Time-Dependent Behavior of a Reattaching Shear Layer

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Conditionally sampled velocities have been measured in a reattaching turbulent shear layer behind a rearward facing step in an effort to understand unsteady behavior of reattaching flows. Laser-Doppler velocimeter measurements were conditionally sampled on the basis of instantaneous flow direction near reattachment. Conditions of abnormally short reattachment and abnormally long reattachment were considered. Ensemble-averages of measurements made during these conditions were used to obtain mean velocities and Reynolds stresses. In the mean flow, conditional streamlines show a global change in flow pattern which correlates with wall-flow direction. This motion can loosely be described as a "flapping" of the shear layer. Stresses shown also vary with the change in flow pattern. Yet, the global "flapping" motion does not appear to contribute much to the fluctuating energy in the flow. A second type of fluctuating motion (vortical) was observed. Spectral analysis of both wall static pressure and streamwise velocity show that the majority of energy in the flow resides in frequencies characteristic of roll-up and pairing of vortical structure seen in free shear layers ($St = 0.2$). Two-point velocity correlations also indicate a vortical behavior of the flow. It is conjectured that the "flapping" is a disorder of the roll-up and pairing process occurring in the shear layer.

Nomenclature

b = width of the shear layer, vorticity thickness, $b = \Delta U/(\mathrm{d}U/\mathrm{d}y)_{max}$
C_p = time-averaged pressure $= (\bar{P} - \bar{P}_{ref})/\tfrac{1}{2}\rho U_{ref}^2$
$C_{p'}$ = fluctuating pressure $= \sqrt{\langle p^2 \rangle}/\tfrac{1}{2}\rho U_{ref}^2$
$E(n)$ = contribution to $\langle u^2 \rangle$ in frequency band Δn,

$$\langle u^2 \rangle = \int_0^\infty E(n)\mathrm{d}n = \int_{-\infty}^{\infty} nE(n)\mathrm{d}[\log(n)]$$

f = frequency, Hz
$F(n)$ = contribution to $\langle p^2 \rangle$ in frequency band Δn,

$$\langle p^2 \rangle = \int_0^\infty F(n)\mathrm{d}n = \int_{-\infty}^{\infty} nF(n)\mathrm{d}[\log(n)]$$

H = step height
L = length of separation bubble ($L = 6.1H$)
n = nondimensional frequency ($n = fL/U_{ref}$)
P = pressure
$\langle p^2 \rangle$ = mean square pressure fluctuations
Q = $\tfrac{1}{2}\rho U_{ref}^2 = 1160$ N/m^2
$R_{uu}(Y)$ = two-point correlation of streamwise velocity fluctuations $R_{uu}(Y) = \langle u(Y)u(Y+\Delta Y)\rangle \div \sqrt{\langle u(Y)^2\rangle \langle u(Y+\Delta Y)^2\rangle}$
St = nondimensional frequency, Strouhal ($St = fb/U_{sl}$)
$\langle u^2 \rangle$ = mean square of streamwise velocity fluctuations
$\langle uv \rangle$ = mean product of streamwise and normal velocity fluctuations
U = mean velocity in the streamwise direction
U_{sl} = shear layer velocity, average of high-speed and low-speed sides of shear layer taken to be $\tfrac{1}{2} U_{ref}$
U_e = mean velocity at the edge of the boundary layer
X = streamwise coordinate parallel to model centerline measured from the edge of the step
X_r = instantaneous streamwise location of reattachment
Y = vertical coordinate normal to the step sidewall measured from the bottom of the step
γ = fraction of the time, $U > 0$
δ = boundary-layer thickness
$\psi(y)$ = $\int_0^{y/H} (U/U_{ref})\mathrm{d}(y/H)$
$\langle(\ )\rangle$ = ensemble-average value

Subscripts

ref = reference station ($X/H = -4$) conditions

Superscripts

$(\bar{\ })$ = long time-average value

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Introduction

SEPARATING and reattaching flows quite often exhibit an unsteady low-frequency behavior (frequencies much lower than turbulence frequencies). Unsteadiness occurs on stalled airfoils, in diffusers, and in cavities, and often produces cyclic structural or thermal loading. Although this phenomenon is frequently observed it is poorly understood. Since the separation and reattachment processes by themselves have strong viscid-inviscid interaction, it seems likely that the unsteady behavior is also strongly influenced by viscous effects. Studying the turbulence in such flows can be difficult though, since details of the turbulence may be obscured by the unsteadiness. If the unsteadiness of the flow goes unnoticed, measurements of turbulence can be difficult to interpret. Consequently, experiments that help distinguish turbulence from unsteadiness may make it possible to improve turbulence modeling in such flows.

