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M. A. Badri Narayanan and Joseph G. Marvin

Ames Research Center
Moffett Field, California

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SUMMARY

The period of the large coherent structure in a subsonic, compressible, turbulent boundary layer was determined using the autocorrelation of the velocity and pressure fluctuations for Reynolds numbers R_θ between 5,000 and 35,000. As observed previously by Laufer and Badri Narayanan, in low Reynolds number flows the overall correlation period ($\bar{T}$) scaled with the outer variables – namely, the free-stream velocity U and the boundary-layer thickness δ. Also, the value of $U\bar{T}/\delta$ was the same as previously, a nearly constant 6.0 ± 1. A simple model is proposed for the coherent structure.

SYMBOLS

U	free-stream velocity
U*	friction velocity = $\left(\frac{\tau_w}{\rho}\right)^{1/2}$
u	mean velocity
u'	fluctuating velocity in the direction of the free stream
p'	fluctuating static pressure
w	subscript w means wall conditions
δ	boundary-layer thickness at 99.5% of U
θ	momentum thickness
R_θ	$\frac{U\theta}{\nu}$
ν	kinematic viscosity

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*National Research Council.

ρ density

τ_w wall shear stress

c_f skin-friction coefficient $= \dfrac{\tau_w}{(1/2)\rho U^2}$

$R_{tt}(Z)$ autocorrelation coefficient $= \left[\dfrac{\overline{Z(t)Z(t+\Delta t)}}{\overline{Z(t)}^2}\right]_{\Delta t\ 0 \rightarrow T}$

$\bar{T}$ period of the second zero in R_{tt}

T_1 period of the first zero in R_{tt}

INTRODUCTION

The existence of some well-defined patterns in the velocity fluctuations in a turbulent boundary layer now has been well established. In the wall region of a turbulent boundary layer a series of activities such as eruptions, sweep, inrush, etc., have been observed and they are generalized as events of the bursting phenomenon (refs. 1-4). Similarly, some recognizable wavy motion exists in the outer region of a boundary layer, the envelope of the wave separating the rotational turbulent motion from the outer potential flow. Originally, it was conceived that the outer wavy interface and the bursts in the wall region were entirely different, independent processes. However, recent investigations have clearly shown the existence of a near-cyclic motion across the boundary layer. The interface and the wall eruptions are just two phases of the same process.

Laufer and Badri Narayanan (ref. 5) observed that the period of the bursts $\bar{T}$ near the wall was essentially the same as that of the interface and that in addition, $\bar{T}$ scaled with the outer variables, namely, the boundary-layer thickness δ and the free-stream velocity U. From this finding they inferred that even though the bursts occurred near the wall region, they were triggered by some large-scale structure pervading the whole width of the boundary layer. Very recently, Brown and Thomas (ref. 6) have shown by detailed measurements that an organized structure indeed exists in the boundary layer, confirming the speculation made by Badri Narayanan et al. (ref. 7). When this recirculating structure approaches the wall from outside, it gets retarded, and because of the high shear encountered, the flow in this region breaks up, producing fresh packets of turbulence or bursts that are convected into the outer part of the boundary layer. During this upwelling motion, the small-scale structure either dissipates faster, leaving the large ones, or coagulates into large-scale motion, which appears in the interface region as wavy motion. The physics of the process is yet to be understood. In a broad sense, the large-scale structures play a primary role in maintaining balance between production, convection, and diffusion of turbulence. This macrostructure could be considered as the largest eddy in the flow or as a coherent structure, a terminology coined after the well-organized eddy patterns observed in a free-mixing layer by Brown and Roshko (ref. 8).

A study of the properties of the coherent structure is of considerable importance in understanding the dynamics of turbulence since it could be viewed as the primary eddy in the flow extracting energy from the mean motion to produce turbulence through a series of breakup processes. In principle it should be possible to extract most of the information on the turbulent structure from this large-scale motion.

Identification of these coherent structures from the overall random fluctuations in the boundary layer presents a major experimental difficulty. The coherent structures in a fully developed turbulent boundary layer do not occur with a well-defined periodicity and there is always some randomness associated with it. In addition the three-dimensional nature of turbulence has a smearing effect on the structural pattern. However, various techniques employed for evaluating the periodicity of the coherent structure have yielded the same result. Among these techniques are visual observation using microscopic size hydrogen bubbles (ref. 1), autocorrelation of hot-wire signals (ref. 5), and filtered hot-wire traces (ref. 4). $U\bar{T}/\delta$ is nearly a constant equal to 5 ± 1, suggesting that the average length of the coherent structure of a flat-plate turbulent boundary layer is nearly five to six times the boundary-layer thickness and is independent of Reynolds number.

Information so far available in the literature is mainly confined to incompressible boundary layers having R_θ less than 10,000. One of the major aims of the present investigation was to extend the data to high Reynolds numbers, as well as to compressible flows. A facility capable of producing boundary layers with R_θ of 35,000 for a Mach number range between 0 to 0.5 was used to make the measurements. Autocorrelations of the velocity and pressure fluctuations were analyzed to determine the period of the coherent structure.

EXPERIMENTAL ARRANGEMENT AND MEASUREMENTS

The experiments were conducted in a 10.2 cm by 15.2 cm wind tunnel where the flow was produced by suction from a large capacity vacuum source. A sketch of the wind tunnel is shown in figure 1. An adjustable sonic throat downstream of the test section controlled the speed of the flow and minimized the upstream propagation of the sonic disturbances and the pressure fluctuations from the diffuser region. The Mach number at the test section could be varied from 0 to 0.6. Reynolds numbers R_θ up to 35,000 could be obtained with a maximum boundary-layer thickness of 42 mm. Zero pressure gradient was maintained all along the test section by using a divergent wall whose inclination was adjusted to account for the growth of the boundary layer. Downstream of the contraction, at the entry of the test section, a pair of coarse emery trips were pasted in tandem to fix transition. Boundary-layer measurements were made at two stations, x = 1.12 m and 3.0 m downstream of the trips. The mean-velocity profiles indicated that the boundary layer was two-dimensional

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even though the wind tunnel was small. The characteristics of the profiles are discussed in the next section.

