Modification of Vortex Interactions in a Reattaching Separated Flow

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Recent experimental observations have shown that large-scale organized vortices are produced in reattaching separated flows. Interactions between these vortices are important in the development of these flows downstream. Experimental studies from a downstream-facing step flow are presented to demonstrate that substantial changes in a reattaching flow can be produced by controlled forcing techniques. The forcing apparently works by affecting the vortex merging process in a fashion similar to that observed in forced mixing-layer experiments. The separated mean flow spreading rate could be increased most effectively by forcing at a nondimensional frequency (based on step height and freestream velocity) between 0.2 and 0.4. This result was found to be relatively independent of step Reynolds numbers over the range (26,000-76,000) studied. A significant decrease in the reattachment length accompanied the increased growth of the separated shear layer. Considerable changes in the turbulence energy and the Reynolds stress levels were also observed for the forced flows.

Nomenclature

F = frequency, Hz
H = step height
Re_H = step Reynolds number, U_0H/ν
St = Strouhal number, FH/U_0
u = downstream velocity fluctuation
U = downstream mean velocity
U_0 = freestream velocity prior to step edge
v = cross-stream velocity fluctuation component
X = downstream distance from step edge
Y = cross-stream distance from step edge
Z = spanwise distance
ν = kinematic viscosity
$\overline{(\ )}$ = time average of quantity
$(\ )_{rms}$ = root mean square of fluctuating quantity

Introduction

RECENT experiments on reattaching separated flows have demonstrated the importance of large-scale vortex dynamics in the development and overall features of these flows. Two of these experiments[1,2] involved separated flows over lifting surfaces at moderate to high angles of attack. The visualization results from these two studies indicated the presence of coherent vortices in the outer shear layer created by the separation region. These vortices were aligned parallel to the leading edge of the lifting surface and were observed to go through pairing interactions as they convected downstream. Ahuja[1] also found that the separated flow could be modified by the application of acoustic forcing. In fact, significant enhancement of the wing lift was observed for selected forcing frequencies.

The previous visualization results are consistent with recent experimental results obtained by Troutt et al.[3] for the flow downstream of a two-dimensional step. These experimental observations were obtained primarily through the use of multiple hot-wire anemometry techniques. The hot-wire results demonstrated that spanwise vortex structures similar to previously observed mixing-layer structures[4-6] were produced by the separated shear layer. The results indicated that vortex pairing interactions occurred upstream of the reattachment region, implying that the growth of the separated shear layer may be strongly dependent on the vortex pairing process.

Previous mixing-layer studies[7,8] have demonstrated that the vortex merging process and thus the growth of plane mixing layers can be substantially affected by controlled forcing techniques. The effectiveness of the controlled forcing procedures on the growth of the mixing layer, however, has been found to be strongly frequency-dependent. Forcing at a frequency corresponding to the natural local vortex passage frequency tends to regulate the spacing of the vortices and thus inhibit the merging interactions. However, forcing at a subharmonic of the vortex passage frequency can enhance the vortex merging process and consequently increase the spreading rate of the mixing layer.

The primary focus of the current research is to investigate the possible effects of controlled forcing on the character of a reattaching separated flow. The reattaching flow downstream of a two-dimensional step was chosen for this study because of its geometrical simplicity. The similarity of the natural vortex structures produced by this flow and those seen in the recent visualizations over lifting surfaces, however, implies that the results from this study should have general applicability to reattaching flows with more complicated boundaries.

Experimental Facilities and Procedures

The experiments were performed in an open-circuit wind tunnel described previously.[3] The test section was of rectangular cross section with dimensions of 240 cm in the downstream (X) direction, 61 cm in the cross-stream (Y) direction, and 91 cm in the spanwise (Z) direction. A schematic of the test section is shown in Fig. 1. The step height for the experiments was kept constant at 5.6 cm. All working surfaces were constructed from plexiglass.

The measurements were obtained using single-sensor hot wires for the multiprobe measurements and cross-wire and pitot-static probes for the single-probe surveys. The cross wires were calibrated using a calibration jet facility in which both the velocity magnitude and its angle with respect to the wire could be varied. The calibration was checked in this facility and found to be accurate for flow velocities above

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1 m/s and angles up to ±30 deg from the downstream direction. The single-sensor hot wires were used only on the outer edge of the rotational flow at low turbulent intensities where voltage fluctuations could be assumed proportional to downstream velocity fluctuations.

Data acquisition was accomplished with a 16-bit microcomputer employing a 12-bit digitization resolution. The maximum digitization rate was 10 kHz per channel. The more complex data analyses were done on a virtual memory minicomputer.

Measurements are reported for freestream velocities, U_0, prior to the step edge varying from 7 to 25 m/s. These velocities correspond to step Reynolds numbers, $Re_H = U_0H/\nu$, from 26,000 to 76,000. For all flow conditions, the boundary layer at the step edge was in a fully turbulent or late transitional stage, and the ratio of boundary-layer momentum thickness to the step height at the step edge varied from 0.018 at the lowest Reynolds number studied to 0.015 at the highest Reynolds number condition.

The forcing technique employed a single acoustic speaker located above the step edge. The forcing frequencies involved in this research were less than 200 Hz. The acoustic wavelengths associated with these low frequencies are large compared with the facility dimensions, therefore, an approximately two-dimensional perturbation can be expected at the step edge. Microphone measurements of the acoustic field confirmed that the sound level at the step edge was uniform within ±1 dB. A constant forcing level of 92 dB at the step edge was used for the forced flow measurements reported herein.