The step flow, by virtue of its fixed detachment point, is usually thought to be steady; however, Eaton and Johnston[1] reported that their back step flow exhibited a low-frequency unsteadiness. Using wall-flow direction probes, they demonstrated that the short-time-averaged reattachment point deviated from the long-time-averaged reattachment point by as much as ± 2 step heights. Although this was determined not to be a problem with a pulsing inlet, the actual mechanism causing it was not identified. Eaton and Johnston found a frequency $fH/U_{ref} = 0.07$ in their flow (using a hot wire) and interpreted it as unsteadiness. Similar unsteady behavior had been previously documented in two-dimensional free shear layers[2,3] and in two-dimensional flow over a cavity.[4,5]

Mabey,[6] in reviewing the literature, found that unsteadiness in separating flows (as detected by a wall pressure sensor) scales with the freestream velocity and length of the separation bubble. He found that separated flows have a weakly defined maxima in turbulent energy spectra (wall pressure fluctuations) at nondimensional frequencies, fL/U_{ref} in the range of 0.5 to 0.8. This is the same frequency that Eaton and Johnston found in their flow; the normalization is different ($L = 8H$ for Eaton).

The largest visualized structure seen by Pronchick and Kline[7] in their step-flow comes from the roll-up and multiple pairing of spanwise vortices in the shear layer. This structure is thought to be similar to the vortex roll-up and pairing process seen in the planar free shear layer by Winant and Browand.[8] Pronchick and Kline in their step flow, did not observe any structure larger than these vortices, owing to the prohibitively long waiting time that would have been required (work done in low-speed water tunnel). They observed that the spanwise organization of these vortical structures starts to break down beyond three step heights downstream of detachment. These vortex and subsequent large-eddy structures were of much smaller length-scale and time duration than the unsteadiness that Eaton and Johnston[1] saw in their flow. Troutt, Scheelke, and Norman[9] also saw large spanwise coherent mixing layer type vortices in their step flow (using a spanwise hot-wire rake). McGuinness[10] and Roos and Kegelman[11] manipulated the roll-up and pairing process in their separated flows by introducing periodic disturbances in the bubble at frequencies characteristic of the passing of vortices; this substantially shortened the separation bubble.

The aim of the present experiment is to determine the amplitude and time scales of the fluctuating motion seen in reattaching shear layers, in an effort to gauge the relative importance of these motions to turbulence modeling and computational solutions. This paper presents conditionally sampled measurements in a reattaching, turbulent shear layer behind a rearward-facing step. This work is a continuation of that presented in Ref. 12. Conditionally sampled laser-Doppler velocimeter measurements were used to visualize mean flow streamlines and shear stress contours during conditions of abnormally long and short reattachment lengths. In addition, frequency content of the fluctuating wall pressures and velocities were measured along with two-point velocity correlations.

Experiment

The experiment was conducted on the tunnel floor of a low-speed wind-tunnel facility (see Fig. 1). The test configuration consisted of a 1.0-m-long × 0.1016-m-tall × 0.1524-m-wide rectangular inlet duct followed by a 0.0126-m rearward-facing step in the floor. The test configuration has a large aspect ratio (12/1) to minimize three-dimensional effects in the separated region, and a small expansion ratio (1.125/1) to minimize freestream pressure gradient effects due to expansion.

The experiment was performed at a freestream velocity of 44.2 m/s and atmospheric total pressure and temperature. These conditions correspond to a freestream Mach number of 0.128, a boundary-layer thickness of $1.5H$, and a Reynolds number (based on momentum thickness) of 5000 at a location 4 step heights upstream of the step. The Reynolds number based on step height is 37,000.

Surface measurements of near-wall intermittency were made using a thermal tuft.[13] Flowfield measurements were made using a two-dimensional, synchronous, two-color laser-Doppler velocimeter previously described in Ref. 14.