The mean velocity profiles were measured using a small fineness ratio pitot tube with an opening of 50 μ, in conjunction with a Barocell pressure gauge. A hot-wire probe with a 5-μ-diam, 1-mm-long tungsten element was employed to measure velocity fluctuations; the wire was operated by a Disa constant temperature anemometer. The system was tuned to a frequency response from 0 to 20 kHz, approximately. A hot-wire surface heat-transfer gauge was used to measure the near-wall velocity fluctuations. This gauge was made by placing a 2-mm-long, 5-μ-diam pt-rh wire on the surface of a flat ceramic plug fitted flush with the tunnel wall. An overheat ratio of 1.2:1 was used for heating the wire.

Wall pressure fluctuations were obtained using a commercially available, Thermo System Inc., bleed-type hot-wire pressure probe with its opening mounted flush with the surface of the tunnel wall. A suction pressure of nearly 50 mm of water was maintained between the two ends of the bleed probe by a vacuum pump with a control valve in series. The probe was connected to a constant temperature hot-wire anemometer. When tested under steady conditions the output of the probe varied linearly with input pressure. In the other region of the boundary layer, static pressure fluctuations could not be measured with this probe in its commercially available form, and it was modified as shown in figure 2. The open end of the probe was fitted with a hemispherical nose with four static pressure holes (0.8 mm diam) drilled at right angles along the circumference nearly 3 diam behind the tip. With the axis of the probe kept parallel to the flow, the mean static pressure was the same as that of the free stream. Calibration of the probe under dynamic conditions was not carried out. However, when exposed to the fluctuations in the boundary-layer, oscilloscope traces indicated that the probe was capable of sensing fluctuations up to 15 kHz.

The autocorrelation of the velocities and pressures was measured using a Saicor real-time correlator and the correlations were carried out for a period of nearly 10 sec. An X-Y plotter was employed to draw the correlation curves. During the experiment, output from the hot-wire anemometer was directly recorded on an analog tape and later played back into the correlator.

RESULTS AND DISCUSSION

Since the boundary-layer thickness is one of the key parameters used in the data analysis to normalize the length of the coherent structure, two x positions far apart were chosen to obtain significant variation of it. The velocity profiles in the boundary layer were measured at these two stations, namely at $x = 1.12$ m and 3.0 m where the boundary-layer thicknesses were nearly 25 and 44 mm, respectively. At both the stations, the free-stream velocity was varied from 30 to 200 m/sec. At each station, δ did not vary appreciably over this range of test conditions.

Some of the measured mean velocity profiles are plotted in figure 3 in the standard semilogarithmic form, U/U^* versus yU^*/ν, where U^* is the friction velocity. The skin-friction coefficients for the above plots were obtained by using the Ludwig-Tillman formula, namely

$$c_f = 0.246/R_\theta^{-0.268}\ 10^{-0.678\ H} \tag{1}$$

with Van Driest's correction for Mach number. The boundary-layer parameters are shown in table 1 and figure 4. All the profiles exhibit a definite logarithmic region which follows the law, $U/U^* = 5.6 \log_{10} yU^*/\nu + 5.4$, indicating that the values of C_f, obtained using Ludwig-Tillman's formula, agree well with those inferred from the profile measurements. The maximum velocity defect of nearly 2.60 is a good indication of the fully developed nature of the boundary layer (ref. 9).

The autocorrelation measurements made at the wall and in other regions of the boundary layer, at R_θ of 10,000 are shown in figure 5. All across the boundary layer, the curves look similar. Correlation curves corresponding to different Reynolds numbers measured at $x = 3.0$ m at 1 mm away from the wall are given in figure 6. Sample R_{tt} curves for the pressure fluctuations are shown in figure 7.

The aim of the present investigation is to study the period of the coherent structure in a boundary layer using the measured autocorrelation R_{tt}

$$R_{tt}(Z) = \left[\frac{\overline{Z(t)Z(t + \Delta t)}}{\overline{Z(t)^2}}\right]_{\Delta t\ 0 \to T} \tag{2}$$

where T is a period much larger than that of the large-scale structure and $R_{tt} = 1$ at $\Delta t = 0$ by definition.

The value of t where R_{tt} reaches zero is a measure of the overall period of a coherent structure. In turbulent flows, especially at high Reynolds numbers, R_{tt} reaches zero rapidly, extending to the negative region and returning to zero once again (figs. 5 and 6). Beyond this period, low-magnitude oscillatory traces were observed. The second zero, corresponding to the end of the negative portion of R_{tt}, is of considerable importance in determining the period of the coherent structure. Laufer and Badri Narayanan (ref. 5) used the extent of this second zero to represent the overall correlation time $\bar{T}$ and the same method is adopted in the present investigation.

The determination of $\bar{T}$ from the experimental correlation curve has a certain amount of uncertainty due to the oscillatory nature of the correlation curve. In the present investigation, the curves are smoothed to evaluate $\bar{T}$. The correlations were obtained with an averaging period of 10 sec; the results were repeatable within the error indicated in figure 8.