Results

Effects of Forcing on Vortex Structures

An example of the frequency dependence of the forcing on the vortex formation process is shown in Fig. 2. Figure 2a is a natural power spectrum from a single-sensor hot wire placed near the high-velocity edge of the separated flow at $X/H = 2$. The spectrum has a relatively broad peak ranging approximately between Strouhal numbers of 0.20-0.60. From our previous correlation and multisensor measurements,[3] this broad peak in the spectrum can be associated with the large-scale spanwise vortex passage period at this downstream position. Figures 2b and 2c demonstrate the effect of forcing at widely spaced Strouhal numbers. Figure 2b shows the effect of forcing at $St = 0.20$, which is near the low-frequency side of the broad peak. A large effect of over an order of magnitude above the surrounding frequencies is observed. Figure 2c shows that forcing at a frequency far above the typical vortex passage frequency has apparently little or no effect on the spectrum.

The downstream development of both forced and natural velocity spectra is depicted in Fig. 3. Each spectrum is normalized by the mean square of its associated time signal. The natural spectra have a broad rounded peak that gradually shifts toward lower frequencies with downstream position. This shift can be attributed to the large-scale vortex amalgamations occurring in the separated shear layer. The forced spectra demonstrate that the large-scale vortex passage period is preferentially enhanced at the forcing frequency for all three downstream positions. This enhancement is indicated by a spike in the forced spectra that is apparent at all three downstream positions. The effect of the forcing on the overall character of the spectra, however, appears to maximize at $X/H = 4$. The largest differences in the amplitude of the spectra for frequencies away from the forced spike are found at this position. These differences are most pronounced for frequencies just above the forcing frequency with the amplitude difference diminishing with higher frequency. By $X/H = 8$ the relative energy in the forcing spike has decreased and differences between the natural and forced spectra have considerably diminished. These spectral results indicated that the largest changes in the separated flow for forcing at frequencies around $St = 0.2$ should be expected for downstream positions

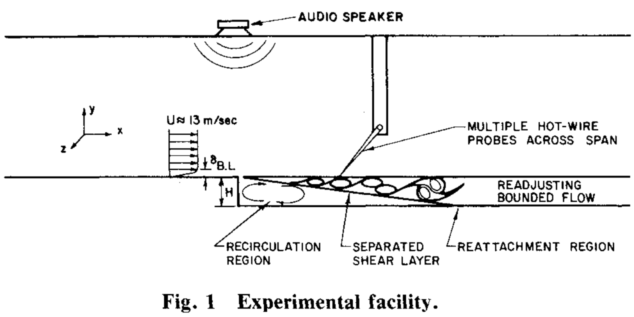
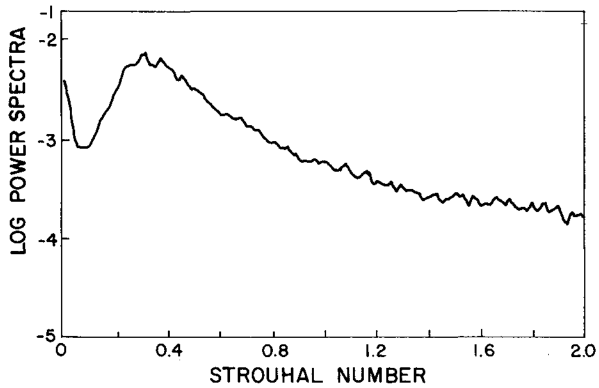
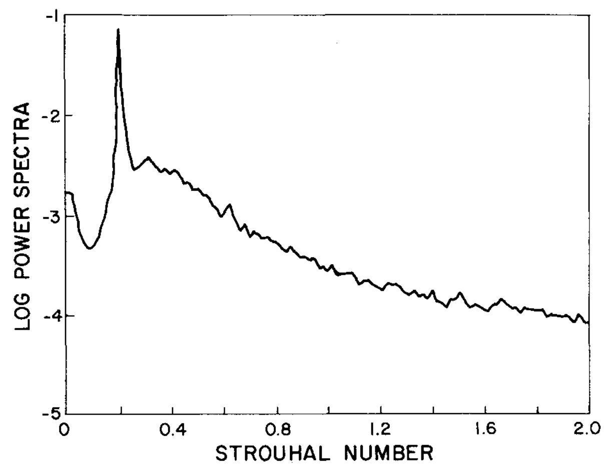


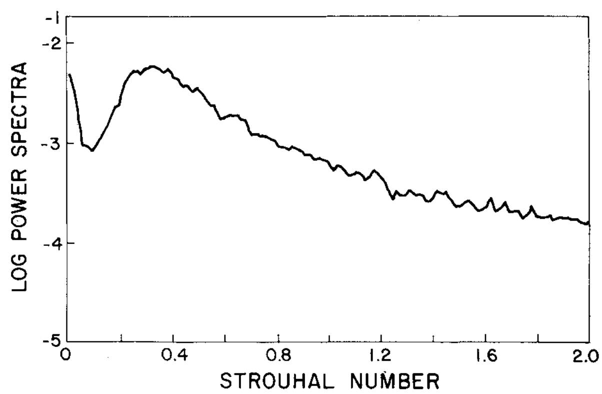
Fig. 1 Experimental facility.



a) Natural.



b) Forced at $St = 0.20$.



c) Forced at $St = 1.2$.

Fig. 2 Power spectra from high-speed edge of separated shear layer; $u_{rms}/U = 2\text{-}3\%$, $Re_H = 32,500$.

near $X/H=4$. Results concerning effects within the separated flow presented subsequently show this to be the case.

An example of the effect of forcing on the time signals from a line of single-sensor hot wires is shown in Fig. 4. The hot wires are aligned in the spanwise dimension along the top edge of the separated shear layer at $X/H=4$. The total spanwise distance covered by the probe positions is $\Delta Z/H=2.5$. Figure 4a shows a typical, nonforced, simultaneous time sequence from the four hot wires. The large-scale fluctuations in the signals can be assumed to be caused by large convecting vortices in the separated shear layer. The nonforced signals can be described as quasicorrelated across the span. Figure 4b shows a typical example of time traces from the same sensors, but now with the flow forced at $St=0.20$. The signal to the acoustic speaker is also shown. The velocity traces could now be described as being strongly correlated.

