EFFECT OF FREE-STREAM TURBULENCE ON TURBULENT PROPERTIES OF A SEPARATION-REATTACHMENT FLOW*

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Studied in this paper is the effect of free-stream turbulence on the turbulent structure of a separation bubble formed at the leading edge of a blunt plate with right-angled corners. The free-stream turbulence was introduced by a thin circular rod placed upstream of the plate along its stagnation streamline. This paper is a sequel to the authors' previous papers (Kiya & Sasaki 1983, Kiya et al. 1984) in which time-averaged properties of the separation bubble are given in terms of the turbulence intensity at a reference point near an edge of the plate. The longitudinal and spanwise integral length scales of vortices in the separation bubble were given as functions of the free-stream turbulence intensity. The cross correlations between the surface-pressure and velocity fluctuations suggested that large-scale vortices are similar in shape independently of the free-stream turbulence intensity. Moreover, the maximum r.m.s. surface pressure was found to be estimated in terms of the longitudinal gradient of the time-mean surface-pressure profile and the longitudinal length scale of vortices in the reattaching zone.

Key Words : Turbulence, Separation bubble, Free-Stream Turbulence, Blunt Plate, Cross Correlation, Pressure Fluctuation, Turbulent Wake

1. Introduction

This paper describes an experimental study on the effect of the free-stream turbulence on a separation-reattachment flow (i.e. a separation bubble). Changes in time-mean and fluctuating surface pressures are of practical significance in estimating unsteady forces experienced by partially-separated cascade wings, surface load of buildings and structures during strong winds, etc.

We consider a separation bubble formed at the leading edge of a blunt flat plate with right-angled corners. The plate is aligned in such a manner that the sides are parallel to the approaching flow. Some important features of the free-stream turbulence effects on this separation bubble were studied by Hillier & Cherry⁽¹⁾, Kiya & Sasaki⁽²⁾ and Kiya et al.⁽³⁾ The present paper supplements these works by providing further experimental information, especially the nature of unsteady flow in the reattaching zone. The plate is long enough for the interaction between separated shear layers emanating from both edges to be prohibited. Accordingly attention can be confined to one of two separation bubbles. Effects of periodic vortex shedding is suspected to be included in the results of Robertson et al.⁽⁴⁾ and Wedding et al.⁽⁵⁾; these authors studied a separation bubble

along a side of a square cylinder with a non-zero angle of attack.

In the present study, the free-stream turbulence was introduced by a thin circular rod placed at a distance upstream of the plate along its stagnation streamline. The turbulent wake of a rod is a convenient means to introduce a free-stream (i.e. external) turbulence (Gartshore⁽⁶⁾). It is shown in Kiya & Sasaki⁽²⁾ and Kiya et al.⁽³⁾ that various characteristic parameters (such as the bubble length, the width of the reattaching zone, characteristic lengths of the time-mean pressure profile, the maximum pressure difference in the bubble, etc.) are well correlated with the turbulence intensity just outside the separated shear layer near the edge. This position at which the free-stream turbulence property was measured is referred to as the reference position; the turbulence at the reference position will be called as the reference turbulence.

The present paper demonstrates, in terms of the free-stream turbulence, the unsteady nature of flow in the separation bubble associated with the motion of large-scale vortices and properties of the surface-pressure fluctuations.

2. Experimental apparatus and method

Experimental apparatus and procedure were the same as those in the previous experiments^{(2),(3)}, so that they will be described only briefly. Experiments were performed in an open-return, low-speed air tunnel with a 40 cm high, 20 cm wide and 1 m long test section. The turbulence level in the empty test section was 0.3% at

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the speed of 20 m/s. The blunt plate tested was 2 cm thick, 20 cm wide and 50 cm long. The plate spanned the test section horizontally along the centreline, thus having an aspect ratio of 10. A number of pressure taps were fitted along the other side of the plate at the midspan position.

