The reason for the occurrence of separation jump with a flat ellipsoid is the same as that for a body of revolution, that is, the interplay between the pressure gradient $\partial p / h_\theta \partial \theta$ and the lateral pressure curvature $\partial^2 p / h_\mu \partial \mu^2 \sim U_\mu^2$. Their effects on the profiles of v and u_μ and hence the skin friction were explained in Ref. 2 and in more detail in Ref. 10. We shall omit such discussion herein.

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Wall Shear Fluctuations in a Turbulent Boundary Layer

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Introduction

IN the last two decades, the instantaneous structure of a turbulent boundary layer has been examined by many in an effort to understand the dynamics of the flow. Distinct and well-defined flow patterns that seem to have great relevance to the turbulence production mechanism have been observed in the wall region.[1,2] The flow near the wall is intermittent with periodic eruptions of the fluid, a phenomenon generally termed "bursting process." Earlier investigations in this field were limited to liquid flows at low speeds and the entire flow pattern was observed using flow visualization techniques. Study was later extended to boundary-layer flows in wind tunnels at higher speeds and Reynolds numbers using hot-wire signals for the analysis of the bursting phenomenon.

Using a selective filtering technique, Rao et al.[3] found that the occurrence rate of the intermittent signals was constant across an entire given boundary layer, with the average time interval T between two consecutive events scaling with the freestream velocity U and the thickness of the boundary layer δ. The value of UT/δ was around 5.0. The time scales obtained from autocorrelation measurements of the fluctuating signals[4,5] have also yielded the same values as those of Rao et al.[3] A further study of the instantaneous hot-wire records by Badri Narayanan et al.[6] indicated that T could also be obtained from the zero crossings of the fluctuating signals. Recent measurements of boundary layers over highly curved walls by Ramaprian and Shivaprasad[8] substantiate the above view.

The fact that the same time scale T has been obtained by different methods scaled with the other variables clearly suggests that large-scale eddy-like structures exist in a boundary layer and that they span the entire thickness of the layer. A number of speculations have been made about the shape of these eddies.[6,7] However, a well-defined picture has yet to emerge.

In the present investigation, the wall shear fluctuations are examined. It is observed that, while the zero crossings do yield the time scale for the large-scale motions, the average period of the overall fluctuations is governed by the wall shear.

Experimental Setup

The experiments were conducted in the turbulent boundary layer formed on the top wall of a low-speed wind tunnel having a 30 cm^2 test section. In the region where the measurements were made, the thickness of the boundary layer was about 25 mm and it remained nearly constant in the freestream velocity range of 5-30 m/s. A thin-film heat-transfer gage (1 mm wide, 2 mm long), operated at constant temperature and an overheat ratio of 1.05, was employed to sense the fluctuating wall shear. The output signals from the system were recorded on a film after filtering frequencies beyond 5000 Hz.

Results and Discussion

The output signals from the thin-film heat-transfer gage were directly analyzed for 1) an average period for the fluctuations T_l and 2) the rate of zero crossings around the

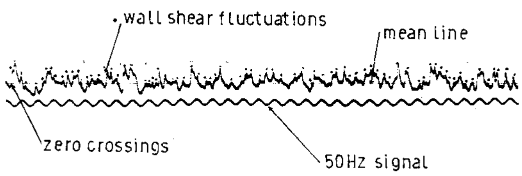

Fig. 1 Sample trace of the wall shear fluctuations (this trace has 78 zero crossings and 90 shear fluctuations).

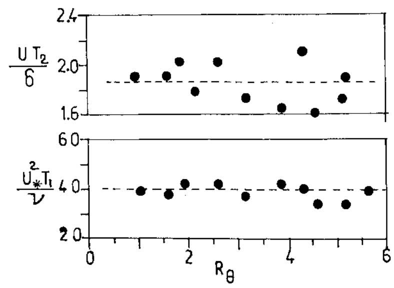

Fig. 2 Scaling of T_l with friction velocity and T_2 with boundary-layer thickness.