To detect the instantaneous near-wall flow direction, two thermal-tuft probes were mounted in the vicinity of reattachment. The thermal-tuft wall probe (described in Ref. 13) employs a center heated wire and two sensor wires (lying parallel to the heated wire), one upstream and one downstream, to detect the wake of the central heated wire. All three wires were located approximately 0.25 mm above the floor. The tungsten sensor wires were 0.005 mm in diameter, and the Monel heater wire was 0.125 mm in

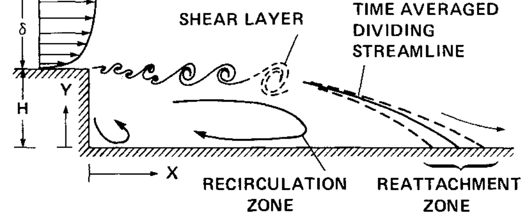

Fig. 1 Rearward-facing step-flow experimental geometry and inlet conditions: H = 1.27 cm, W = 12 H, U_{ref} = 44.2 m/s, M_{ref} = 0.128, d = 1.9 cm, Re_θ = 5000.

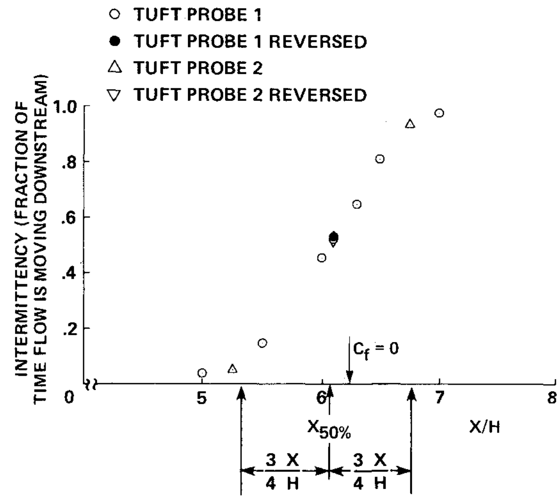

Fig. 2 Distribution of near-wall flow intermittency along stepside wall.

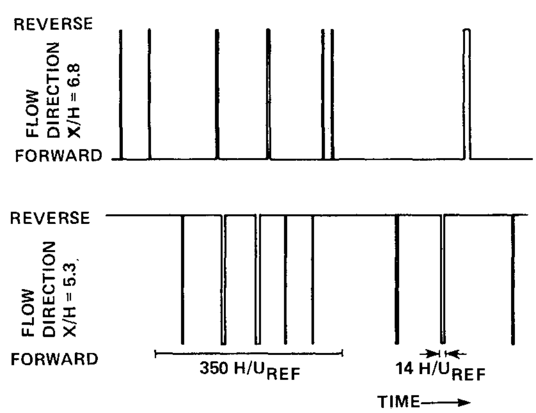

Fig. 3 Simultaneous records of instantaneous near-wall flow direction at two points in the reattachment zone.

diameter. Spacing was 1.8 mm and the wires were 3.0 mm long. The resistances of the two sensor wires were compared in a bridge circuit to determine which of the two wires was the hotter; the bridge circuit was balanced before the heater wire was turned on. A positive bridge voltage indicated flow in the downstream direction; a negative voltage indicated flow in the upstream direction. The frequency response of the tuft probe is limited by time of flight of the heated wake.[15] The turbulence velocities in the reattachment zone were, on the average, 6 m/s. This implies a cutoff frequency of 1000 Hz. Therefore the tuft probe does not sense the instantaneous flow direction, but rather it senses a short-time-averaged flow direction. For the purpose of the present paper, this short-time-averaged flow direction will be called instantaneous. Long-time-averaging the signal was used to determine the intermittency (percentage of time the flow direction was downstream). A probe was repositioned along the floor of the tunnel to locate the reattachment point as determined by 50% intermittency.

Measurements of mean velocities, Reynolds stresses, and turbulent triple-products were obtained with a two-color laser-Doppler velocimeter (LDV) described in Ref. 14. The 0.488- and 0.5145-μm-wavelength beams of an argon-ion laser were used to produce two LDV fringe patterns with spacings of 4.48 and 4.57 μm. The measuring volume was estimated to be less than 0.3 mm in diameter and 1.0 mm long in the spanwise direction. Each of the two pairs of beams had one beam Bragg-shifted by 40 MHz to eliminate ambiguity of flow direction. The two channels of LDV were operated simultaneously with beams aligned at +45 and −45 deg to the axis of the tunnel for measurements of $U+V$ and $U-V$ components of velocity. Forward-scattered light from particles passing through the measuring volume was detected by photomultiplier tubes. The signals from the photomultiplier tubes were processed in counters which performed five to eight period tests of the signal periodicity and digitized the period with 0.1-ns resolution.