The values of $\bar{T}$ obtained from the present experiments at and near the wall are plotted in figure 8, in the nondimensional form $U\bar{T}/\delta$ versus R_θ for Reynolds number and Mach number ranges of 5,000 to 35,000 and 0 to 0.5,

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respectively. In the region of R_θ between 10,000 and 18,000 the wall pressure and the velocity fluctuation may exhibit a trend with R_θ. Evidently, as will be shown later, this trend is a result of the dependence of $\bar{T}_1$, the period of the first zero, on the flow Reynolds number. However, based on the overall uncertainties of the technique, it was decided not to speculate on such trends and a mean line with a value of 6.0 for $U\bar{T}/\delta$ was fit to the points in figure 8.

At any given Reynolds number, the variation in $\bar{T}$ with position across the boundary layer is also nearly single-valued, as shown in figure 9. Such a result is significant since it indicates, though not directly, that a coherent structure exists throughout the boundary layer as a whole. The recent investigation of Brown and Thomas (ref. 6) fully supports this view.

As shown in figure 10, the period $\bar{T}_1$, corresponding to the first zero of the positive correlation, is nearly three to six times less than $\bar{T}$ from the u' fluctuations. The value of $\bar{T}_1$ could be determined within an accuracy of ±10%; hence, the variation of $U\bar{T}_1/\delta$ with R_θ is considered genuine. However, due to lack of information on the dynamic characteristics of the pressure probe, speculation on the differences in $\bar{T}_1$ obtained from p' and u' autocorrelations is unwarranted.

Even though the autocorrelation is unique, attempts to extract the actual fluctuating velocity distribution from the experimental correlation curve would be futile. However, it is interesting to make some general observations and postulate a model of the structure. First, some assumptions are necessary. The structure as a whole has to be considered to form a single identity unaffected by the neighboring eddies, and the fluctuating velocity should have a positive and a negative region so that a stationary mean can result. Autocorrelation curves for simple velocity variations that have these properties are shown in figure 11. A single-cycle sine wave results in a correlation curve with the same shape as that observed in the present experiments. T_1 is nearly four times less than $\bar{T}$, even though the velocity variation is symmetrical. As the other waveforms illustrate, $T_1/\bar{T}$ depends to some extent on the period of the first lobe. Thus, the front segment of the coherent structure may be shorter. As the experiments showed, this portion of the structure depends on the Reynolds number of the flow. A sketch of such a velocity structure is shown in figure 12.

CONCLUSIONS

The period $\bar{T}$ of the large-scale, coherent structure in a flat-plate boundary layer was obtained from the autocorrelation measurements of the fluctuating pressure and the longitudinal velocity. Measurements were made in the range of Reynolds number R_θ and Mach numbers from 5,000 to 35,000 and from 0 to 0.5, respectively. The value of $U\bar{T}/\delta$ was nearly constant, equaling 6 ± 1 all across the boundary layer, independent of Reynolds number and Mach number.

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TABLE 1.- BOUNDARY-LAYER PARAMETERS

δ, mm	θ, mm	H	C_f	R_θ	M
		x = 1.12 m			
27	1.88	1.31	0.0031	6220	0.146
27	1.95	1.31	.0028	8780	.20
27	1.96	1.32	.0026	11320	.255
27	1.72	1.36	.0017	12260	.316
27	1.85	1.40	.0018	15460	.369
27	2.00	1.38	.0023	20530	.455
		x = 3.0 m			
42	3.32	1.366	0.00196	38800	0.510
42	3.36	1.395	.00195	36200	.482
42	3.51	1.377	.00194	32800	.413
42	3.38	1.361	.00205	26400	.346
42	3.56	1.333	.00218	22600	.281
42	3.50	1.320	.00230	18000	.219
42	3.64	1.310	.00250	13750	.167
42	3.72	1.320	.00265	9990	.112

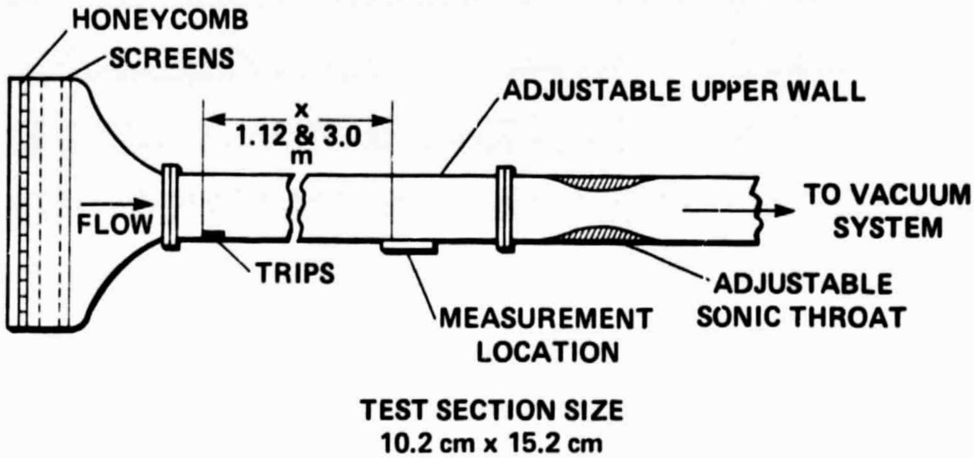

Figure 1.- Sketch of the wind tunnel.

