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Final Scientific Report AFOSR-82-0048

"Turbulent Boundary Layer Structure and Drag Reduction"

by

M.T. Landahl

and

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(Principal Investigators)

AFOSR-TR- 89-1402

SUMMARY

During the present grant period, the research work ~~has~~ progressed along the following lines: i) completion of the development of kinematic wave theory for propagation of waves for wave trains or wave packets with small dissipation through homogeneous or non-homogeneous media; ii) development of a simplified model for the influence of a large-eddy breakup device on turbulent boundary layer eddies; iii) completion of experimental and theoretical studies of transition spots in a plane channel flow; iv) preparation of experimental research on flat-plate laminar and turbulent boundary layers.

Theoretical Work

The work on kinematic wave theory for wave trains and wave packets with small dissipation has been completed and the work has been published (Landahl, 1982). In this it is shown that a proper extension of kinematic wave theory to wave packets with small dissipation and weak dispersion requires the use of complex wave numbers such that the group velocity becomes real. General evolution equations for waves in homogeneous and nonhomogeneous media are derived. This work allows the calculation to be made of the evolution over long distances of propagation of linear wave-like disturbances in a slowly varying boundary layer or other almost parallel shear flows and should be useful for transition studies.

The large-eddy breakup devices studied experimentally at IIT and at other laboratories achieve a reduction of the turbulence level in the turbulent boundary layer through the inhibition of the fluctuating vertical velocity by means of thin flat plates located at a distance from the surface of approximately 80% of the boundary layer thickness and spanning the plate. In our theoretical model a quasipotential inviscid flow is assumed with vortical disturbances hitting the thin plates. A preliminary analysis for one plate shows that a significant inhibitory effect is only obtained for eddies whose scales are of equal order or smaller than the chord of the thin plate. Inclusion in the model of a second plate downstream of the first (now in progress) is expected to show larger effects for gust scales of the order the plate separation distance.

In our experimental studies of the growth of turbulent spots in plane Poiseuille flow (see below), we observed strong oblique waves both at the front of the arrowhead-shaped spot as well as trailing from the rear tips. Growth of the region of small-scale turbulence occurred through the mechanism of breakdown of the leading-edge oblique waves, indicating that wave propagation and breakdown play a crucial role in transition to turbulence in Poiseuille flow.

A conceptual model has been proposed to explain the growth of the spot at Reynolds numbers well below the critical R_e of linear theory (approx. 5700). It has been proposed that three physical processes interact cyclically to generate and enlarge the spot: a moving region of mass-flow blockage; waves generated by a steady traveling disturbance; and three-dimensional instability of this wave field.

The moving region of blockage, which plays a crucial role in wave generation, comes about in the following manner: since the average wall-shear stress is larger, per unit mass flow, in the region of turbulent flow than in the surrounding laminar region, in the constant pressure drop of plane Poiseuille flow the mass flow in turbulent region will be less than that in the surrounding laminar region. Therefore, the moving region of small-scale turbulence within the spot acts as a moving region of blockage.

Calculations were done on the basis of linear theory to determine what wave field would be generated by such a moving region of blockage modeled as a moving point disturbance in a plane Poiseuille flow. Fourier analysis leads to a non-homogeneous Orr-Sommerfeld equation. Solutions, using the method of stationary phase and the requirement that the characteristics be real, predict that the wave field generated in a plane Poiseuille flow by a moving region of blockage consists of spatially damped oblique waves radiated both to the front and the rear of the blockage, in qualitative agreement with the experimental observations. It is postulated that these oblique waves are forced by the region of blockage to amplitudes such that they become unstable to three-dimensional disturbances along their crests, in agreement with theoretical results for three-dimensional instability of finite-amplitude shear waves and other such two-dimensional concentrations of vorticity. These instabilities further break down into small-scale turbulence which then increases the size of the region of turbulence of the spot and the cyclical process continues.

This model and the results of the calculation were presented at the Ninth Congress on Applied Mechanics, Cornell and at the Annual Meeting of the Division of Fluid Dynamics/APS, Rutgers.

2b) Experimental Work

Flow visualization of artificially-triggered transition in plane Poiseuille flow by means of 10-20 micron titanium dioxide-coated mica particles in a water channel revealed some striking features of turbulent spots. This method allows visualization of flow phenomena that do not remain with the fluid particle, and unlike tracer methods (ink, smoke or bubbles), allows the visualization of waves that travel through the flow. Both natural and artificially-triggered transition were observed to occur for Reynolds numbers slightly above 1000. The spots were followed visually downstream of their origin to a distance x/h of about 300.Video-taped records of spot development show that the front of the spot moves with a propagation speed of about 2/3 the centerline velocity while the rear portion moves at about 1/3 U_{cl}. The spot expands into the flow with a spreading half-angle of about 8 . After growing to a size of some 35 times the channel depth, h, at a downstream distance x/h of about 130, the spot begins to split into two spots, accompanied by strong wave activity. A paper on the results of this study has been prepared, Carlson et al. (1981), and has appeared in the Journal of Fluid Mechanics.

Strong oblique waves, thought to be Tollmien-Schlichting waves, were observed both at the front of the arrowhead-shaped spot as well as trailing from the rear tips. Both natural and artificially triggered transition were observed to occur for Reynolds numbers slightly above 1000, above which the flow became fully turbulent. Breakdown to turbulence was observed to occur on the wave crests and to be highly correlated with the wave field. These results indicate that wave propagation and breakdown play a crucial role in transition to turbulence in Poiseuille flow. We believe that such wave activity is an important cause of continued breakdown in wall-bounded turbulent flows.

Striking similarities as well as some differences were observed between transition spots in a channel flow as compared to those in a boundary layer. The observed strong wave activity is felt to be a characteristic of both types of spots; our flow visualization made visible what had been suggested by the hot-wire measurements of Wygnanski, Haritonidis and Kaplan (1979) that Tollmien-Schlichting waves play an important role in the breakdown to turbulence.

The observation of the splitting of the spot has not been reported for boundary layers. The role of the bounded geometry in removing the free stream as a possible source for new energy to sustain the flow, and the subsequent relaminarization of the center of the spot should prove an important input to the development of theoretical models of turbulence.

During the past year, use was made of the LDV system to measure the structure of the laminar flow in the channel. No difficulties were encountered in achieving sufficiently high signal-to-noise ratio from the system used in the back-scatter mode. During the continuation of these experiments, to be supported by NSF, we will use the LDV system to obtain transient data.

Considerable effort has been devoted to the preparations for experimental research on flat-plate laminar and turbulent boundary layers. Most of the equipment to be used in the boundary layer studies has been acquired. Specifically, a PDP-11/55 DEC computer and peripherals have been installed and made operational. The peripherals include two CRT terminals, a system console, a hard-copy unit, a 160Mb disk, a 125 ips vacuum-column tape drive and a 16 channel, 12 bit, analogue-to-digital converter with a throughput to memory of 325 KHz, which is necessary for high Reynolds number studies.

The wind tunnel to be used for the boundary layer studies is also operational and a special test section was constructed for the flat plate. The three aluminum plates which will constitute the flat-plate to be used have been machined to specifications, including measuring ports, smoke injection slots for flow visualization etc. What remains, is to assemble them in the test section along with the traverse.

Additional equipment which has been acquired includes a microscope for hot-wire construction, assorted hot-wire construction material, an oscilloscope and all the components for the hot-wire sets.

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