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An investigation of small scales of turbulence in a boundary layer at high Reynolds numbers

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The assumption that turbulence at large wave-numbers is isotropic and has universal spectral characteristics which are independent of the flow geometry, at least for high Reynolds numbers, has been a cornerstone of closure theories as well as of the most promising recent development in the effort to predict turbulent flows, viz. large eddy simulations. This hypothesis was first advanced by Kolmogorov (1941, 1962) based on the supposition that turbulent kinetic energy cascades down the scales (up the wave-numbers) of turbulence and that, if the number of these cascade steps is sufficiently large (i.e. the wave-number range is large), then the effects of anisotropies at the large scales are lost in the energy transfer process. Experimental attempts have repeatedly been made to verify this fundamental assumption. However, Van Atta (1991) has recently suggested that an examination of the scalar and velocity *gradient* fields is necessary to definitively verify this hypothesis or prove it to be unfounded. Of course, this must be carried out in a flow with a sufficiently high Reynolds number to provide the necessary separation of scales in order unambiguously to provide the possibility of local isotropy at large wave-numbers. An opportunity to use our 12-sensor hot-wire probe to address this issue directly was made available at the 80'x120' wind tunnel at the NASA Ames Research Center, which is normally used for full-scale aircraft tests. This is an initial report on this high Reynolds number experiment and progress toward its evaluation.

1. Previous studies

Veeravalli and Saddoughi (1991), of the Center for Turbulence Research (CTR), performed experiments with an X-array of two hot-wire sensors in the boundary layer of the upper wall of the NASA Ames 80 ft. x 120 ft. wind-tunnel at a streamwise station with a 50 m fetch. At this location, with a freestream velocity $U_\infty \approx 40\ m/s$, the boundary layer thickness was $\delta \approx 1.0\ m$, the Reynolds number based on momentum thickness was $R_\theta (\equiv U_\infty \theta/\nu) \approx 300{,}000$, and the turbulence Reynolds number at $y/\delta \approx 0.4$ was $R_\lambda (\equiv u_{rms}\lambda/\nu) \approx 1{,}450$, one of the largest ever achieved in a laboratory. Under these conditions and at this location, the Kolmogorov length scale was $\eta \approx 0.1\ mm$. Veeravalli and Saddoughi (1991) obtained one-dimensional velocity component spectra, at $y/\delta = 0.4$, which have a two-decade range of the inertial wave-number subrange. They tested the isotropy of the velocity field where, for isotropic flow,

$$\phi_v(k_x) = \phi_w(k_x) = 1/2[\phi_u(k_x) - k_x d\phi_u(k_x)/dk_x]. \tag{1}$$

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They found that the streamwise and spanwise velocity components, u and w, exhibit isotropic spectral properties in the inertial subrange but that the normal component, v, does not. Furthermore, although they obtained more than a decade of spectral data at wave-numbers in the dissipation range, this data was contaminated by electronic noise.

Van Atta *et al.* (1992) have also analyzed our moderately low Reynolds number boundary layer at $Re_\theta \approx 2700$ [Balint *et al.* (1991)], and two-stream mixing layer at $Re_\theta (\equiv \Delta U\theta/\nu) \approx 7200$ [Balint *et al.* (1989)] databases for evidence of local isotropy, utilizing an expression which gives the isotropic relationship between the one-dimensional vorticity spectrum components. This expression is analogous to that for the velocity spectrum components and is given by

$$\phi_{\omega_y}(k_x) = \phi_{\omega_z}(k_x) = 1/2[\phi_{\omega_x}(k_x) - k_x d\phi_{\omega_x}(k_x)/dk_x]. \tag{2}$$

They found that the local isotropy hypothesis is not valid deep in the boundary layer at $y^+ \approx 18$. Only at the highest wave-numbers in the mixing layer on the splitter plate plane is there any indication of its validity. However, the boundary layer flow examined had no extended $k^{-5/3}$ inertial subrange, and the mixing layer flow had only a limited one. A definitive test requires relatively well resolved measurements of the velocity and velocity gradient fields at much higher Reynolds numbers.

2. Objectives

The present experiments have been designed to provide direct measurements of the velocity vector as well as the velocity gradient tensor fields at high Reynolds number, which is necessary for a definitive test of the large wave-number local isotropy hypothesis.