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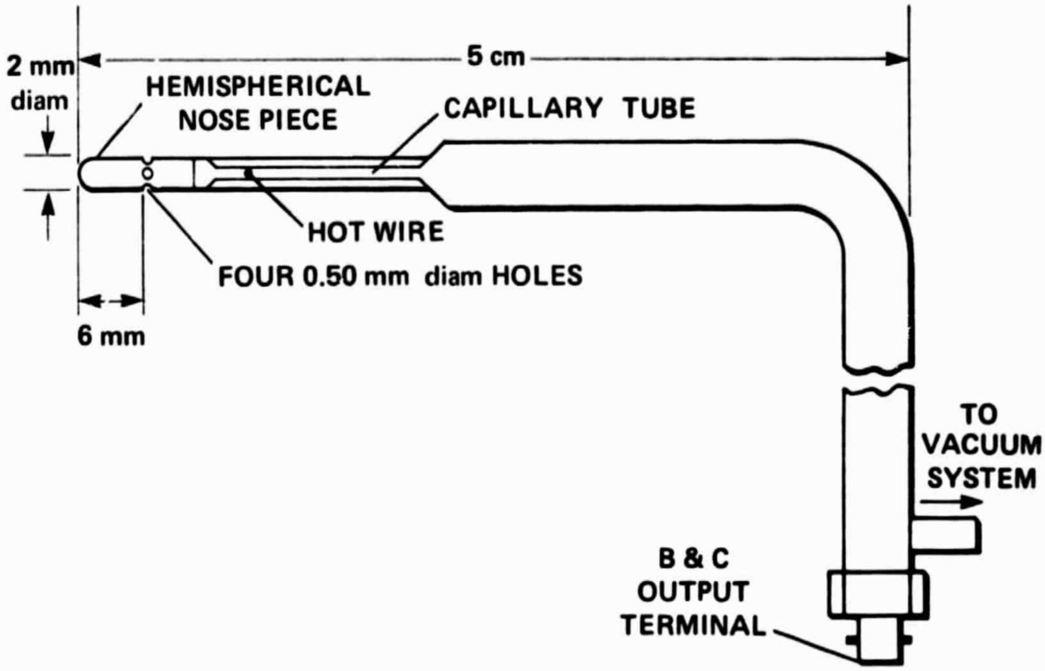

Figure 2.- Sketch of the modified bleed-type static pressure probe.

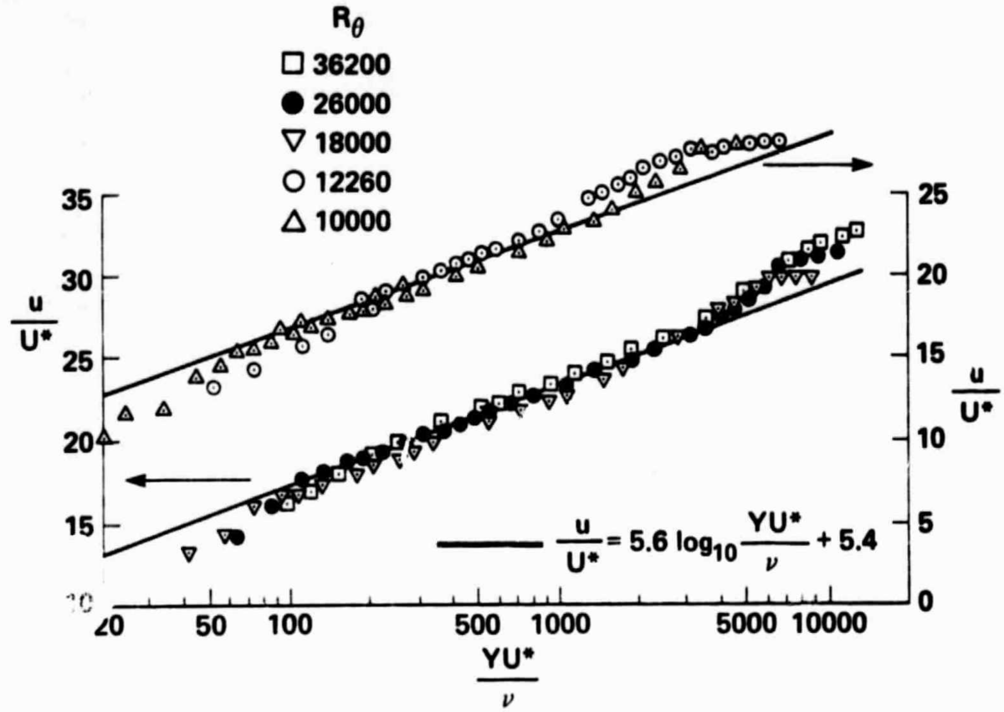

Figure 3.- Mean-velocity profiles in the boundary layer.

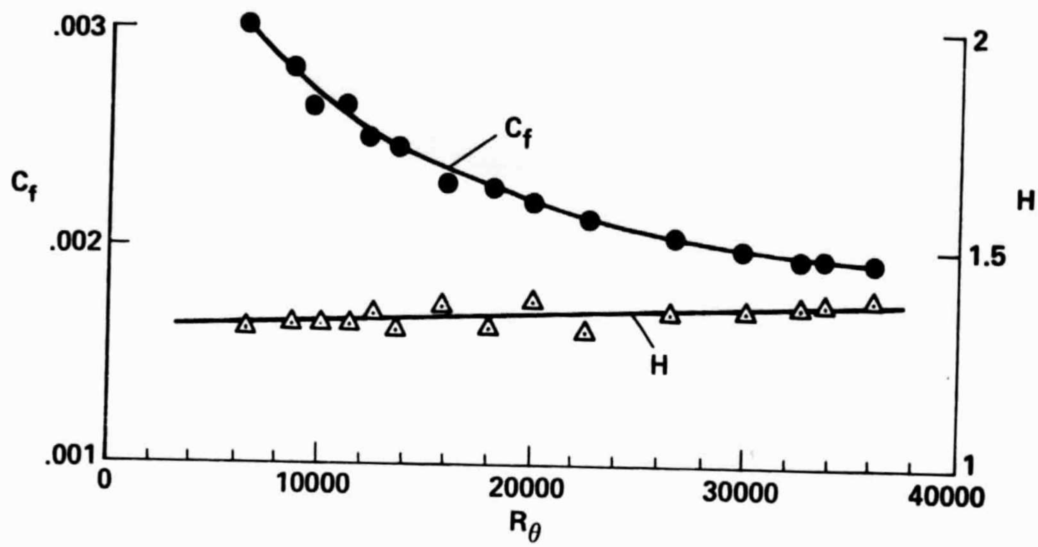

Figure 4.- Boundary-layer parameters.