Simultaneous measurements of $U+V$ and $U-V$ velocity components along with flow direction from the two thermal tufts (one situated 0.75H upstream of the mean reattachment line and the other 0.75H downstream) were performed. Uniformly sized light scattering particles (0.5-μm polystyrene spheres) were introduced into the plenum chamber of the tunnel. At each measurement station, more than 10,000 particles were observed and recorded at a rate that varied from 50 samples/s in the separated zone to 2000 samples/s at the outer edge of the boundary layer. The seed distribution was nearly uniform, and the variation in sample rate was due to variation in local convective velocities through the flow.

Thermal-tuft probes placed on either side of the average reattachment line detected one of the following conditions for the instantaneous reattachment:

$$X_r < \bar{X}_r - 0.75H! \text{ short}$$

$$\bar{X}_r - 0.75H < X_r < \bar{X}_r + 0.75H! \text{ intermediate}$$

$$\bar{X}_r + 0.75H < X_r \text{ ! long}$$

The LDV measurements were sorted into these categories. The tuft probes actually output a short-time average of the flow direction, but for the purpose of this paper it will be termed instantaneous. Each of the three categories of LDV measurements was ensemble-averaged to obtain mean velocities and Reynolds stresses. Streamlines were determined for each of the three cases. Uncertainties (with 95% confidence level) in the mean velocity were ±4% of the freestream value, and in the Reynolds shear-stress ±15% of the local value.

Instantaneous surface pressure was sensed by a 0- to 13.6-kN/m^2 (0–2.0 psid) differential pressure transducer (3-mm-diam diaphragm) flush-mounted in the floor of the wind tunnel. The sensitivity of the transducer was ±0.1% of full scale and its frequency response was rated at 45 kHz. Actually, spatial resolution of the transducer is more of a limitation; the 3-mm-diaphragm (0.26*H*) senses the average pressure over that area, making it unlikely to detect any frequencies above 1500 Hz.

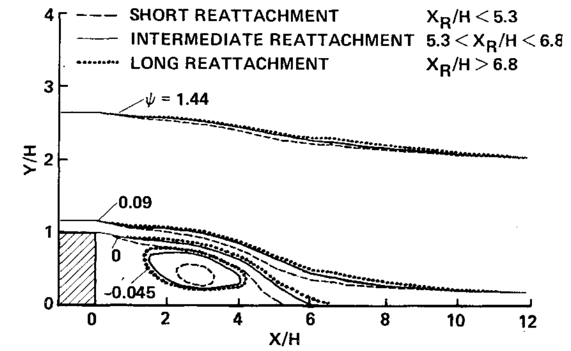

Fig. 4 Streamlines during periods when reattachment is less than 5.3 *H* (---); between 5.3 and 6.8 *H* (——); greater than 6.8 *H* (···).

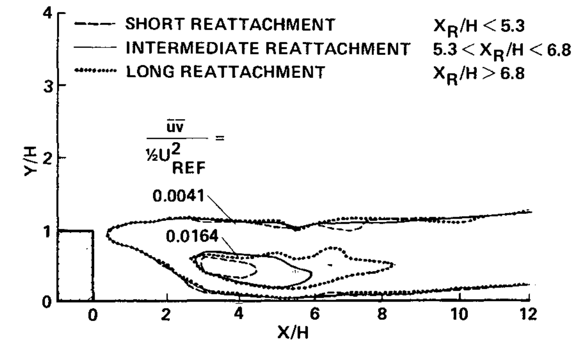

Fig. 5 Contours of constant Reynolds shear stress during periods when reattachment is less than 5.3*H* (---); between 5.3 and 6.8 *H* (——); and greater than 6.8 *H* (···).

Results and Discussion

In the reattachment zone, the flow continually changes direction. A thermal tuft was used to measure the fraction of the time that the flow was moving downstream (sometimes called the intermittency). Figure 2 shows the distribution of intermittency along the wall. Measurements repeated with a different probe and with probes reversed agreed very well. Also shown is the location of zero-average skin friction as deduced by the oil-flow laser interferometer measurements of skin friction reported in Ref. 12. The 50%-intermittency location measured by the thermal tuft probe coincides with the location of zero-average skin friction to within the accuracy of the measurements. Flow near the wall is seen to be intermittently changing directions over a range of ±1.0 step heights from the mean reattachment point. At a location 0.75*H* upstream of the 50% intermittency point, the intermittency is approximately 8%. And at a location 0.75*H* downstream of the 50% intermittency point the intermittency is approximately 93%. Thermal tuft probes were used at these points to provide a signal on which to trigger the LDV measurements.