The tunnel wall blockage which originally amounted to 5% was corrected by fitting false boundaries along the ceiling and floor of the test section. The false boundaries were curved according to the blockage-free streamline, flared by an amount equal to the displacement thickness of the boundary layer along the tunnel walls, and smoothly joined to the bell entrance of the test section. Circular rods of diameter 1.1 mm - 5.0 mm were placed separately at various distances upstream of the front face of the plate along the stagnation streamline. The rods spanned the test section horizontally.

The fluctuating velocities were measured by constant-temperature hot-wire anemometers using an I-probe. A split-film probe⁽⁹⁾ was used to measure the reverse-flow intermittency in the reattaching zone. The pressure fluctuations on the plate surface were detected by a semi-conductor strain-gauged transducer mounted flush with the side of the plate. The gain factor was 1.0 ± 0.1 up to 450 Hz with a negligibly small phase shift. The velocity and pressure fluctuations were recorded on two or three channels of an analogue data recorder and later analyzed on a digital signal processor to obtain the cross correlations and the power spectra. No sensible phase lag existed between the outputs of the hot-wire anemometers and between the outputs of the hot-wires and the pressure transducer.

The Reynolds number $U_0(2H)/\nu$ was 2.6×10^4 throughout the present experiment. Here U_0 is the approaching velocity, H is the half thickness of the plate and ν denotes the kinematic viscosity of fluid.

Flow visualization was also made using a recirculating open water channel with a 25 cm high, 20 cm wide and 86 cm long test section. The turbulence intensity at the centre of the empty test section was 0.5%. A test plate was 9.7 mm thick, 25 cm wide and 48 cm long; this was set vertically along the centreline of the test section. The depth of water in the test section was 20 cm during the experiment, so that the aspect ratio of the test plate was 20. Moreover, the blockage ratio amounted to 5%; this degree of blockage probably had only a negligible influence on the structure of flow in the separation bubble.

The visualization of flow was made by a hydrogen-bubble technique; a platinum wire of 50 μ m diameter was attached to the side of the plate, parallel to and 0.3 mm downstream of the edge. Hydrogen bubbles generated from the wire were entrained into the separated shear layer to visualize the vortex structure in a plane parallel to the surface of the plate. The effect of buoyancy was insignificant. Reynolds number of the flow-visualization experiment was 855. Although this was approximately an order of magnitude smaller than that of the wind-tunnel experiment, the free-stream turbu-

lence effect on large-scale structure in the separation bubble can probably be inferred from this result. The free-stream turbulence was introduced in the same manner as in the wind-tunnel experiment.

3. Results and discussion

The definition sketch of symbols and the co-ordinate system is depicted in Fig. 1. U_0 and P_0 are the velocity and pressure, respectively, of the approaching stream. The X-axis is taken in the longitudinal direction along the side of the plate, the Y-axis vertically outwards from the surface and the Z-axis normal to the X- and Y-axes, the origin being at the edge of the plate. The fluctuating velocity components in the X and Y directions are denoted by u' and v' ; the velocity fluctuation (measured by an I-probe) at the reference position ($X/H = 0$, $Y/H = 0.1$) is written as q' , which can be interpreted as the fluctuation of the absolute velocity in the X, Y plane. Moreover, p' is the surface-pressure fluctuation. The diameter of the turbulence-producing rod is d and the distance between the centre of the rod and the front face of the plate is denoted by l . In the following presentation of the experimental results, those obtained without the turbulence-producing rod will be referred to as 'undisturbed'. The results will mostly be presented for the minimum (i.e. the undisturbed case), medium and maximum intensity of the reference turbulence.

3.1 Properties of reference turbulence

Properties of the reference turbulence are shown in detail in Kiya & Sasaki⁽²⁾, so that main results only are summarized in Table 1. In Table 1, L_s and L_{sz} are the longitudinal and spanwise integral length scales, respectively, of the reference turbulence. Moreover, X_R is the time-mean bubble length and L_R denotes the longitudinal integral length scale of the large-

d mm	l mm	$\sqrt{q'^2}/U_0$	L_s/H	L_{sz}/H	L_R/H	X_R/H
5.0	100	0.069	0.64	0.60	0.547	2.9
3.0	180	0.037	1.37	1.01	0.725	5.9
UNDISTURBED		0.012	6.30	1.59	1.01	9.5

Table 1 Turbulence properties at reference position near separation edge.