The acquired database will be archived at the Turbulence Research Laboratory of the University of Maryland and at the Center for Turbulence Research of Stanford University/NASA Ames. This database, of course, will not only be useful for the verification of the local isotropy hypothesis. It will be used for investigating the structural characteristics of the turbulent kinetic energy dissipation rate field which can only be examined through an analysis of the turbulent strain-rates. Furthermore, almost all of the statistical and structural characteristics of the velocity and vorticity fields have been obtained only at moderately low Reynolds numbers. Many of these are known only for the quite low Reynolds numbers of the direct numerical simulations of turbulent boundary layer and parallel channel flows. It is an article of faith, but an often questioned one, that these characteristics are Reynolds number independent. This database should make possible the direct experimental test of this article of faith.

3. Experimental facility and instrumentation

These experiments were performed with the freestream velocity of the wind tunnel at $U_e \approx 10\ m/s$, which corresponds to a momentum thickness Reynolds number of $R_\theta \approx 65{,}000$ and a maximum turbulence Reynolds number of $R_\lambda \approx 600$ at

$y/\delta \approx 0.5$ [Saddoughi (1992)], with the boundary layer thickness $\delta \approx 1.0\ m$. Under these conditions, the Kolmogorov length scale is estimated to be $\eta \approx 0.32\ mm$. This is about the spatial resolution we can achieve in our tunnel at the University of Maryland, but in the present flow it is achieved at almost 25 times higher Reynolds number based on momentum thickness. The range of values of the turbulence Reynolds numbers R_λ at the tunnel freestream speed of 10 m/s is still much higher than those which normally can be achieved in the laboratory. For example, in our University of Maryland wind-tunnel, the momentum thickness Reynolds number $R_\theta \approx 2,700$ at $U_\infty = 3.5\ m/s$ [Balint *et al.* (1991)], and $R_\lambda \approx 250$ in the logarithmic layer.

The present experiments were conducted on the ceiling of the wind tunnel at approximately 50 m from the inlet and about 6.6 m from the side wall. This is the location of one of the side viewing ports because the centrally located viewing port was unavailable for the present experiments. It is still to be determined whether secondary corner flow affected the measurements. The Plexiglass window was replaced with a specially designed probe-holder platform. The probe was mounted on a stainless steel rod that was fitted through the platform, and measurements were made with the probe at $y/\delta \approx 0.1$, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 1.6 from the ceiling of the wind tunnel.

3.1 Data acquisition procedure

The hot-wire sensors were operated in the constant temperature mode at an overheat ratio of 1.2 with a A.A. Lab Systems 12-channel hot-wire anemometer. The maximum sustainable throughput of the our Optim 5017A Megadac data acquisition system was approximately 72 kHz, i.e. 6 kHz per channel when sampling twelve channels simultaneously. This relatively low sampling frequency could not sufficiently resolve the expected Kolmogorov frequency range, which was estimated to be approximately 4.5 to 5.5 kHz [Saddoughi (1992)]. In order to overcome this technical limitation, the outputs of the anemometer channels were analog recorded on FM tapes. In this manner, to achieve a high digitization rate, one could either play back the tape at a slower speed than the record speed or digitize each of the channels individually. The second method requires a synchronization signal to be simultaneously recorded on the tape in order to uniquely identify a common trigger time for all the channels. The trigger used was simply a switch connected to a 1.5 V battery. The switch was activated a few seconds into the data recording and kept closed for the duration of the measurement. The 16 channel V-Store FM tape recorder used was provided by RACAL Recorders Inc. through H. Keating Moore and Associates. This FM instrumentation recorder was operated at 40 in/s providing a frequency response of approximately 20 kHz, which is roughly 4 times greater than the expected Kolmogorov frequencies. A total of 13 channels (including the synchronization channel) were recorded at each measurement location for recording durations of 180 s.

3.2 The 12-sensor hot-wire probe

The new 12-sensor probe used in the present study, constructed and tested by P.