The time record of two thermal-tuft probes which were straddling reattachment is shown in Fig. 3. The top trace is the downstream probe; spikes in this trace are an indication that the flow is moving upstream, and reattachment is abnormally long. The bottom trace is the upstream probe; valleys in this trace are an indication that the flow is moving downstream at this point, and reattachment is abnormally short. Flow reversals appear to occur randomly, with times between flow reversals ranging from 50–300 H/U_{ref}. This time is long compared to the relatively short lifespan of the reversals ($14H/U_{ref}$).

Mean flow streamlines were determined for each of three conditions using stream function and conditionally averaged velocity measurements. See Fig. 4. The entire separation bubble is enlarged with abnormally long reattachment, and is contracted with short reattachment. The streamline patterns are an indication of a globally organized phenomenon which correlates with reattachment location. The spatial coherence of this phenomenon extends upstream to separation and several step heights downstream of reattachment; this is a scale of motion bigger than the largest eddy (largest eddy about the size of the step). The shear layer appears to be "flapping," and for lack of a better word will be termed flapping throughout the paper. The amplitude of the flapping motion is estimated to be less than 20% of the shear layer width b. The oval-shaped streamline in the separation bubble traces out a path along which an average particle would travel. The area enclosed by the oval-shaped streamlines is an indication of the recirculation mass-flow rate. In the case of shortened reattachment, the area is smaller, which means that the recirculating mass-flow rate is substantially less than that of the other two cases.

Ensemble-averaged Reynolds shear stress for each of three conditions is shown in Fig. 5. High levels of shear are sustained further downstream for the longer reattachment case than for the intermediate reattachment case. The higher levels of shear downstream are produced by instantaneously steeper velocity gradient due to the increased extent of the separation bubble. One might argue from a more physical standpoint that, owing to a longer shear layer, the large turbulent or vortical structure or both are carried further downstream before being damped or destroyed by collision with the wall. Conversely, the level of shear for the shorter reattachment condition is drastically reduced downstream in comparison to the shear during the intermediate reattachment condition.

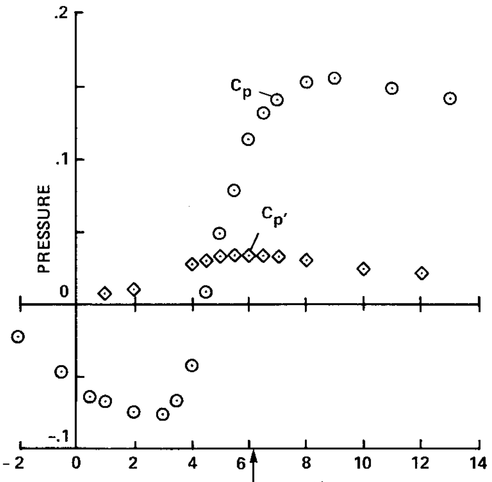

Fig. 6 Surface pressure distribution along stepside wall time average ⊙; root mean square of the fluctuations ◇.

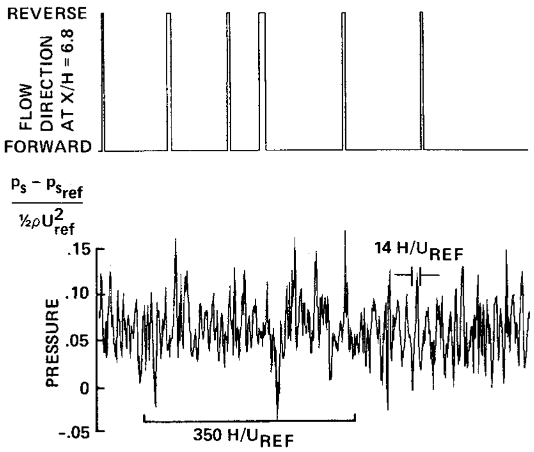

Fig. 7 Simultaneous time records of a tuft at X/H = 6.8 and a pressure sensor at X/H = 5.5.

It is interesting to note that the measurements of mean velocities and Reynolds stresses in the intermediate reattachment condition were not significantly different from unconditional sampled measurements using long-time averages. This is perhaps surprising, since it might be expected that the flapping motion would contaminate the turbulence measurements. Evidently, there is little apparent shear stress produced by the flapping motion. This implies that fluctuating motions other than flapping, is responsible for most of the Reynolds stress. This also implies that the previous analysis using long-time averages of Ref. 12 are not contaminated by the effects of globally coherent motion being studied here.

