Laser Interferometer/Preston Tube Skin-Friction Comparison in Shock/Boundary-Layer Interaction

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Introduction

THE Preston tube is a simple surface-pitot-pressure method by which skin friction may be estimated. It is known to be effective for attached turbulent boundary layers at equilibrium or subject to mild pressure gradients. However, because there have been no reliable methods to evaluate Preston tube accuracy in strong viscous/inviscid interactions and separated flows, previous Preston tube measurements in such flows have been of unknown accuracy.

A recent development, the laser interferometer skin-friction (LISF) meter,[1-3] has been shown to produce reliable skin-friction data in a wide range of flow situations, including strong viscous/inviscid interactions. This technique interferometically senses the time rate of thinning of an oil film on a polished surface subjected to aerodynamic shear. The experimental calibration[3] of the LISF meter for use in compressible flows revealed that the accuracy of the LISF data was within ± 3 to $\pm 6\%$ of the mean of the calibration standards used, depending on Mach number. No known skin-friction technique has a trusted accuracy better than about $\pm 3\%$.

The purpose of this Note is to evaluate the accuracy of the Preston tube by comparison with the already proven LISF meter in a swept shock-wave/turbulent boundary-layer interaction, thus determining whether or not Preston tube measurements are, in fact, useful in such flows. Specifically, the Preston tube was applied to estimate the local shear-stress distribution in a fin-generated swept shock-wave/turbulent boundary-layer interaction. The nominal freestream Mach number was 4.0, the Reynolds number Re_θ was 11,160 at the location of the fin leading edge, the wall temperature was almost adiabatic, and the fin shock-generator angle was 16 deg.

Brief Review of the Preston Tube

A Preston tube is a circular, flat-ended pitot tube resting on a test surface and measuring an impact pressure from which the local shear stress is estimated. This method is based on the universal law-of-the-wall similarity of turbulent boundary layers. Many investigators have studied the Preston tube in zero and mild-pressure gradient flows and proved the validity of this technique. However, in strong-pressure gradient flows, the wall similarity on which the Preston tube relies can break down. Patel[4] and Brown and Joubert[5] discussed the accuracy and limiting conditions of the Preston tube in severe favorable- and adverse-pressure gradient flows and concluded that the Preston tube overestimates skin friction in such flows. However, Winter[6] noted, based on the measured velocity profile in a strong adverse-pressure gradient flow, that even though the logarithmic region in the boundary-layer profile may be entirely absent, a sufficiently small Preston tube might still be applicable.

Allen[7] thoroughly discussed the existing *compressible-flow* Preston tube calibration methods and reevaluated[8] them, based on available skin-friction data. Those calibrations due to Fenter and Stalmach; Sigalla; Hopkins and Keener; Patel; Allen; and Bradshaw and Unsworth were considered.[7] All these calibration methods except that of Bradshaw and Unsworth[9] (which is entirely based on wall conditions) use the reference temperature concept, which is based on boundary-layer edge conditions. However, in strong viscous/inviscid interactions with separated flow, a boundary-layer edge often cannot be identified. Furthermore, logarithmic wall similarity is dependent only on the flow conditions near the wall. Keener and Hopkins[10] previously realized this problem and showed theoretically that the fluid properties in their calibration equation could be evaluated at wall conditions without serious loss of accuracy. Thus, in this paper, the Bradshaw-Unsworth method as reevaluated by Allen[8] and the Keener-Hopkins[10] method are used to evaluate the skin-friction distribution measured by a Preston tube.