Fig. 1 Configuration of flow and definition of symbols and co-ordinate system.

scale vortices above the time-mean reattachment point.

3.2 Properties of separated-reattaching shear layer

A locus of the maximum turbulence intensity can be interpreted as a nominal centre of the separated shear layer. Figure 2 compares the loci for the three intensities of the free-stream turbulence. The loci more and more approach the surface as the turbulence intensity is increased. This is consistent with previous observations (Gartshore⁽⁶⁾, among others). This approach is probably caused by an enhanced rate of entrainment of the shear layer due to the free-stream turbulence.

Figure 3 shows visualized flow patterns of vortices in the X, Z plane; Fig. 3a is for the undisturbed case while Fig. 3b is for the maximum turbulence intensity. Vortices in Fig. 3b are highly three-dimen-

Fig. 2 Changes in centreline of separated shear layer with free-stream turbulence intensity. For reference-turbulence property, see Table 1.

Fig. 3 Flow pattern in X, Y plane visualized by hydrogen bubbles. Reynolds number $U_0(2H)/\nu = 855$. Note enhanced rolling up near the edge and large three-dimensionality in (b).

sional; that is, the free-stream turbulence destroys the spanwise coherency of the rolling-up vortices. The three-dimensionality appears immediately from the edge of the plate. This suggests that the separated shear layer is most sensitive to the free-stream turbulence at an early stage of its formation, i.e. in the region of transition from laminar to turbulent flow. The longitudinal scale of the rolled-up vortices shortly downstream of the edge is seen to be greater in Fig. 3b (for the maximum turbulence) than in Fig. 3a (for the undisturbed case). It is possible that the spanwise non-uniformity of the flow pattern near the edge is scaled to the spanwise length scale L_{sz} (see Table 1) of the reference turbulence.

The large-scale vortices are shed downstream from the reattaching zone of the separation bubble⁽⁷⁾. The longitudinal length scale L_R of such vortices was

Fig. 4 Longitudinal integral length scale L_R of vortices above time-mean reattachment point divided by the bubble length X_R as a function of reference turbulence.

Fig. 5 Cross correlation coefficient of longitudinal velocity fluctuations at two points separated in spanwise direction. Velocity fluctuations were detected at centre of shear layer above time-mean reattachment point.

obtained at the centre of the shear layer above the time-mean reattachment point. Results are presented in Fig. 4 in the form of L_R/X_R plotted against the reference turbulence intensity. It is well established that the bubble length X_R decreases monotonically with increasing turbulence intensity⁽²⁾⁽³⁾. On the other hand, as seen in Fig. 4, the ratio L_R/X_R increases with increasing turbulence intensity. This suggests that the scale of the rolled-up vortices (i.e. the thickness of the shear layer) grows faster when the free-stream turbulence of sufficient intensity is present than when it is absent or sufficiently low. Such increase in the scale of the vortices is consistent with the visualized flow pattern of Fig. 3.

Figure 5 shows the cross correlation coefficient $R_{u,u'}$ of the longitudinal velocity fluctuations at two points separated by ΔZ in the spanwise direction. The velocities were detected at the centre of the shear layer above the time-mean reattachment point. The spanwise separation is normalized by L_R in Fig. 5. The correlation coefficient collapses onto a single curve, thus suggesting that the shape of the large-scale vortices in the reattaching zone remains similar for different turbulence intensities. The ratio of the spanwise length scale to the longitudinal length scale is approximately 0.6.