To estimate the frequencies invlolved in flapping, a pressure transducer was flush mounted in the wall near the midpoint of the steep pressure rise associated with reattachment (see Fig. 6). Associated with separation is a relatively high level of pressure fluctuations also seen in Fig. 6 (high, relative to attached boundary layers where $C_{p'} \simeq 0.005$). Figure 7 shows a time history of instantaneous wall static pressure (at $X=5.5H$) as well as instantaneous flow direction (at $X=6.8H$) as sensed by a thermal tuft. The time history of pressure shows large fluctuations which occur somewhat periodically (time duration $\sim 14H/U_{ref}$). This time scale is comparable to that of spanwise vortical structures seen in free shear layers ($St=0.2$). Flow direction and pressure appear to be uncorrelated, and indeed the ensemble-averaged pressure during extraordinarily long reattachment was only slightly lower than the pressure using a long-time average.

This short lifespan is comparable to the time scale of spanwise vortical structures seen in free shear layers given by a Strouhal number of 0.2. Pronchick and Kline[7] visualized vortical structures in their backstep flow similar to those studied by Winant and Broward[8] in free shear layers. In free shear layers, the passage of vortical structures produces periodic velocity fluctuations at frequencies that scale with the shear-layer average velocity and shear-layer thickness ($fb/U_{sl}=0.2$).

Spectral analysis of the pressure is shown in Fig. 8. The function $F(n)$ represents the fraction of the total mean-square pressure fluctuations in a band width $\Delta n = 0.01$;

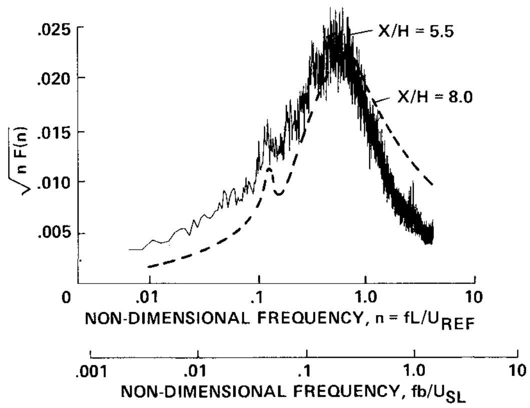

Fig. 8 Energy spectra of surface static pressure at X/H = 5.5 and X/H=8.

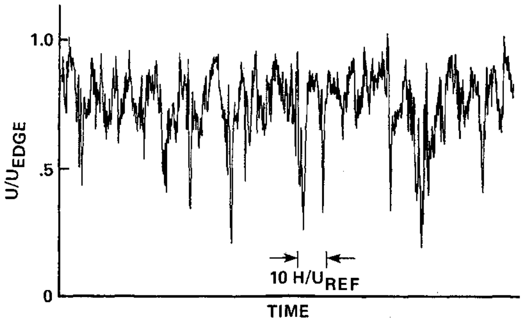

Fig. 9 Time-history of streamwise velocity fluctuations at $X/H = 6$, $Y/H = 1$.

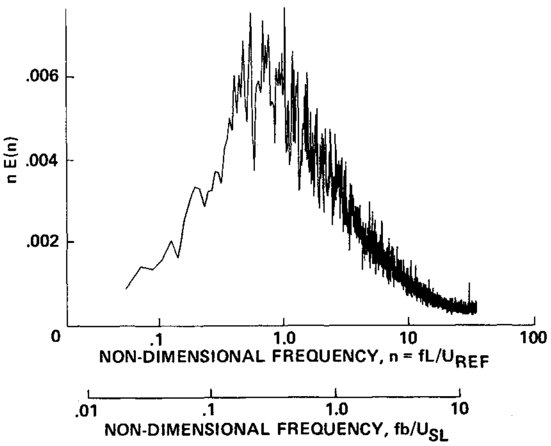

Fig. 10 Energy spectra of streamwise velocity measurements by a hot-wire at $X/H = 6$, $Y/H = 1$.