Experimental Methods

The experiment was conducted in the Supersonic Wind Tunnel Facility of the Penn State Gas Dynamics Laboratory, which has a test section 152 mm wide, 165 mm high, and 610 mm long. The interaction test surface was a flat plate, 495 mm long, that spanned the test section. The plate was fitted with both surface-pressure taps and surface thermocouples. An unswept fin shock-generator was located with its sharp leading edge 216 mm from the plate leading edge and 26.2 mm from the tunnel sidewall. The fin was 76 mm high, 127 mm long, and 6.35 mm thick. The test Mach number M_∞ was fixed at 3.96 ± 0.043 in this study. The stagnation pressure $p_0 = 1.524$ *MPa* $\pm 0.6\%$ and stagnation temperature $T_0 = 287.5$ K $\pm 2.2\%$ yielded a freestream unit Reynolds number $R_e = 7.06 \times 10^7$/m $\pm 3.6\%$. The incoming boundary-layer thickness, displacement thickness, and momentum thickness at the location of the fin leading edge were 3.0, 0.91, and 0.16 mm, respectively. For more information concerning the wind tunnel and test geometry, refer to Kim et al.[3]

To determine local shear-stress directions in this three-dimensional flow, the kerosene-lampblack-adhesive tape technique[11] was used. This method produces undistorted, full-scale surface-streamline patterns. Such a pattern[3] was obtained for the present test conductions and was used to measure the local surface-streamline direction corresponding to a given Preston tube measuring location.

For the Preston tube, a stainless-steel hypodermic tube having a circular, squared-off end was used. The inner diameter was 0.457 mm and the outer diameter was 0.813 mm, yielding a diameter ratio of about 0.6, as in previous investigations.[4,7,12] This geometry and the present test conditions produce a ratio of the Preston tube outer diameter to the incoming boundary-layer thickness, d/δ, of about 0.27. According to Allen's criterion,[13] the useful range of Preston tube size, d/δ, for the current test conditions lies within $0.07 < d/\delta < 0.375$. Further, based on Hopkins and Keener's criterion[12] for the current test conditions, d should lie between 0.19 and 1.04 mm. Thus, the present Preston tube satisfies both criteria.

Eleven Preston tube measuring locations were chosen along a circular arc of $R = 108$ mm about the fin leading edge. This arrangement was chosen to take advantage of the quasiconical

Received April 5, 1990; revision received July 25, 1990; accepted Aug. 1, 1990.

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symmetry of the interaction.[14] At each measuring location, the Preston tube was aligned parallel to the local surface-streamline in the pattern described previously. The Preston tube pressure p_{preston} and the wall pressure p_w were read at each measuring location. However, p_w was measured 5.1 mm upstream of the Preston tube along a conical ray from the virtual origin, as allowed by the concept of quasiconical interaction symmetry. Seven channels of data were recorded simultaneously: p_0, p_∞, p_w, p_{preston}, T_0, and two T_w channels, where p_∞ is the freestream static pressure and T_w the wall temperature.

Results and Discussion

The measured Preston tube pressure and wall-pressure distributions are plotted in Fig. 1 as functions of the angle β, which is the angle with respect to the freestream direction measured from the fin leading edge. Both Preston tube pressure and wall-pressure distributions show the same trend as the skin-friction distribution measured by the LISF meter (shown in Fig. 2). There is a small local peak just before the secondary separation line at $\beta_{ss} = 32.6$ deg. From this location aft to the primary-flow attachment line ($\beta_{pa} = 19.2$ deg), a steep rise in both p_{preston} and c_f occurs. This is due to the λ-shock structure of the interaction, which causes the impingement of a high-speed jet upon the flate plate near the attachment line. The subscripts of β_{ui}, β_{ps}, and β_{is} in Fig. 2 represent the upstream influence, primary separation, and inviscid shock, respectively.

A comparison of Preston tube c_f obtained using the Bradshaw-Unsworth and Keener-Hopkins calibrations with the LISF c_f data is also given in Fig. 2. Both Preston tube calibrations show similar results. From the beginning of the interaction to the secondary separation line, the Keener-Hopkins method produces c_f values within $\pm 5\%$ of the LISF result. Aft of this location, the Preston tube c_f overestimates that of the LISF meter by a maximum of 40% around the attachment line of the interaction.