To quantify the spanwise correlation of the vortex structures for both forced and natural conditions, the zero time delay cross correlation between pairs of sensors at varying spanwise displacement was computed. Figure 5 shows the results from these computations for the downstream position at $X/H=4$. The natural correlations display a substantial reduction in correlation values with spanwise position. The trend displayed is very similar to measurements reported earlier[3] for the same flow at a somewhat higher Reynolds number condition. The dropoff in correlation as spacing is increased can be attributed to the three-dimensionality associated with naturally occurring vortex pairing interactions in the separated shear layer. On the other hand, the forced correlations display significantly increased values at the smallest separation combined with much greater values at larger separations. These results demonstrate the large enhancement of two-dimensionality at this downstream position produced by the controlled forcing.

The development of the spanwise correlation values for a fixed displacement as a function of downstream position is shown in Fig. 6 for both natural and forced conditions. The natural correlation levels increase in the downstream direction implying that the large-scale vortices are growing in scale with downstream position. The quantitative and qualitative features of this development are again quite similar to previously published results[3] for a somewhat higher Reynolds number flow. The forced results show a much steeper initial increase in correlation value with downstream position reaching a maximum at $X/H=4$ and then falling to approximately the nonforced levels by $X/H=8$

The enhanced development of spanwise correlation values in the region upstream of $X/H=4$ can probably be associated with an increased growth of the vortex structures in the

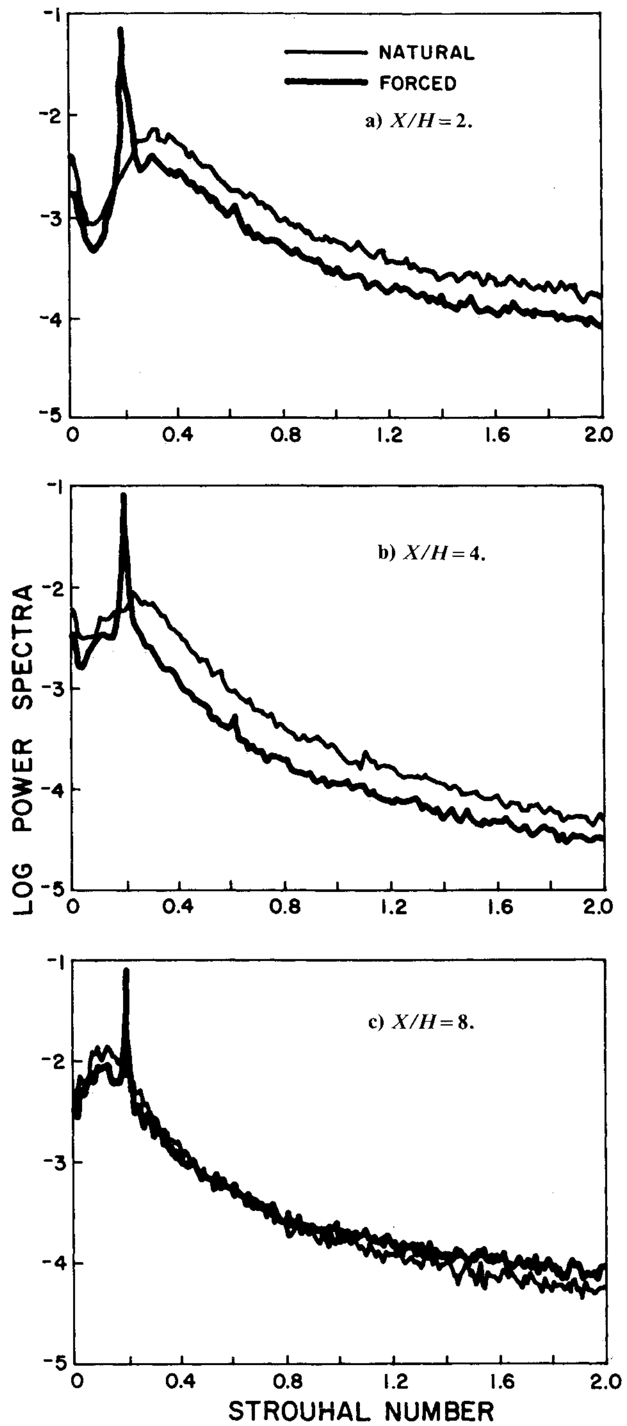


Fig. 3 Power spectra from downstream positions; $u_{rms}/U=2\text{-}3\%$, $Re_H=32{,}500$.