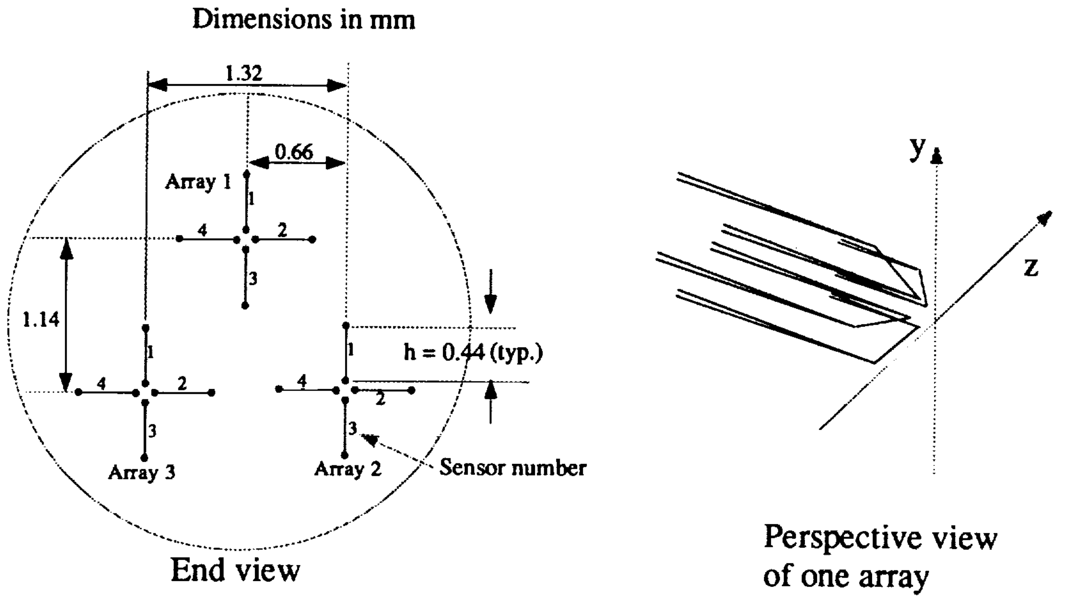

FIGURE 1. Schematic diagrams of the twelve sensor probe

Vukoslavčević, consists of three arrays of 4 hot-wire sensors each, arranged as shown in Figure 1. This probe is able to extend the range of acceptable angles of attack of the velocity vector, which was previously a problem with the 9-sensor design [Vukoslavčević *et al.* (1991)], and to resolve uniqueness problems in the solution of the cooling law equations at these large angles of attack.

During calibration, the probe was placed at the exit of a calibration jet where a uniform velocity profile is generated. The probe was pitched and yawed through $\pm 20^o$ at several fixed flow velocities to simulate the range of angles of attack which the flow in the wind-tunnel is expected to impose on the probe. Following Jorgensen (1971), each sensor's response to the various velocity vectors can be described by defining an effective cooling velocity:

$$U_{eff}^2 = a_1 U^2 + a_2 V^2 + a_3 W^2 + a_4 UV + a_5 UW + a_6 VW. \tag{3}$$

This cooling velocity is also a function of the bridge output voltage which for the present study was fitted with a fourth order polynomial:

$$U_{eff}^2 = P(E) = A_1 + A_2 E + A_3 E^2 + A_4 E^3 + A_5 E^4. \tag{4}$$

The probe response equation is thus a combination of the above two expressions, where the calibration coefficients a and A are obtained by a least squares fit of the calibration data. It is easily seen that when three calibrated hot-wire sensors are subjected to the same flow, one can write a set of three coupled response equations where the only unknowns are the three velocity components. Conceptually, with three arrays of at least three sensors each, one can simply obtain the velocity components at each array and calculate the gradients by finite differences. However, it is necessary to account for velocity *gradients* in the solution of the response equations. This can be done by re-writing the velocity components in a Taylor's series expansion (to first order) about the centroid of the probe and iteratively solving the set of 9 coupled equations, where the unknowns are now the velocity vector and gradient tensor components: $U, V, W, \partial U/\partial y, \partial U/\partial z, \partial V/\partial y, \partial V/\partial z, \partial W/\partial y, \partial W/\partial z$. The streamwise gradients can then be obtained by Taylor's hypothesis [Piomelli *et al.* (1989)] to within the buffer layer of the boundary layer.