3.3 Surface-pressure fluctuation

The r.m.s. surface-pressure fluctuation divided by the free-stream dynamic pressure $P_{d\infty} (=0.5\rho U_0^2, \rho = \text{the density of fluid})$ is shown in Fig. 6 plotted against the longitudinal distance X/H . The r.m.s. pressure attains a maximum shortly upstream of the time-mean reattachment point, as also demonstrated by Wedding et al.⁽⁵⁾ and Hillier & Cherry⁽⁵⁾. It is worth mentioning that the maximum value is higher for higher intensity of the free-stream turbulence. This is of practical significance because the time-mean pressure also

Fig. 6 R.m.s. value of surface-pressure fluctuation plotted against longitudinal distance. Vertical arrows show location of time-mean reattachment point.

attains a lower minimum for higher turbulence intensity, so that the instantaneous pressure can become significantly low for high turbulence. This extremely low pressure exerts a high local surface load on buildings and structures during strong winds.

Figure 7 shows the power spectra of the surface-pressure fluctuation near the time-mean reattachment point. As the turbulence intensity increases, the energy decreases in the low-frequency range while it increases in the high-frequency range. This feature suggests that smaller and smaller vortices prevail in the reattaching zone as the turbulence intensity is increased. Such decrease in the vortex scale is well demonstrated by the integral time scale T_p of the surface-pressure fluctuation, see Fig. 8. An extremely large time scale is associated with the low-frequency, large-scale unsteadiness in the separation bubble⁽⁸⁾. This unsteadiness accompanies a bodily oscillation of the

Fig. 7 Power spectra of surface-pressure fluctuations near time-mean reattachment point.

Fig. 8 Integral time scale of surface-pressure fluctuations plotted against longitudinal distance.

shear layer in the first half of the separation bubble. The oscillation of the shear layer produces a low-frequency (i.e. long-period) component of the surface-pressure fluctuations.

The spectrum peak at $fH/U_0 \approx 0.6$, f being the frequency, for the undisturbed case is associated with the shedding of the large-scale vortices from the reattaching zone. The peak is seen to become more and more obscure as the turbulence intensity increases; this indicates that the large-scale vortices are more and more randomized.

Figure 9 shows the skewness $S_k(p')$ of the surface pressure fluctuation as a function of the longitudinal distance. The skewness becomes positive in the reattaching zone (see Fig. 5 of Kiya et al.⁽³⁾) which is represented by a hatched area in Fig. 9. Positive skewness indicates that the time history of the pressure is positively spiky; the positive spikes are probably produced by the inrush of outer irrotational fluid of high total pressure towards the surface. The inrush is brought about by the large-scale vortices in the reattaching zone.

3.4 Relation between velocity and surface-pressure fluctuations

In this section, the reverse-flow intermittency and the velocity fluctuations are related to the pressure fluctuation p'_R near the time-mean reattachment point. Figure 10 shows the longitudinal distribution of the reverse-flow intermittency $\langle I_r \rangle$ averaged over the time during which p'_R is negative or positive; $X_{0.5}$ implies a position where the overall reverse-flow intermittency I_r attains to 0.5, coinciding with X_R (Kiya et al.⁽³⁾). The measurement of $\langle I_r \rangle$ was made by a split-film probe set at a height 0.5 mm above the surface. The result of Fig. 10 demonstrates that the

Fig. 9 Skewness of surface-pressure fluctuations plotted against longitudinal distance. Hatched areas show longitudinal extent of reattaching zone.

separation bubble shrinks when $p'_R > 0$ while it enlarges when $p'_R < 0$. Moreover, the data for three different intensities of the free-stream turbulence collapse onto a single curve if the longitudinal distance is normalized by the integral length scale L_R . This suggests a similarity of the motion of the reverse-flow region in the reattaching zone.

Figure 10 suggests that the pressure fluctuation near the reattachment point is produced by the oscillatory motion of the reattachment point. We assume that the motion of the reattachment point is accompanied by the longitudinal motion of the time-mean surface pressure profile whose shape is unchanged during the motion, see Fig. 11. This quasi-steady approach can give an estimate of the maximum r.m.s. surface pressure. The time-mean pressure profile has a point of inflexion near the reattachment point, so that an observer fixed near this point records the following amplitude of the pressure fluctuation;

Fig. 10 Longitudinal distribution of reverse-flow intermittency near plate surface separately averaged for positive and negative surface-pressure fluctuations.