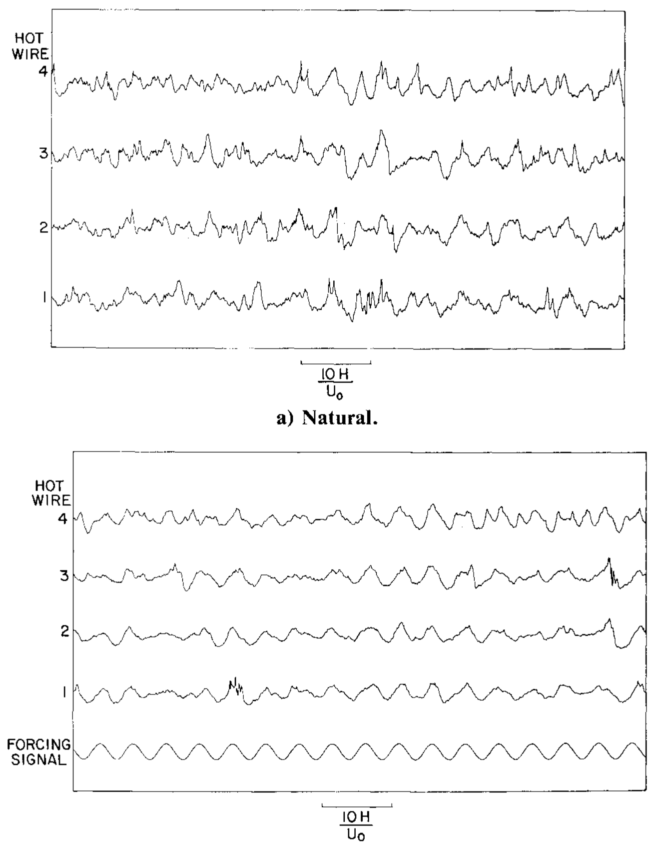


Fig. 4 Simultaneous velocity traces from high-speed edge of separated shear layer; $X/H=4$, $u_{rms}/U=2\text{-}3\%$, $Re_H=32{,}500$.

separated shear layer. This increased growth of the vortex structures can be produced by encouraging the vortex merging process, as was observed in previous forced mixing-layer studies.[7,8] (Simultaneous visualizations from the sensor array presented in Fig. 7 demonstrate a similar mechanism at work in the separated shear layer.) Downstream of $X/H=4$ the $St=0.20$ forcing is no longer significantly lower than the natural vortex passage frequency and, consequently, vortex mergings are not stimulated and spanwise correlation levels do not increase. Boundary wall effects also become important in this downstream region.

Bilevel topological plots generated from the instantaneous time signals are displayed in Fig. 7. The dark areas on the plots depict times in which the instantaneous downstream velocity levels are equal to or above the mean. Branches in the dark patterns indicate that the vortices are interacting or pairing.

Figure 7a shows a typical plot for the flow forced at $St=0.20$ for the $X/H=2$ position. At this position the forcing is encouraging the pairing process but not all pairing interactions have been completed. Two obvious examples of structures involved in a pairing interaction are apparent in the figure. One structure located approximately one-third of the total plot time from the bottom indicates a completed pairing near the extreme right-hand side with two approximately equal width separated branches extending across the remaining span of the measurement. Another structure with two separated branches extending from the right to a merged section on the left-hand side of the plot is located in the top one-third of the plot.

Figure 7b shows the structures resulting from the $St=0.20$ forcing at the downstream position of $X/H=4$. The structures at this position are highly two-dimensional, indicating that the pairing events observed at $X/H=2$ are now predominantly completed. The high degree of two-dimensionality seen in this plot is consistent with the cross-correlation values reported earlier for the forced flow at this position. A typical plot for the natural flow at $X/H=4$ is shown in Fig. 7c.

A visual comparison between Figs. 7b and 7c indicates that the $St=0.20$ forcing produces structures at this position which, on the average, have increased time scales and enhanced two-dimensionality. By comparing Figs. 7a and 7b it seems apparent that the forced structures resulting at $X/H=4$ are produced from the amalgamation of smaller structures prior to $X/H=4$.

The controlled forcing at $St=0.20$ apparently affects the separated flow by enhancing the vortex merging process. This result is quite similar to the observations reported by Ho and Huang[7] and Oster and Wygnanski[8] demonstrating that subharmonic forcing can enhance the vortex merging process and increase the two-dimensionality of the resulting structures. This enhancement of the vortex merging process also results in increased growth in the plane mixing layer. A similar

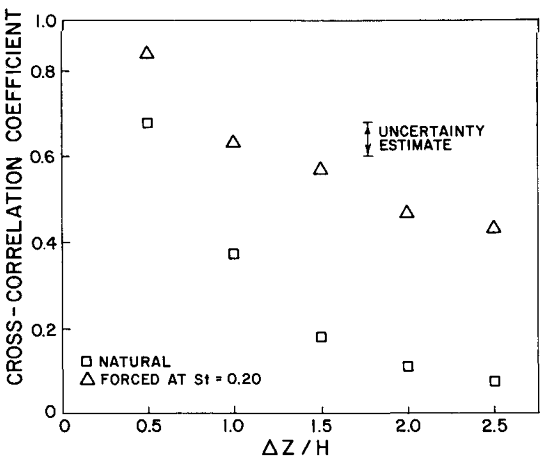


Fig. 5 Cross-correlation coefficient as a function of spanwise displacement; $X/H=4$, $Re_H=32{,}500$.