This error was observed to be primarily due to calculating the Preston tube Mach number using the familiar Rayleigh pitot formula. Near the primary-flow attachment line, the observed flow structure[15] involves jet impingement on the flat plate. Due to the resultant flow angularity, the Rayleigh pitot

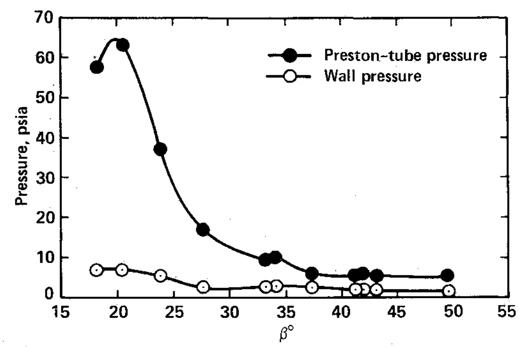

Fig. 1 Preston tube pressure and wall-pressure distributions.

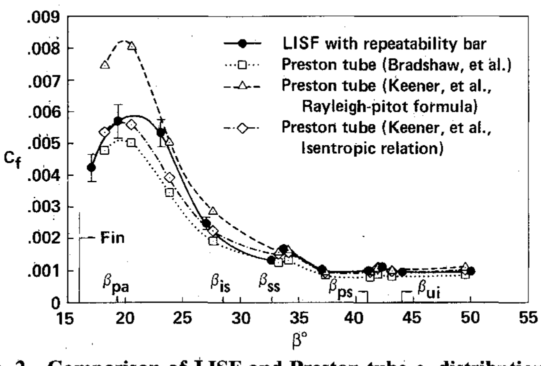

Fig. 2 Comparison of LISF and Preston tube c_f distributions.

formula appears not to produce a reliable Mach number here. Instead, the isentropic relation was found to produce a Mach number leading to better c_f agreement in this particular case. The c_f result thus obtained agrees within $\pm 10\%$ with the LISF c_f result, as shown in Fig. 2.

Unlike the Keener-Hopkins method, the method of Bradshaw and Unsworth uses a "friction Mach number" instead of the Preston tube Mach number to account for compressibility. Overall, the Bradshaw-Unsworth method consistently underestimates the LISF c_f values by about 20%.

Both Preston tube calibrations appear to have been successful in providing useful estimates of the present skin-friction distribution, even though the presence of a traditional logarithmic wall region is doubtful in the present flow. However, the discrepancy between the results of these calibrations is not understood, especially since no such discrepancy occurred in similar experiments by Fernando et al.[16]

Conclusions

Preston tube measurements have been made of the wall shear stress in a fin-generated swept shock-wave/turbulent boundary-layer interaction. The freestream Mach number is 4.0 and the fin shock-generator angle is 16 deg. Preston tube c_f results are compared with the more fundamental LISF c_f measurements, which are used as a standard. The Keener-Hopkins calibration method using the isentropic relation to calculate the Preston tube Mach number produces the best result (within $\pm 10\%$) in this case. However, this conclusion cannot be extended to strong viscous/inviscid interactions in general, because, in principle, the Preston tube calibration assumptions are violated in such flows. More experiments would be required to decide the general applicability of the Preston tube in such flows.

Acknowledgments

This research was supported by the NASA Ames Research Center. The authors thank Morris Rubesin of NASA Ames for having suggested this experimental comparison. Helpful discussions with E. R. Keener of NASA Ames are also greatly appreciated.

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Mechanical Fastening of FGRP Composites

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Introduction

In this study, high-sensitivity moire interferometry was used to obtain the stress/strain distribution in the vicinity of hole arrays in composite materials. Three configurations were considered, one having the two holes in a row parallel to the load direction. Ideally, in this case, if all of the pins are identical and the pin/hole interactions are the same, symmetry can be assumed; then each pin will carry one-half of the applied load. This situation was simulated first using cables and pulleys to divide the load. However, in less ideal conditions, some load misalignment can exist, thus producing a nonuniform distribution of load between the hole pins. In order to simulate the worst condition, the holes were loaded individually, one at a time.