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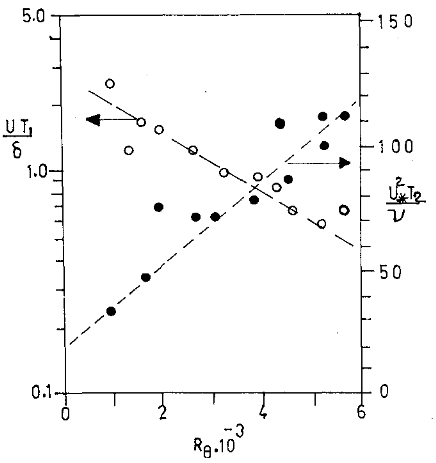

Fig. 3 Variation of UT_1/δ and $U^{*2}T_2/\nu$ with Reynolds number.

mean temperature T_2. A typical trace of the signal is shown in Fig. 1, illustrating the method adopted for identifying the two time scales. For the evaluation of T_1 and T_2, a sufficient length of the trace was used until consistent average values were obtained. Based on these data, the nondimensional parameters (namely, UT_1/δ, UT_2/δ, $U_*^2T_1/\nu$, and $U_*^2T_2$) were calculated and the results are shown in Figs. 2 and 3. It can be observed that the values of UT_2/δ and $U_*^2T_1/\nu$ are nearly constant at 1.9 and 40, respectively, irrespective of Reynolds number R_θ, whereas UT_1/δ as well as $U_*^2T_2/\nu$ vary with R_θ. The value of UT_2/δ obtained in the present investigation is in reasonable agreement with earlier measurements of zero crossings of the fluctuating turbulence signals,[6] as well as with the results obtained employing autocorrelation and selective filtering techniques.[3-5] Hence, it is justifiable to assume that T_2 in the present measurements represents the period when large eddy-like structures are present in boundary-layer flows.

The independence of $U_*^2T_1/\nu$ with R_θ presents an entirely different picture, which suggests that the wall shear fluctuations are influenced by some effect different from the large-scale motions. This result seems to have relevance to the streaks and oscillatory motions, observed by Kim et al.[1] very close to the wall in a turbulent boundary layer, that later coagulated into bursts in a quasiperiodic manner. According to them, the period of these visually observed bursts (T_3) follows the relation, $T_3 = 0.001102U_*^2$, where T_3 is in seconds and U_* is in feet/second. Assuming that their experiments were carried out at a comfortable temperature of 30°C, the kinematic viscosity for water being 1.77/105 m^2/s, the value of $U_*^2T_3/\nu$ would be around 110.0 and independent of R_θ. This value of 110.0 in nearly twice from that of $U_*^2T_1/\nu$ in the present experiments. However, their independence with R could mean that T_1 and T_3 are governed by the same physical process. The authors speculate that these wall eruptions might undergo pairing as they are lifted away from the wall, hence $T_3 = 2T_1$.

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A New Aerodynamic Integral Equation Based on an Acoustic Formula in the Time Domain

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Nomenclature

b	$=\lambda M_t + \lambda_l t_l$; $b = \lvert b \rvert$
b_v	$= b \cdot v$
c	= speed of sound
g	$= \tau - t + r/c$
H	= local mean curvature of the blade surface
h_n	$= \lambda M_n + \lambda_l \cos\theta$
M	= local Mach number vector based on c, $M_n = M \cdot n$, $M_r = M \cdot \hat{r}$
M_p	= projection of the local Mach number vector on the local plane normal to the edges (e.g., trailing edge) of the blade surface, $M_p = \lvert M_p \rvert$
M_t	= projection of M on the local tangent plane of the blade surface for fixed source time τ, $M_t = \lvert M_t \rvert = v_t/c$
n, n_i	= unit normal to $f = 0$, τ fixed
p'	= acoustic pressure
$p_B(\eta,\tau)$	$\equiv p[y(\eta,\tau),\tau]$ blade surface pressure described in a frame moving with the blades
Q_F, Q_N	= Eqs. (3a) and (3b), respectively
Q_F'	$=(\dot{M}_n - M_t \cdot \dot{\Omega})/c + M_t^2\kappa_t - 2M_n^2 H$
r, r_i	$= x - y$, $r = \lvert x - y \rvert$
$\hat{r}, \hat{r}_i$	= unit radiation vector r/r
$\hat{r}_p$	= unit vector in the direction of the projection of r on the local plane normal to the edges (e.g., trailing edge) of blade surface, τ fixed
t_l	= projection of the unit radiation vector $\hat{r}$ on the local tangent plane to $f = 0$, τ fixed (not unit vector $\lvert t_l \rvert = \sin\theta$)
α_n	$=(1+M_n^2)^{1/2}$
θ	= angle between n and r
κ_1, κ_2	= principal curvatures
κ_b	= normal curvature along b
κ_t	= normal curvature along t
λ	$=(\cos\theta - M_n)/\tilde{\Lambda}^2$
λ_l	$=(\cos\theta + M_n)/\tilde{\Lambda}^2$
Λ	$=(1 + M_n^2 - 2M_n\cos\theta)^{1/2}$
$\tilde{\Lambda}$	$=(\Lambda^2 + \sin^2\theta)^{1/2}$
Λ_0	$=[M_p^2\cos^2\psi + (1 - M_p \cdot \hat{r}_p \sin\psi)^2]^{1/2}$

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