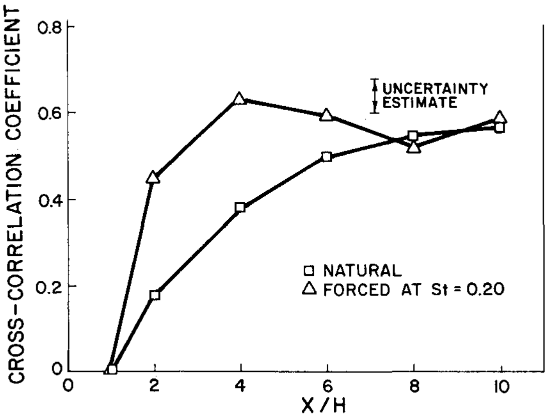
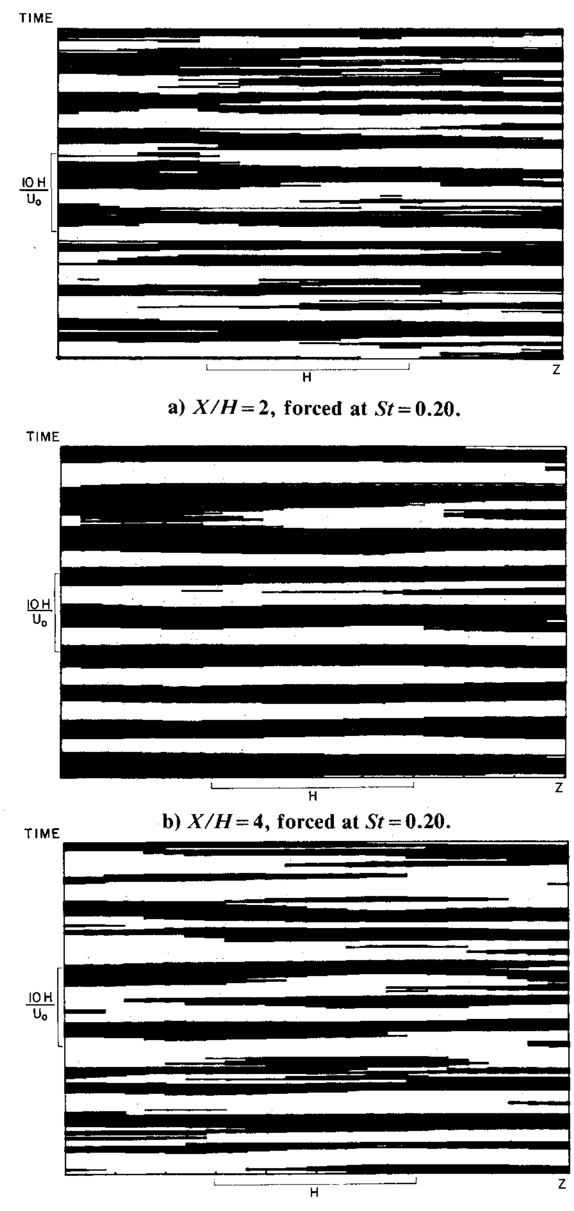


Fig. 6 Cross-correlation coefficient as a function of downstream position; $\Delta Z/H=1.0$, $Re_H=32{,}500$.



a) $X/H=2$, forced at $St=0.20$.

b) $X/H=4$, forced at $St=0.20$.

c) $X/H=4$, natural.

Fig. 7 Topological plots of fluctuating downstream velocity; $Re_H=32{,}500$.

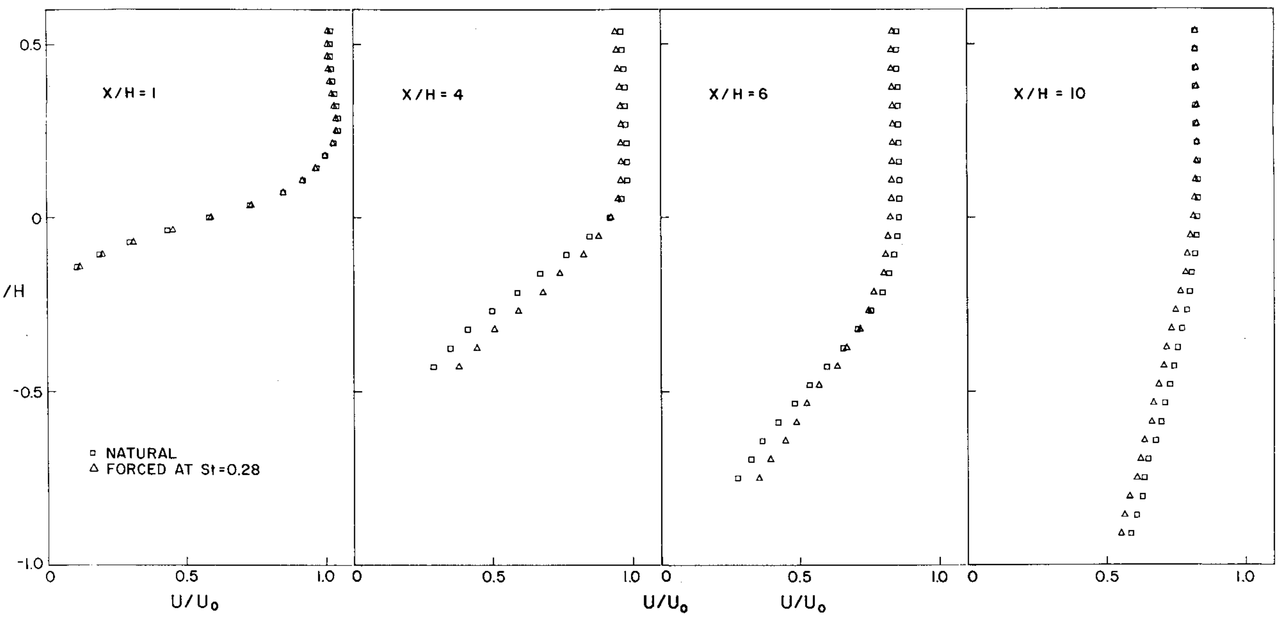


Fig. 8 Mean downstream velocity profiles; $Re_H = 45{,}000$.

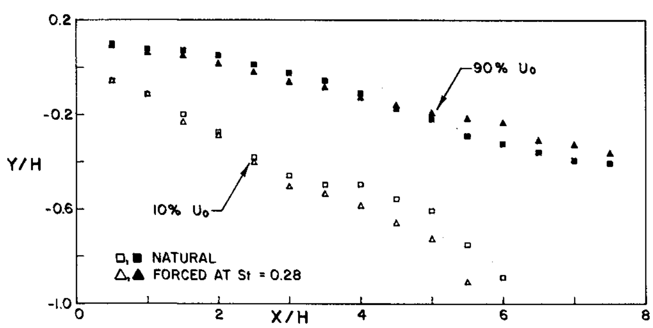


Fig. 9 Location of points of 10 and 90% freestream velocity; $Re_H = 45{,}000$.

enhancement of the separated shear-layer spreading rate with a consequent change in the size of the recirculation region should also be expected for the step flow under appropriate frequency forcing.