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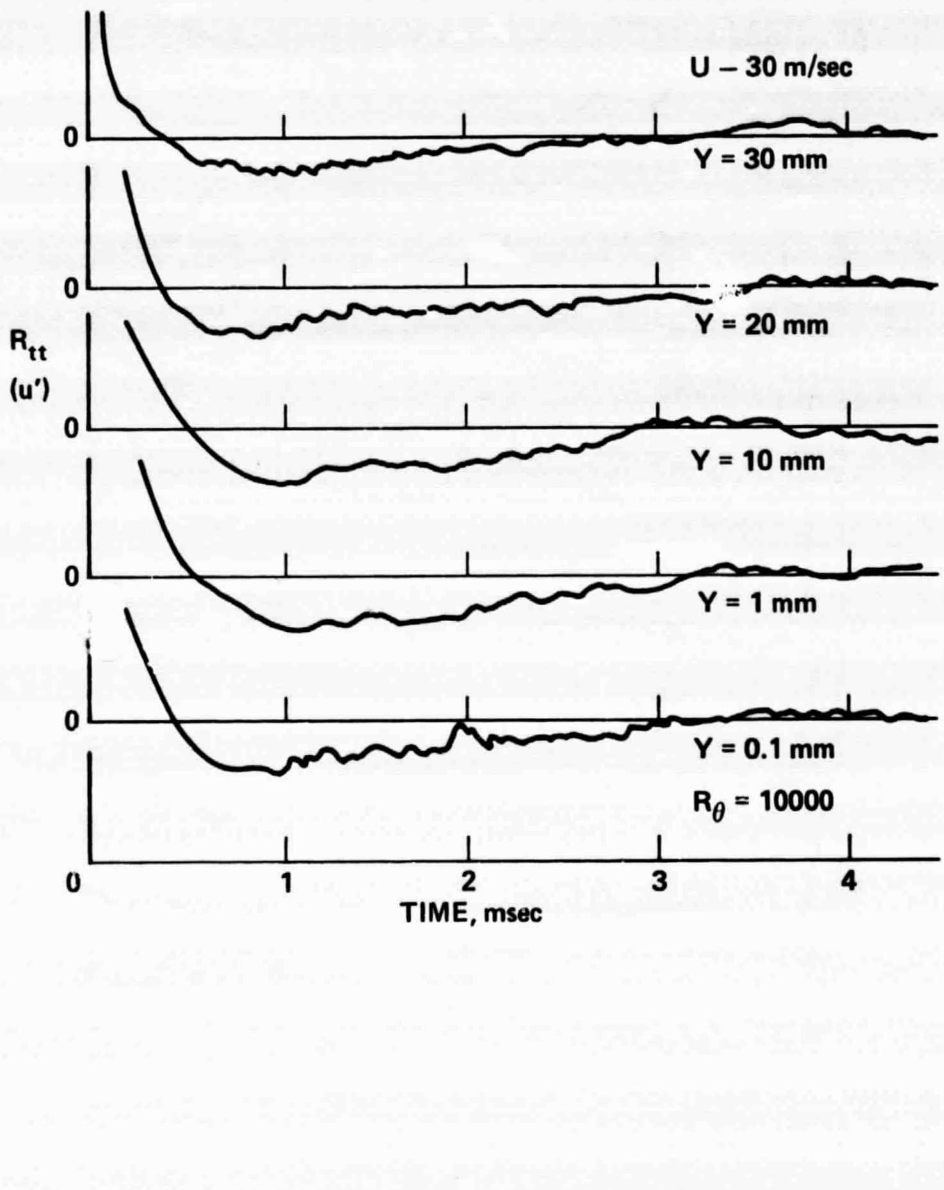

Figure 5.- Autocorrelation of u' across the boundary layer.