The purposes of these experiments were 1) to determine the stress/strain distribution around the loaded holes for the arrays; 2) to study the interactions between the holes; and 3) to determine the effects on the stress/strain distribution when only one hole is loaded.[1,2]

Background

Because of lower manufacturing costs, improved strength/weight performance, and greater design flexibility, composites are replacing metals in many fields. The increasingly large range of ingredients available, the improving quality of resin and fiber materials, and the increasing knowledge of the mechanics of fiber-reinforced materials further expands the potential range of application.

The automotive and aerospace industries, which use composite materials widely, seek improved design criteria and design guidelines. This creates the necessity for analyzing the most efficient joining methods from both the mechanics and production viewpoints. Mechanically fastened joints are necessary since, for reasons of maintenance repair and assembly, adhesive joining becomes inappropriate. This idea of mechanical connectors creates concern because the internal structure of the composite is disturbed, maybe even destroyed, by cutouts or holes.

Received Sept. 18, 1989; revision received Oct. 25, 1989.

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Composite materials are frequently joined by single or multiple bolts or rivets. The strengths of such joints depend on the number and spacing of the bolts, end distance, bolt clearance, load distribution, material properties, hole treatment, presence of washers, preloads, and so on. This introduces design problems since a design approach based on scientific knowledge, as opposed to phenomenological testing, is not yet available.

What is lacking is a thorough knowledge of the interaction of mechanical fasteners and the composite material. Modeling of fastener/material interactions and experimental inquiry with emphasis on stress/strain failure are necessary steps which will lead to the desired design protocol. This experimental analysis was endeavored to gain the needed mechanics data to aide in devising a further advanced model design.

Applications of Composites

There are many reasons for the use of fiber-reinforced composite materials; some are stated here: 1) To strengthen and stiffen the matrix, 2) to achieve controlled mechanical and physical properties, 3) to enhance the ratios between mechanical properties and the specific weight of structural materials, and 4) to attain manufacturing cost reductions while maintaining mechanical and other properties.

The aircraft industry has recognized the countless advantages of high-strength, low-weight composites, i.e., carbon and graphite fiber laminates, and is presently using these materials in wing assemblies and in various other areas. A drawback in using these high-duty composites is their extraordinary cost. This has kept their use in the automotive industry low, but the future should create the availability of other high-duty fibers instigating a competitive market and lower costs.

This great interest in composite materials leads us back to the investigation of mechanical fasteners, since they play a major role in maintenance and assembly.

Principle Mechanical Observations

A unique moire interferometer system and computer-based data acquisition and reduction capability, for measuring surface strains along three directions over a region, was developed and proven to have the correct sensitivities for research on composites.

Surface strain maps were obtained by the moire methods for single hole plus pin, two-hole, and three-hole staggered joint configurations. These maps include strains along the longitudinal, transverse, and 45-deg directions for the entire region of the joint.

A table of stress concentration factors (SCF) fastener arrays in various load configurations was developed from moire investigations of strain fields in the joint regions. For the single-hole array, the maximum SCF was 14, while the two-hole tandem, two-hole parallel, and three-hole staggered, exhibited SCF's of 5.6, 1.16, and 2.95, respectively. Since multiple-fastener arrays result in a statically indeterminate situation, the effect on SCF of manufacturing imperfections, which cause most of the load to be concentrated at one pin of the array, must be considered.

Fasteners that are not at right angles to the specimen surface, as would be caused by misaligned holes or crooked holes, can cause deviations in the stress values in excess of 200% of the value measured or calculated for the ideal case. Similar effects can be shown for holes that are tapered or bell shaped.

The well-fitted pin peak strains obtained by the moire techniques are higher than those observed for ill-fitting pins, and these can probably be taken as accurate worst-case strain distributions. These results can be used to simulate upper and lower bounds on the magnitudes of stresses that will be realized in comparable design situations.

Measurements of surface strain can be catastrophically misleading for laminated composites unless test conditions are carefully established and care is taken in the interpretation of test results.