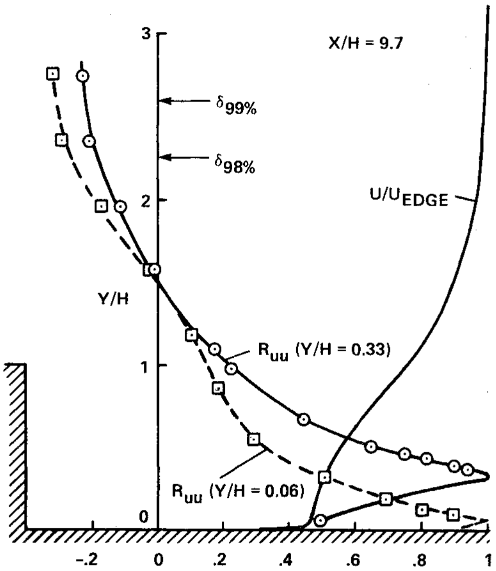

Fig. 11 Two-point velocity correlations and streamwise velocity profile at $X/H = 9.7$.

$nF(n)$ is plotted against the normalized frequency n, suggested by Mabey.[6] The reason for plotting it this way can be seen when the variable of integration is transformed as follows:

$$\langle p^2 \rangle = \int_0^\infty F(n)\mathrm{d}n = \int_{-\infty}^{\infty} nF(n)\mathrm{d}[\log(n)]$$

Also labeled on the abscissa is a nondimensionalized frequency based on the shear-layer width and the mean velocity at the centerline. The maximum contribution to the energy comes at the nondimensional frequency $n = 0.6$, which agrees with Mabey's earlier findings. Furthermore, this is the characteristic frequency of vortical structures seen in free shear layers.[8] $fb/U_{sl} = 0.2$. In addition to the dominant frequency, there is a weak local maxima at the low frequency $fb/U_{sl} = 0.06$. This low frequency is possibly due to the apparent flapping motion seen in the streamlines. Compared to the peak at $fb/U_{sl} = 0.2$, the local maximum is quite weak and insignificant, making it difficult to distinguish flapping motion from vortical motion. The energy spectra of surface pressure for location $X = 8H$ (also shown in Fig. 8) indicates that energy in the low frequencies has dropped relative to $X = 5.5H$, perhaps indicating that flapping motion is less energetic at this point. However, the peak in the spectra at $fb/U_{sl} = 0.2$ continues to persist, perhaps indicating that some vortical structure still exists.

Figure 9 shows a time-history of streamwise velocity (measured with a hot-wire) at $X/H = 6$ and $Y/H = 1$. The velocity trace demonstrates the existance of large events in the flow. Large velocity excursions can be seen which occur fairly periodically with frequency $fb/U_{sl} = 0.2$. Indeed, transforming this signal to Fourier wave space (see Fig. 10) shows that most of the energy resides at the nondimensional frequency $n = 0.6$ ($St = 0.2$). This is further indirect evidence that there is vortical structure in the step flow.

If one looks at two-point velocity correlations (using hot-wires), one becomes more convinced of a vortical type motion in the flow. At a location $X = 9.7H$ (downstream of reattachment), two-point correlations centered around $Y/H = 0.06$ and $Y/H = 0.33$ (see Fig. 11) show a sizable negative correlation in the outer flow. This indicates that streamwise velocity fluctuations near the wall correlate negatively with velocity fluctuations in the outer part of the boundary layer, which is characteristic of clockwise rotating vortex flow.

Conclusions

Two types of fluctuating motion were identified in a rearward facing step flow: 1) a random flapping of the shear layer and 2) a somewhat periodic vortical type motion.

Streamlines of the flowfield demonstrate a global motion of the shear layer (flapping) which correlates with large changes in the reattachment zone. The amplitude of this flapping motion appears to be less than 20% of the thickness of the shear layer. There is a reduction in the reverse-flow rate with abnormally short reattachment of the shear layer.

Shear stress in the flow is seen to increase dramatically with long reattachment. This can be attributed to the coherent structures in the shear layer carrying further downstream before crashing against the wall and breaking into smaller scales. Apparently there is relatively little energy attributed to the flapping motion but it does seem to displace the shear layer from its long-time average position.

Both surface pressure and velocity measurements show that there are low-frequency disturbances in the flow, but they are random and contribute little to the total energy. These frequencies are believed to be caused by a flapping motion of the shear layer. Although the energy spectra of pressure show very low frequencies, the dominant frequency is at a Strouhal number of 0.2. This is a frequency characteristic of spanwise vortical structures as seen in free shear layers. These spectral measurements and two-point correlation measurements along with Pronchick's flow visualizations,[7] strongly suggest that vortical type structure exists in step flows, even at relatively high Reynolds numbers such as in this experiment.