Effects of Forcing on Time-Averaged Flow

To document the effects of controlled forcing on the time-averaged flow, a detailed survey was conducted at a step Reynolds number of approximately 45,000. This Reynolds number was chosen because previous work by Troutt et al.[3] on the natural flow had been performed at this Reynolds number. Less extensive mean flow measurements were also made over a broad range of Reynolds numbers to check the Reynolds number dependence of the results. The following results are for a forcing frequency found to have a relatively large effect on the development of the separated flow.

The effect of forcing at $St = 0.28$ on the mean velocity levels is shown in Fig. 8. At $X/H = 1.0$ the mean velocity profiles are slightly affected by the forcing. However, by $X/H = 4.0$ significant changes in the mean velocity levels within the shear layer region are apparent. Increased mean velocity levels by as much as 30% for the same vertical position occur for the forced flow. These increased mean velocity levels are indicative of a faster spread of the forced flow into the recirculation region. By $X/H = 6$, the solid floor constraint now has a significant influence on the spreading rate of the mean velocity profiles and the changes caused by the forcing decrease. At $X/H = 10$ the mean velocity changes from the forcing have become almost negligible.

Figure 9 shows the effect of forcing on the mean velocity field prior to reattachment by plotting the locations of the 10 and 90% freestream velocity levels as a function of downstream position. As the 10% freestream velocity point approaches the wall an extrapolation can be made for approximating the reattachment location. Forcing at $St = 0.28$ appears to shorten the reattachment length by approximately 0.5-1 step height or, equivalently, a change of between 10 and 15% in reattachment length. The forced 90% freestream velocity points do not show an analogous increased spread for the high-velocity side of the shear layer into the freestream. This asymmetrical type of shear-layer spreading is a well-recognized feature of plane mixing-layer growth. Since the forcing works by promoting vortex pairing, it is probably not surprising that its effect also emphasizes this asymmetry.

The effect of forcing at $St = 0.28$ on the time-averaged turbulence energy levels is shown in Fig. 10. Near the step edge, $X/H = 1$, the fluctuation energy levels are affected only slightly by the forcing. By $X/H = 4$, however, the influence of the forcing on the turbulent energy levels becomes significant. Increases in the peak energy levels of as much as 50% are recorded here. Downstream of $X/H = 4$, the changes in the turbulent energy levels created by the forcing decrease. This decrease continues until the influence on the energy levels becomes relatively small well downstream of reattachment, i.e., at $X/H = 10$.

The influence of forcing on the Reynolds stress levels is shown in Fig. 11. The trends in these levels follow closely those observed for the turbulent energy results.

The previous results are consistent with a physical picture identifying vortex merging as the chief agent for the spread of the separated mixing layer. The relatively low-frequency forcing has little effect close to the step because the initial vortices are just forming. At $X/H = 4$, however, the forcing is enhancing the natural pairing process causing the mean flow to spread faster and increasing the levels of turbulent energy and Reynolds stresses. Downstream of $X/H = 4$ most vortices are large enough such that the influence of the bounding wall becomes important. This influence probably inhibits the vortex pairing process[3] and thus tends to decrease the effect of the forcing, regardless of frequency, on the mean velocity and time-averaged turbulence levels.

Experiments concerning the effect of the controlled forcing on the time-averaged flow were also carried out over a range of freestream velocities. It was found that for each freestream velocity a most effective frequency for enhancing the $X/H \leq 4$ spreading rate of the separated shear layer could be determined. The results of these measurements are summarized in Fig. 12. The most effective frequency on the vertical axis is

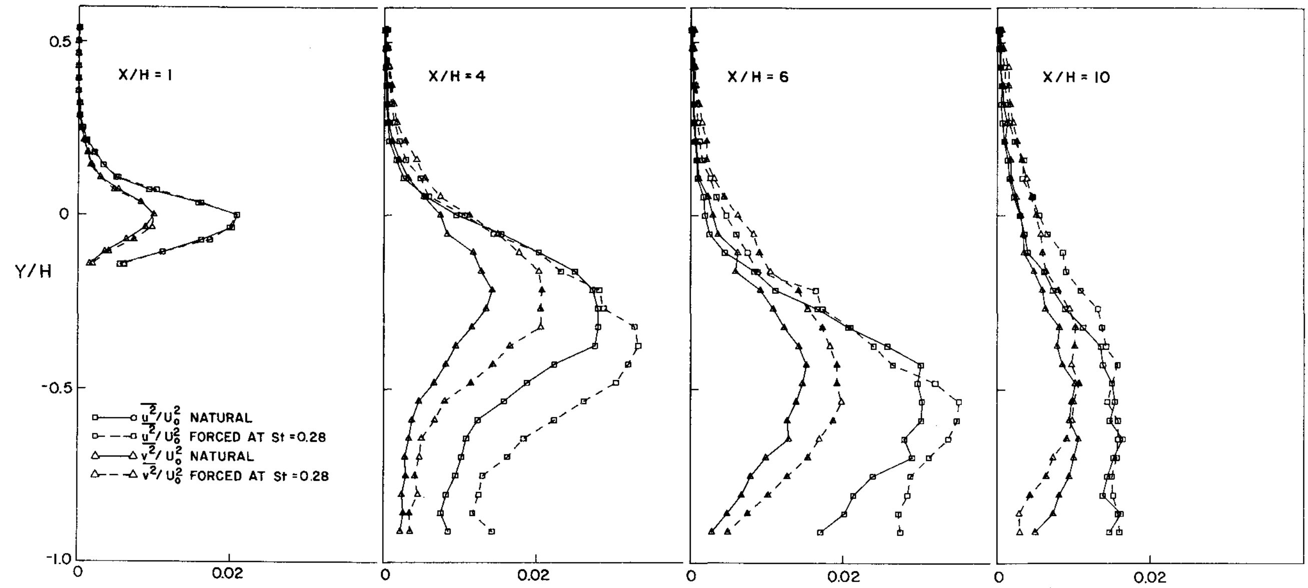


Fig. 10 Turbulence energy profiles; $Re_H = 45{,}000$.