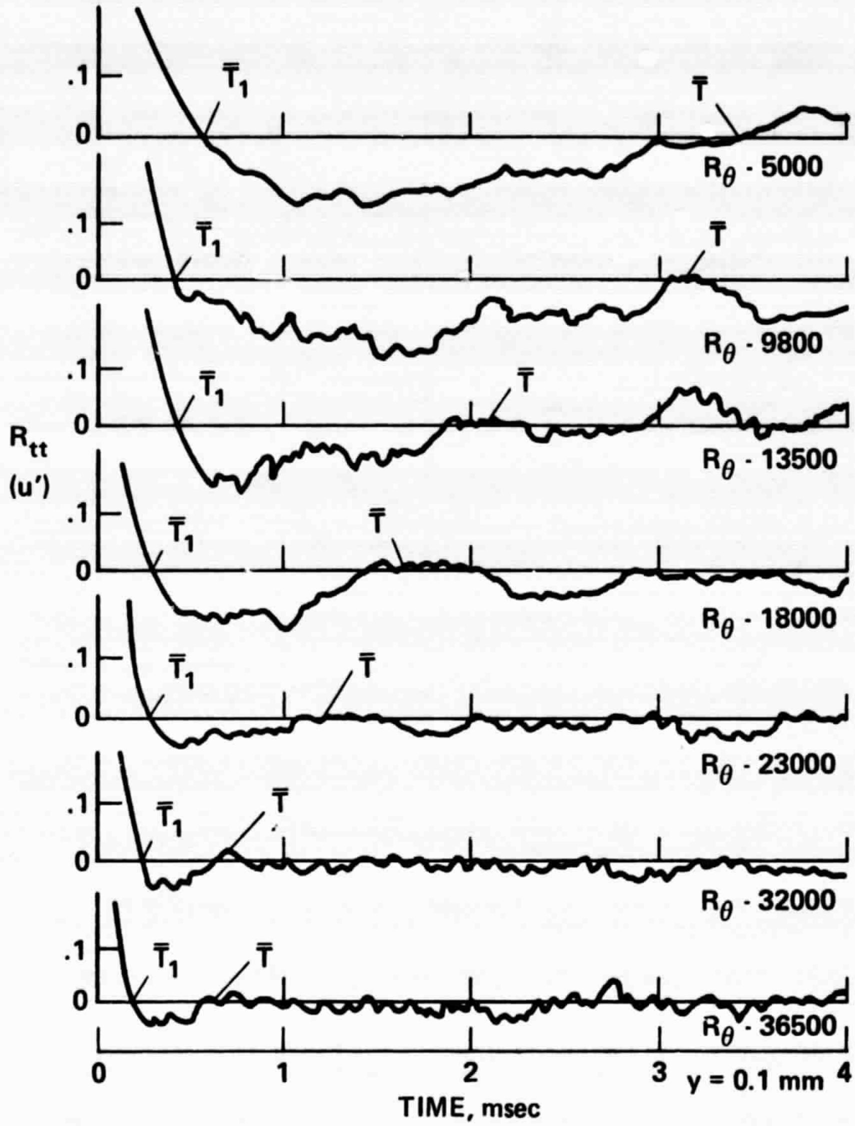

Figure 6.- Autocorrelation of u' at various Reynolds numbers.

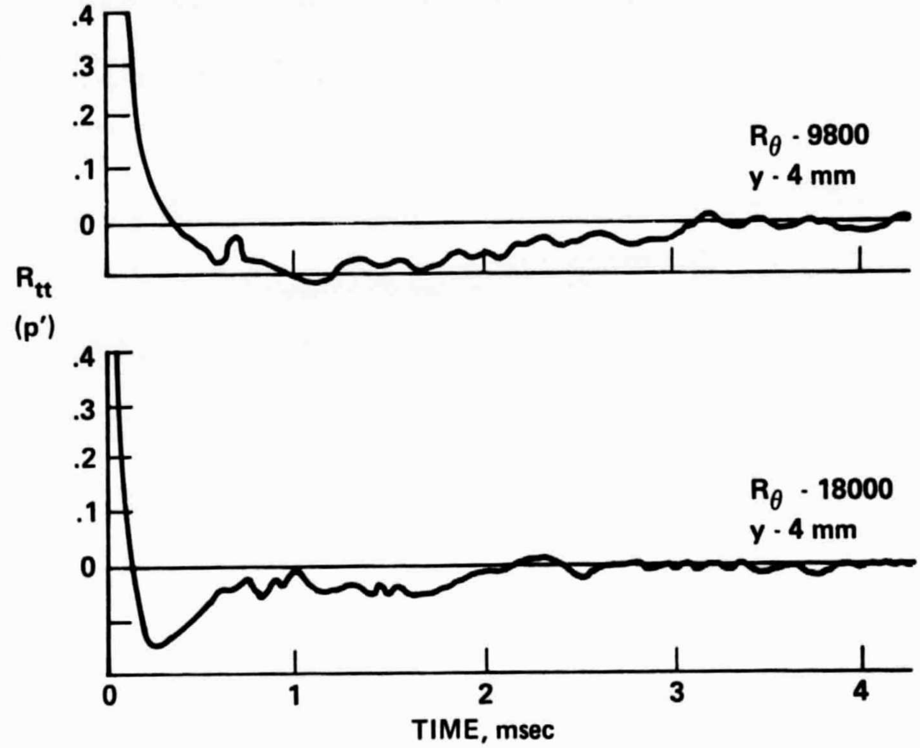

Figure 7.- Correlation of ρ' signal.

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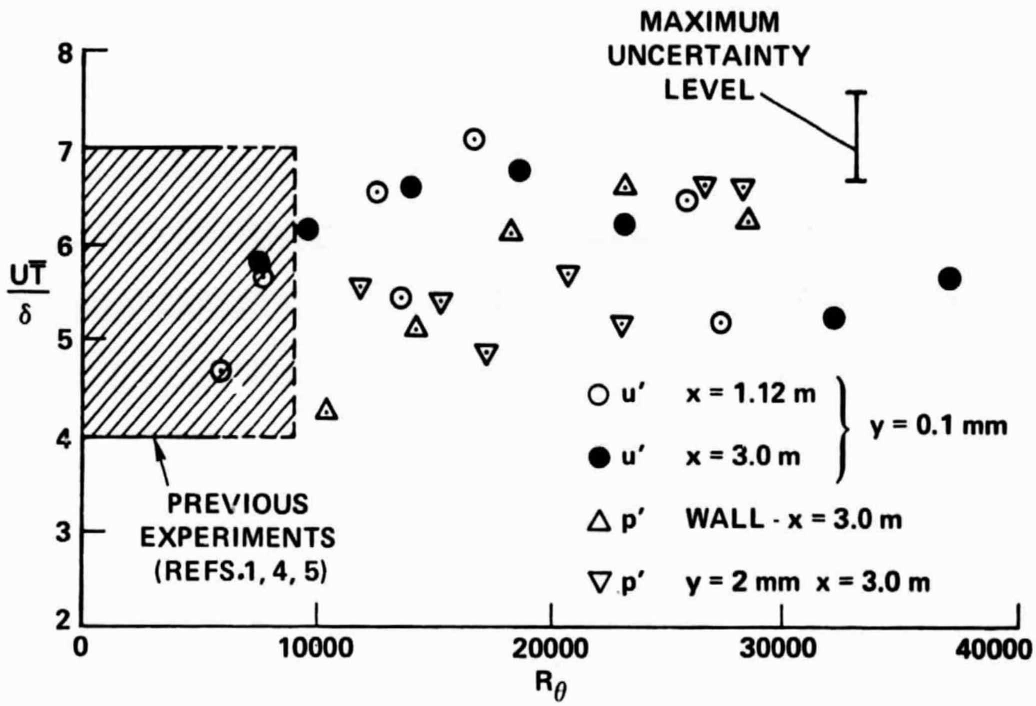

