johnston, J.P., "Investigation of a Reattaching Turbulent Shear Layer: Flow Over a Backward-Facing Step," *Journal of Fluids Engineering,* Vol. 102, Sept. 1980, pp. 302–308.

[6]Eaton, J.K. and Johnston, J.P., "A Review of Research on Subsonic Turbulent Flow Reattachment," *AIAA Journal,* Vol. 19, Sept. 1981, pp. 1093–1100.

[7]Driver, D.M. and Seegmiller, H.L., "Features of a Reattaching Turbulent Shear Layer Subject to an Adverse Pressure Gradient," AIAA Paper 82–1029, 1982.

[8]Troutt, T.R., Scheelke, B., and Norman, T.R., "Organized Structures in a Reattaching Separated Flow Field," *Journal of Fluid Mechanics,* Vol. 143, 1984, pp. 413–427.

[9]Pronchick, S.W. and Kline, S.J., "An Experimental Investigation of the Structure of a Turbulent Reattaching Flow Behind a Backward-Facing Step," Stanford Univ., Dept. of Mechanical Engineering, Thermosciences Div., Rept. No. MD-42, 1983.

[10]Eaton, J.K. and Johnston, J.P., "Turbulent Flow Reattachment: An Experimental Study of the Flow and Structure Behind a Backward-Facing Step," Stanford Univ., Dept. of Mechanical Engineering, Thermosciences Div., Rept. No. MD-39, 1980.

[11]Durst, F. and Tropea, C., "Flows over Two-Dimensional Backward-Facing Steps," *Structure of Complex Turbulent Shear Flow,* Springer-Verlag, New York, 1983, pp. 41–52.

[12]Wygnanski, I., Oster, D., and Fiedler, H., "A Forced, Plane, Turbulent Mixing-Layer: A Challenge for the Predictor," *Turbulent Shear Flows 2,* Springer-Verlag, New York, 1980, pp. 314–326.

[13]de Brederode, V. and Bradshaw, P., "Three-Dimensional Flow in Nominally Two-Dimensional Separation Bubbles: I. Flow Behind a Rearward-Facing Step," Imperial College of Science and Technology, England, Dept. of Aeronautics, Rept. No. 72-19, 1972.

[14]Adams, E.W. and Johnston, J.P., "Effects of the Upstream Boundary-Layer Thickness and State on the Structure of Reattaching Flows," *Fifth Symposium on Turbulent Shear Flows,* Cornell Univ., 1985.

[15]Bhattacharjee, S., Scheelke, B., and Troutt, T.R., "Modification of Vortex Interactions in a Reattaching Separated Flow," *AIAA Journal,* Vol. 24, April 1986, pp. 623–629.