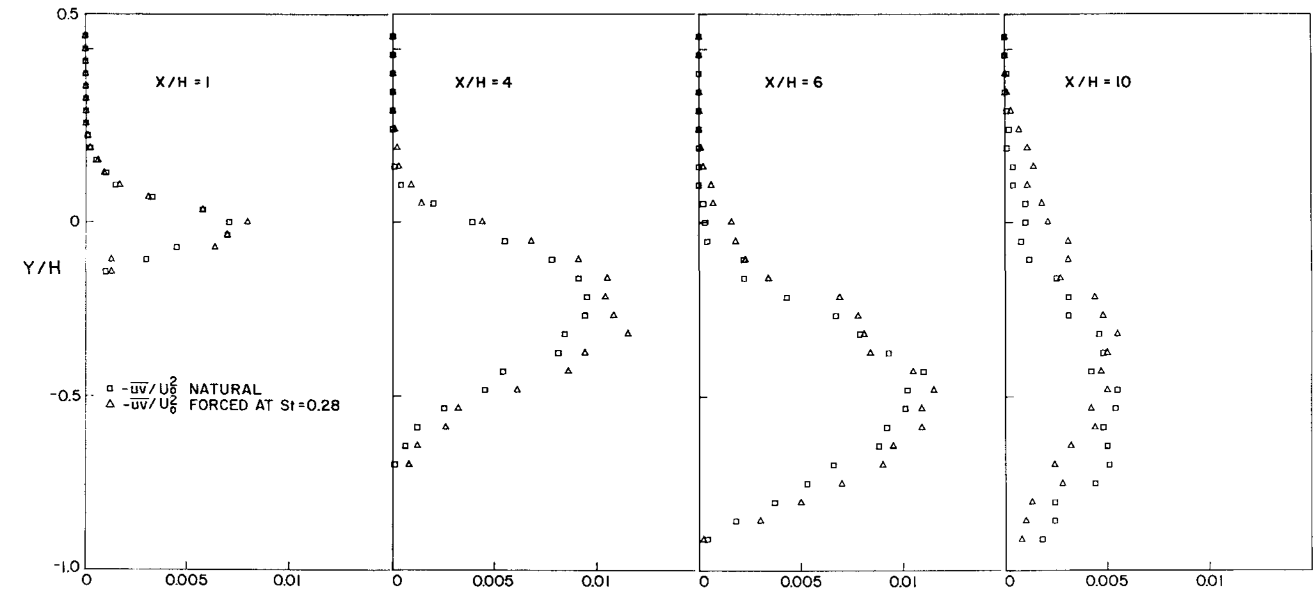


Fig. 11 Reynolds stress profiles; $Re_H = 45{,}000$.

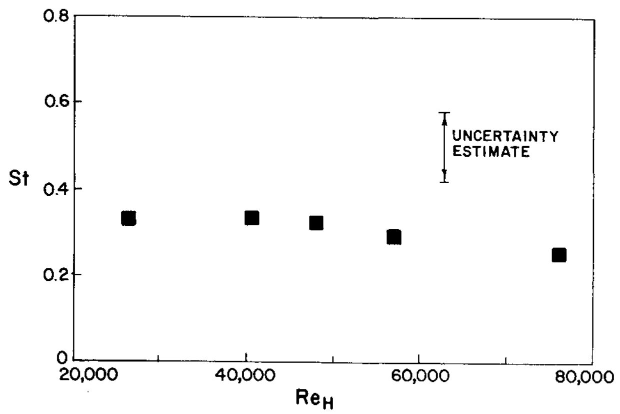


Fig. 12 Most effective forcing Strouhal number as a function of step Reynolds number.

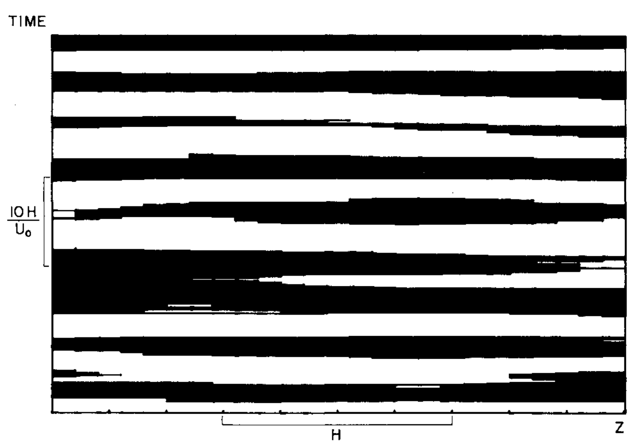


Fig. 13 Topological plot of fluctuating downstream velocity; $X/H = 10$, $Re_H = 32{,}500$, forced at $St = 0.20$.

normalized by the step height and freestream velocity, and the horizontal axis is given as an equivalent step Reynolds number. The uncertainty associated with the most effective frequency indicates a range of frequencies at a specified flow velocity or Reynolds number over which the effect of forcing on the mean velocity profiles is approximately constant. The results indicate that the most effective Strouhal number remains relatively constant between 0.2 and 0.4 over a broad Reynolds number range. This finding implies that the maximum height of the recirculation region and the freestream velocity create a characteristic frequency scale that governs the effectiveness of the forcing.

The most effective forcing frequency of the step flow may be analogous to the preferred mode observed for free jets. In the free jet the diameter or thickness of the jet imposes an additional length scale on the free shear layer just as the step height does in this experiment. The preferred mode in jets is a constant at high jet velocities but is found to have a slight dependence on the initial shear-layer thickness at low jet velocities. A discussion concerning the preferred mode in free jets can be found in Ref. 9.

