Measurements of the Wall Shear Stress in Boundary Layer Flows

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Abstract
It is argued that a direct measurement of the wall shear stress is important in all but the simplest of boundary-layer flow situations. Wall shear stress data obtained with a floating element device are presented for a fully developed turbulent boundary layer on a rough (cast) surface, and for boundary-layer transition on a smooth wall. Comparisons of the data with estimates of the wall shear stress obtained from indirect techniques in common use show considerable differences.

Introduction
An accurate measure of the wall shear stress $\tau_w$ is essential to the proper understanding of the behaviour of any boundary-layer flow. The techniques generally used to determine $\tau_w$ may be classified into three categories: momentum methods, wall similarity techniques and direct measurements. A description of these different approaches and their limitations so far as turbulent boundary layers are concerned is contained in articles by Browp and Joubert (1969) and Winter (1977).

The present paper underlines the importance of a means for the direct determination of the wall shear stress in all but the simplest of boundary-layer flow situations. Similarity techniques are all based on the existence of a region adjacent to the surface where a universal law of the wall $u/u_\tau = f(u_\tau y/v)$ is assumed to exist, and are practically limited to turbulent boundary layers on smooth surfaces. The limitations of momentum integral methods to obtain the wall shear stress are also well known, especially in rapidly developing flows and in the presence of pressure gradients. Even for nominally two-dimensional zero-pressure-gradient boundary layers, an extremely small change in flow cross-section suffices to introduce significant errors into the deduced skin friction.

In view of these limitations, questions are frequently raised about the validity and accuracy of skin friction data obtained using such techniques in “non-standard” boundary layers such as those undergoing transition, or flows with wall roughness, pressure gradients, or three-dimensional effects. Efforts are being made to use laser anemometry for the measurement of the mean velocity gradient close to the wall (Mazumder et al. (1981), Reynolds (1983)) which could provide a useful alternative to obtain the wall shear stress for flow over smooth surfaces. However, at present, the direct measurement of wall shear stress using a floating element device is the only viable possibility in most instances, even though the use of such devices in the presence of pressure gradients is beset with difficulties.

In the following, measurements of the wall shear stress made using a floating element device are presented for two different situations: a fully developed turbulent boundary layer on a rough (cast) surface, and a boundary layer undergoing laminar-to-turbulent transition on a smooth wall. In both cases the flow is incompressible, with a low external turbulence level and zero pressure gradient. The data are examined and discussed in the context of currently accepted ideas about such flows.
Facility and Instrumentation

Wind Tunnel

The experiments were conducted in an open-circuit low-speed boundary-layer tunnel of a design similar to that of Bradshaw (1972). An aerofoil-type centrifugal blower is followed by a straight-sided wide-angle diffuser leading to a settling chamber with nominal dimensions of $800 \times 800$ mm. A honeycomb and screens are installed in the settling chamber which is followed by an $8:1$ two-dimensional contraction leading into the working section. This entire flow-conditioning section is mounted on a frame so as to be moveable as a unit. The 3 m-long test section has an entry cross-section of $800 \times 100$ mm and is mounted on an independent frame. The upper wall of the test section is the working wall on which the boundary layer of interest develops; the lower flexible wall may be adjusted to generate the desired streamwise pressure gradient. The test section and contraction may be bolted together directly or, for transition experiments, a boundary-layer bleed device may be inserted in between to obtain a laminar boundary layer with a well defined origin. Maximum airspeed for zero pressure gradient is about $45$ m/s. A feedback control circuit regulates the blower speed to maintain the static pressure difference across the contraction (i.e., essentially the dynamic pressure at the contraction outlet) at a desired value. Different test plates with the desired surface characteristics may be installed. Each plate carries a series of $90$ mm access ports with interchangeable plugs, so as to enable access to the boundary layer with a floating element device or probe traverse.

Instrumentation

With the exception of the floating element device, all instrumentation used is standard and will not be described here. Data acquisition is accomplished through a custom-built interface to a PDP 11/04 minicomputer. The system enables simultaneous acquisition of 8 channels of data, with a maximum data rate of $500$ kHz for single-channel operation. Up to four channels of data can be pre-conditioned (biased and amplified) to make best use of the $\pm 10$ V (10 bit resolution) dynamic range of the ADC. Boundary-layer profiles are measured under computer control and the data either processed on-line or stored for subsequent processing. Floating element data are individually recorded, with the element being checked for proper operation at each measurement.

Floating Element

The floating element, shown schematically in Fig. 1, is of the nulling type, with a range of $1000$ $\mu$N, and a resolution of $1$ $\mu$N. The central component, which acts as a balance, is the movement of a precision galvanometer which supports the element itself, a disc of $20$ mm diameter. The movement is carried on an assembly of five aluminium slabs. Nine differential screws, each with a movement of $50$ $\mu$m/turn, permit accurate positioning of the element in the surrounding baseplate. The position of the black-white interface on a target mounted on the back of the element is detected by a fibre-optic scanner with a spatial definition of $0.25$ $\mu$m.

The galvanometer coil system and optical position detector operate in a feedback control loop. A force applied to the element moves it away from its null position. The resulting output of the position detector is amplified and integrated to produce a current through the coil which imposes a counteracting torque to drive the element back towards its null position. A proportional-integral-differential (PID) controller is used to ensure high accuracy and good transient behaviour. The coil current is directly proportional to the imposed