One possible scenario explaining the flapping phenomenon is that it results from momentary disorder of the shear layer that alters the rate of reverse flow. This case might arise when a vortical structure carrying more forward momentum than its neighbors is able to escape the reattachment zone without much of its mass getting engulfed by the separation bubble. This reduced reverse-flow causes the bubble to collapse momentarily. Curvature of the shear layer is thus increased, causing an increased angle of impingement of the shear layer and a larger pressure gradient at reattachment. This larger pressure gradient serves to retard more of the low-velocity fluid, thus reinflating the bubble.

While the flapping nature of this flow is interesting, it is of relatively low energy and can probably be ignored for step flows. However, flapping may be a significant influence on the separation process in flows where separation is sensitive to small disturbances. More important to the question of turbulence modeling is how to represent the effect of the vortical structures. A time-dependent solution which solves for these large-scale motions may have more success in solving this relatively unpredictable class of flows.

The coherence of spanwise vortical structure at extremely high Reynolds numbers (typical of separating flow behind airfoils) is worth further investigation. It seems likely most separating flows, whether initiated by leading edge separation from an airfoil, stall in a diffuser or flow over a cavity, will exhibit the same vortical behavior as seen in the rearward facing step flow. The success or failure of flow simulations involving separation may be linked to the ability to model (or calculate) this vortical behavior.

Acknowledgments

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References

[1]Eaton, J. and Johnston, J., "Low Frequency Unsteadiness of a Reattaching Turbulent Shear Layer," *Proceedings of the Third International Symposium on Turbulent Shear Flows*, Davis, CA, Sept. 1981.

[2]Goldschmidt, V. and Bradshaw, P., "Flapping of a Plane Jet," *Physics of Fluids*, Vol. 16, No. 3, March 1973, pp. 354–355.

[3]de Gortari, J. and Goldschmidt, V., "The Apparent Flapping Motion of a Turbulent Plane Jet—Further Experimental Results," ASME Winter Annual Meeting, Chicago, IL, Nov. 1980.

[4]Rockwell, D. and Knisely, C., "Vortex-Edge Interaction: Mechanisms for Generating Low Frequency Components," *Physics of Fluids*, Vol. 23, Feb. 1980, pp. 239–240.

[5]Rockwell, D. and Naudascher, E., "Self-Sustained Oscillations of Impinging Free Shear Layers," *Annual Review of Fluid Mechanics*, Vol. 11, Mar. 1979, pp. 67–94.

[6]Mabey, D., "Analysis and Correlation of Data on Pressure Fluctuations in Separated Flow," *Journal of Aircraft*, Vol. 9, Sept. 1972, pp. 642–645.

[7]Pronchick, S. and Kline, S., "An Experimental Investigation of the Structure of a Turbulent Reattaching Flow Behind a Backward-Facing Step," Stanford University, Mechanical Engineering Dept., Rept, MD-42, 1983.

[8]Winant, C. and Browand, F., "Vortex Pairing: The Mechanism of Turbulent Mixing-Layer Growth at Moderate Reynolds Numbers," *Journal of Fluid Mechanics*, Vol. 63, Pt. 2, 1974, pp. 237–255.

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

[10]McGuinness, M., "Flow With a Separation Bubble—Steady and Unsteady Aspects," Ph.D. Dissertation, Cambridge University, London, England, 1978.

[11]Roos, F. and Kegelman, J., "Influence of Excitation on Coherent Structures in Reattaching Turbulent Shear Layers," AIAA Paper 86-0112, Jan. 1986.

[12]Driver, D.M. and Seegmiller, H.L., "Features of a Reattaching Turbulent Shear Layer in Divergent Channel Flow," *AIAA Journal*, Vol. 23, Feb. 1985, pp. 163–171.

[13]Eaton, J., Jeans, A., Ashjaee, J., and Johnston, J., "A Wall-Flow Direction Probe for Use in Separating and Reattaching Flows," *Journal of Fluids Engineering*, Vol. 101, 1979, pp. 364–366.

[14]Seegmiller, H.L., Marvin, J., Harrison, D., and Kojima, G., "Applications of Laser Velocimetry to an Unsteady Transonic Flow," International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF'79 Record, Sept. 1979, pp. 284–293.

[15]Eaton, J., Westphal, R., and Johnston, J., "Two New Instruments for Flow Direction and Skin-Friction Measurements in Separated Flows," *ISA Transactions*, Vol. 21, No. 1, 1982, pp. 69–78.