Figure 8.- Variation of $U\bar{T}/\delta$ with Reynolds number.

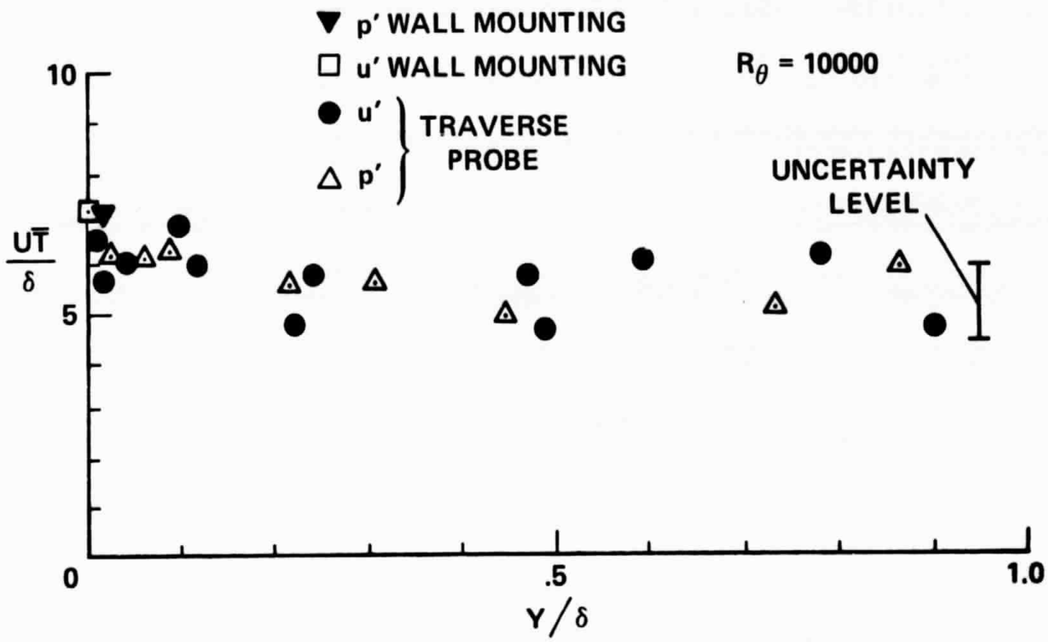

Figure 9.- Variation of $U\bar{T}/\delta$ across the boundary layer.

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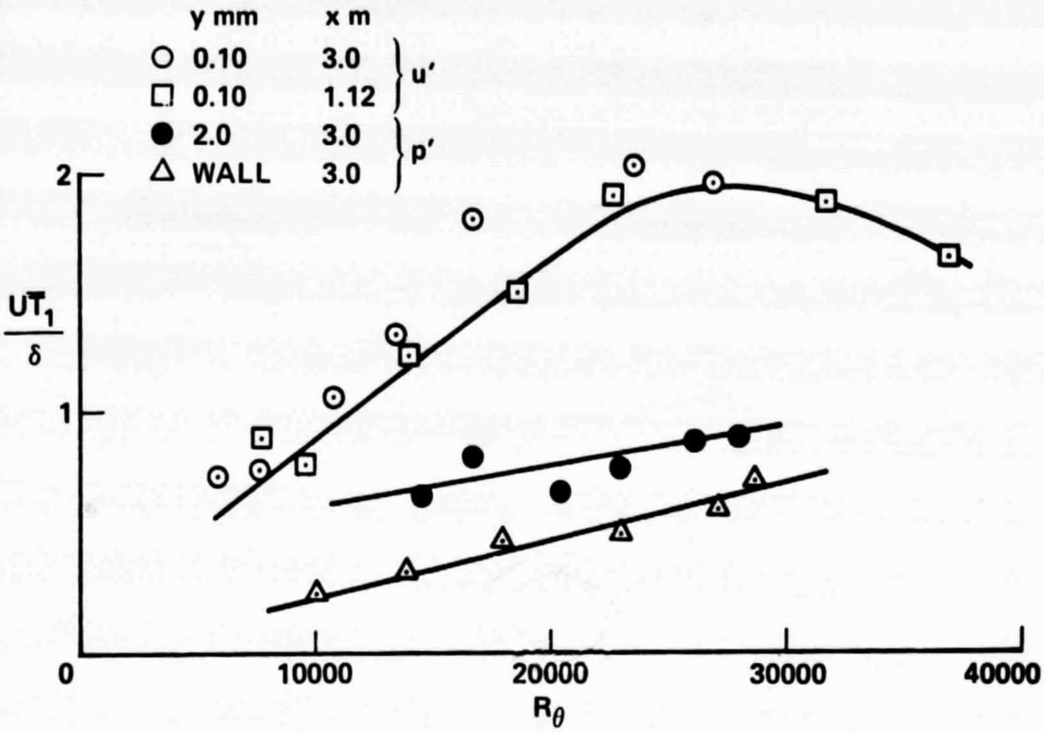

Figure 10.- Variation of $U\bar{T}_1/\delta$ with Reynolds number.