With the present 12-sensor probe, there is a total of three extra sources of information resulting from having one spare wire at each array. This built-in redundancy was designed based on previous experience with the nine-sensor probe that some uniqueness and convergence problems can be circumvented by an optimal choice of a three-sensor arrangement, depending on the angle of attack of the velocity vector. This redundancy can also be exploited by solving the twelve coupled response equations for the nine unknowns by an optimization routine such as that developed by Marasli, Nguyen and Wallace (1992). These two methods are being studied for final implementation for the present set of measurements.

4. Preliminary analysis

At this time, for each of the measurement positions, 30 seconds of data from the FM tape have been digitized at 20 kHz, channel by channel, and archived on digital tape. The trigger signal was simultaneously digitized with each of these channels to ensure proper synchronization of the twelve sets of hot-wire voltages. The twelve digitized data files for each position have been combined into a single file consisting of only the twelve hot-wire voltages. The three measurement positions selected for preliminary analysis are at $y/\delta \approx 0.1$, 0.5 and 1.6. The temporally aligned digital data files for these three positions have been reconstructed. An analysis of the calibration files for the experiments indicated that recovery of the induced calibration velocities from the calibration coefficients and calibration voltages are good.

5. Closure

A unique experiment to measure the velocity vector and the velocity gradient tensor in a very high Reynolds number boundary layer flow has been performed. While the analysis of the boundary layer data is still in progress, evaluation of the calibration data and preliminary turbulence data results indicate that the probe performed as expected. Further work is underway to complete the analysis.

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REFERENCES

BALINT, J.-L., WALLACE, J. M. & VUKOSLAVČEVIĆ, P. 1991 The velocity and vorticity vector fields of a turbulent boundary layer: Part 2, Statistical Properties. *J. Fluid Mech.* **228,** 53.

BALINT, J.-L., WALLACE, J. M. & VUKOSLAVČEVIĆ, P. 1989 The statistical properties of the vorticity field of a two-stream turbulent mixing layer. *Advances in Turbulence 2, edited by H.H. Fernholz and H. E. Fiedler.* (Springer-Verlag, Berlin, **74**

JORGENSEN, F. E. 1971 Directional sensitivity of wire and fiber film probes. *DISA Information.* **11,** 31-37.

KOLMOGOROV, A. N. 1941 The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. *C.R. Acad. Sci. U.R.S.S.* **30,** 301.

KOLMOGOROV, A.N. 1962 A refinement of previous hypotheses concerning the local structure of turbulence in a viscous incompressible fluid at high Reynolds number. *J. Fluid Mech.* **13,** 82.

MARASLI, B., NGUYEN, P & WALLACE, J.M. 1991 A calibration technique for multiple-sensor hot-wire probes and its application to vorticity measurements in the wake of a circular cylinder. *Submitted to Experiments in Fluids.*

PIOMELLI, U. AND BALINT, J.-L. AND WALLACE, J.M. 1989 On the validity of Taylor's hypothesis for wall-bounded turbulent flows. *Phys. Fluids A.* **1,** 609-611.

SADDOUGHI, S. G. 1992 Local isotropy in high Reynolds number shear flows. *CTR Annual Research Briefs,* Center for Turbulence Research, Stanford Univ./NASA-Ames.

VAN ATTA, C. W. 1991 Local isotropy of the smallest scales of turbulent scalar and velocity fields. *A. N. Kolmogorov commemorative issue of Proc. Roy. Soc. A.* **434,** 139.

VAN ATTA, C. W., BALINT, J.-L. & WALLACE, J. M. 1992 Local isotropy of the vorticity field in turbulent flows. *Submitted to Physics of Fluids A.*

VEERAVALLI, S. V. & SADDOUGHI, S. G. 1991 A preliminary investigation of local isotropy in high Reynolds number turbulence. *CTR Annual Research Briefs,* Center for Turbulence Research, Stanford Univ./NASA-Ames.

VUKOSLAVČEVIĆ, P., WALLACE, J. M. & BALINT, J.-L. 1991 The velocity and vorticity vector fields of a turbulent boundary layer: Part 1. Simultaneous measurements by hot-wire anemometry. *J. Fluid Mech.* **228,** 25-51.