The most effective forcing frequency can also be nondimensionalized using the local mixing-layer width and convection velocity of the large vortex structures. From previous measurements[3] in this flow the convection velocity of the structures was found to be $0.58U_0$ and the maximum slope thickness at $X/H=4$ approximatey $0.6H$. A nondimensional forcing frequency based on these values gives most effective forcing Strouhal number again in the range between 0.2 and 0.4.

This rescaled nondimensional forcing frequency can now be directly compared to results from mixing-layer experiments. Experiments on mixing layers[6] show that the predominant nondimensional passage frequency of large-scale vortices in mixing layers is also in the range of 0.2-0.4. The results from forced mixing-layer experiments[7,8] demonstrate that growth of a mixing layer can be best enhanced between the origin and a particular downstream position by forcing at the downstream vortex passage frequency. The results from the step flow seem to agree closely with this result.

Existence of Vortex Structures Downstream of Reattachment

The fate of the large vortices downstream of reattachment has been a topic of recent discussion. In previous work by Troutt et al.[3] on the nonforced step flow, they conjectured, based on correlation and coherence measurements, that the large vortices created in the separated flow retain much of their global organization downstream of reattachment. However, pairing interactions appeared to be suppressed in this region. Because of apparent small-scale irregularities generated by the bounding wall, however, the nonforced spanwise topological plots were unclear on this point. Topological plots from the forced flow do show a clear indication that the large-scale vortices are retaining their two-dimensionality downstream of reattachment. A typical plot from $X/H=10$ is shown in Fig. 13. The spanwise vortices at this point appear almost as uniform as the upstream structures at $X/H=4$.

Conclusion

Controlled forcing can have a significant effect on the development of reattaching separated flows. These effects include and increased spread in the mean velocity profiles accompanied by large increases in the time-averaged turbulence fluctuation quantities. The forcing apparently works by modifying the vortex interaction process within the separation shear layer. The spreading rate of the separated shear layer for $X/H \leq 4$ can be increased most effectively by forcing at a Strouhal number, $St=FH/U_0$, based on step height and freestream velocity in the range of 0.2-0.4. This finding was shown to be in close agreement with previous results from forced mixing layers.

The most effective Strouhal number range was found to be approximately constant over a broad range of step Reynolds numbers, implying that the forcing mechanism is relatively independent of flow conditions and upstream boundary layer properties.

The results presented in this study have been interpreted using a vortex merging model. This model seems reasonable in light of the work of Troutt et al.[3] on the naturally developing step flow, and it appears to be strongly supported by the experimental evidence presented herein. In a recent study of a forced step flow involving laser velocimetry techniques and smoke visualization, Roos and Kegelman[10] also concluded that the vortex merging mechanism was a dominant feature in the flow development. The observation that forcing in a particular Strouhal number range produces the most significant effect on the separated shear-layer spread does not contradict this model. Since the shear layer grows asymmetrically toward the low-speed side, the bounding surface restricts the size of the largest vortex formed to a length scale on the order of the step height. This length scale and the freestream velocity therefore produce a characteristic frequency independent of Reynolds number or initial boundary-layer properties.

The increased spread in the separated shear layer results in a shorter reattachment region. This reduction in the reattachment region may have important applications for some technological situations. Potential applications involve the control of separated flows over airfoils at high angles of attack and the control of turbulent combustion instabilities in sudden expansion combustors. The reduction in reattachment length observed in these experiments using simple acoustic loudspeaker forcing was on the order of 10-15%. However, larger changes in the reattachment length may be possible with more specialized forcing techniques. These larger effects have, in fact, been observed by Roos and Kegelman.[10] It may also be plausible that the reattachment length could be extended if the separated flow is forced at a frequency inhibiting pairing. This possibility has not yet been demonstrated in the authors work.

The effects of forcing on the time-averaged flow properties downstream of reattachment are not as large as the upstream changes, but the coherent vortices organized by the forcing are still apparent.

Acknowledgment

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References

[1]Ahuja, K.K., "Acoustic Control of Separation," *Bulletin of the American Physical Society*, Vol. 28, 1983, p. 1388.

[2]Gad-el-Hak, M., Ho, C-M., and Blackwelder, R.F., "A Visual Study of a Delta Wing in Steady and Unsteady Motion," *Unsteady Separated Flow*, edited by M.S. Francis and M.W. Luttges, University of Colorado, U.S. Air Force Academy, Colorado Springs, 1984, p. 45.

[3]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.

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

[5]Browand, F.K. and Troutt, T.R., "A Note on Spanwise Structure in the Two-Dimensional Mixing Layer," *Journal of Fluid Mechanics*, Vol. 97, 1980, pp. 771-781.

[6]Browand, F.K. and Troutt, T.R., "The Turbulent Mixing Layer: Geometry of Large Vortices," *Journal of Fluid Mechanics*, Vol. 158, 1985, pp. 489-509.

[7]Ho, C-M. and Huang, L.S., "Subharmonic and Vortex Merging in Mixing Layers," *Journal of Fluid Mechanics*, Vol. 119, 1982, pp. 443-473.

[8]Oster, D. and Wygnanski, I., "The Forced Mixing Layer Between Parallel Streams," *Journal of Fluid Mechanics*, Vol. 123, 1982, pp. 91-130.

[9]Ho, C-M. and Huerre, P., "Perturbed Free Shear Layers," *Annual Review of Fluid Mechanics*, Vol. 16, 1984, pp. 365-424.

[10]Roos, F.W. and Kegelman, J.T., "Control of Coherent Structures in Reattaching Laminar and Turbulent Shear Layers," AIAA Paper 85-0554, 1985.