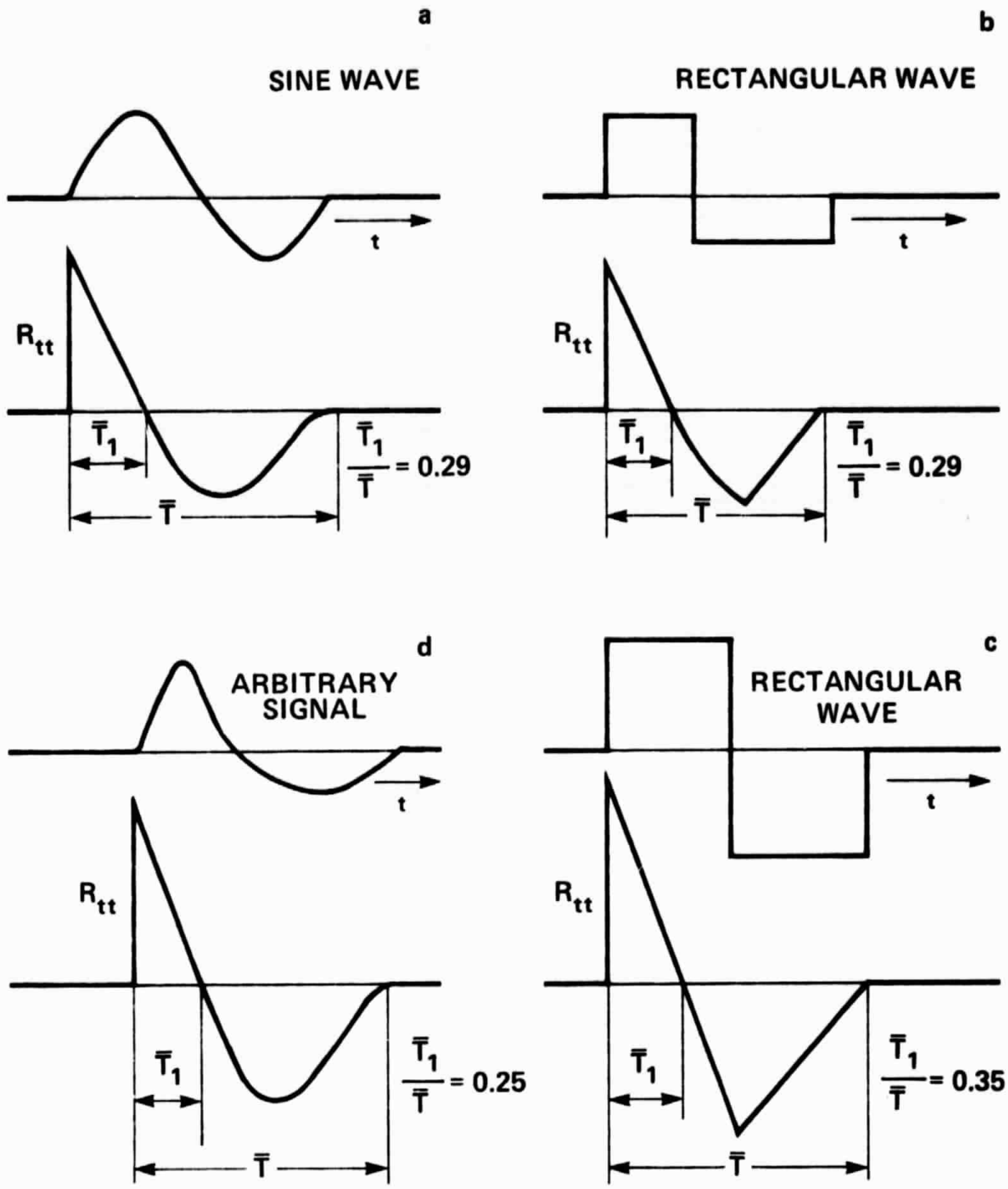

Figure 11.- Autocorrelation of various wave forms.

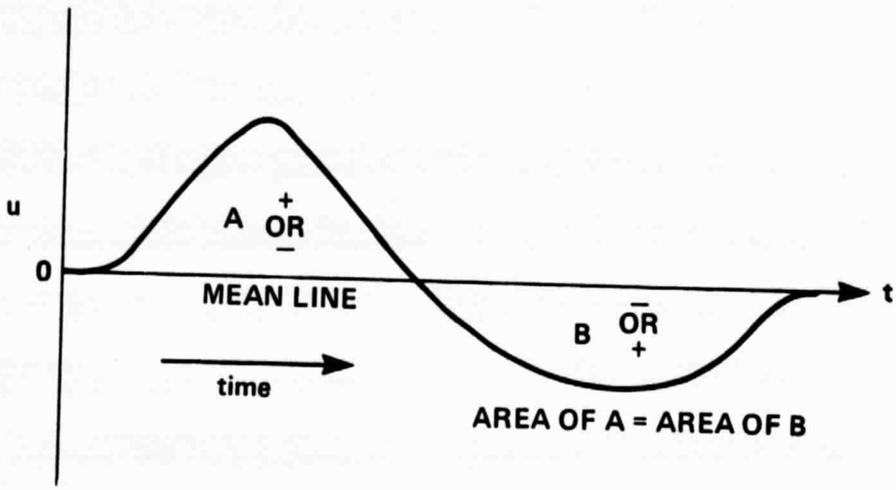

Figure 12.- Proposed model for the velocity distribution in a coherent structure.

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15. Supplementary Notes

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16. Abstract

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