Fig. 11 Quasi-steady model of surface-pressure fluctuation near time-mean reattachment point. Thick solid curve shows profile of time-mean surface-pressure coefficient.

$$\Delta C_p \approx \frac{\partial C_p}{\partial (X/H)} \frac{\Delta X_R}{H}, \quad (1)$$

where ΔC_p is the amplitude of the pressure fluctuation divide by $P_{d\infty}$, C_p the time-mean pressure divided by $P_{d\infty}$ and ΔX_R denotes the width of the reattaching zone, which is approximately equal to $4L_R$ (Kiya et al.⁽³⁾). The width ΔX_R is a measure of the distance of travel of the reattachment point. Accordingly, the maximum r.m.s. value of the surface pressure divided by $P_{d\infty}$ can be written as

$$(\overline{C_p'^2})_{\max}^{\frac{1}{2}} = \alpha [\partial C_p / \partial (X/H)]_{\max} (L_R/H), \quad (2)$$

where α is a numerical factor. The value of α was found to be fairly constant 1.35 ± 0.12 for nine intensities of the free-stream turbulence tested in this experiment. Wedding et al.'s⁽⁵⁾ result also yielded a value of α in the above range.

The cross correlation $R_{p'u}$ between the surface-pressure fluctuation at a fixed position near the time-mean reattachment point and the velocity fluctuations in the reattaching zone was measured at many points in the X, Y plane. The result is presented in Fig. 12 in terms of constant-correlation curves; Fig. 12a is for the undisturbed case while Fig. 12b is for the highest turbulence. The constant-correlation curves are generally inclined towards the plate in such a manner that the downstream side is nearer to the surface. Accordingly, an axis of the large-scale vortices in the reattaching zone is speculated to have a similar inclination. Moreover, it should be noted that the constant correlation curves, and thus the shape of the large-scale vortices, are generally similar in the two cases.

4. Conclusion

In the present paper, the effect of the free-stream turbulence has been described experimentally on the turbulence properties in the separation-reattachment flow formed at the leading edge of an aligned blunt plate with right-angled corners. The free-stream turbulence was introduced by inserting a thin circular rod at various distances upstream of the front face of the plate along the stagnation streamline. The main results can be summarized as follows.

(1) The longitudinal and spanwise integral length scales of the large-scale vortices in the reattaching zone decrease with increasing intensity of the free-stream turbulence. The spanwise scale is approximately 0.6 times the longitudinal scale independently of the free-stream turbulence intensity.

(2) The free-stream turbulence promotes the rolling up of the separated shear layer, thus producing larger and larger vortices near the separation point as the turbulence intensity increases. The large vortices enhance the entrainment rate of the shear layer to reduce the length of the

separation-reattachment flow.

(3) The r.m.s. value of the surface pressure attains a maximum shortly upstream of the time-mean reattachment point; the maximum r.m.s. value increases with increasing intensity of the free-stream turbulence.

(4) The contribution to the r.m.s. surface pressure decreases in the low-frequency range and increases in the high-frequency range as the free-stream turbulence intensity increases.

(5) The separation bubble experiences the enlargement and shrinkage, which are respectively related to negative and positive pressure fluctuations near the time-mean reattachment point. This is also the case when the free-stream turbulence is present. The extent of the enlargement and shrinkage is a constant multiple of the longitudinal integral length scale of vortices above the time-mean reattachment point.

Fig. 12 Contours of cross correlation between surface-pressure fluctuation near time-mean reattachment point and longitudinal-velocity fluctuations in reattaching zone; (a) for undisturbed case and (b) for highest turbulence intensity.

(6) The maximum r.m.s. surface pressure can be evaluated in terms of the longitudinal gradient of the time-mean pressure profile near the inflexion point and the longitudinal integral length scale of vortices in the reattaching zone.

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