Transducer for Direct Measurement of Skin Friction in Hypervelocity Impulse Facilities

C. P. Goyne,*, R. J. Stalker,† and A. Paul‡
University of Queensland, Brisbane, Queensland 4072, Australia

An acceleration compensated transducer was developed to enable the direct measurement of skin friction in hypervelocity impulse facilities. The transducer incorporated a measurement and acceleration element that employed direct shear of a piezoelectric ceramic. The design integrated techniques to maximize rise time and shear response while minimizing the affect of acceleration, pressure, heat transfer, and electrical interference. The arrangement resulted in a transducer natural frequency near 40 kHz. The transducer was calibrated for shear and acceleration in separate bench tests and was calibrated for pressure within an impulse facility. Uncertainty analysis identified only small experimental errors in the shear and acceleration calibration techniques. Although significant errors were resolved in the method of pressure calibration, total skin friction measurement errors were low at 9–12% and the transducer was successfully utilized in a shock tunnel and sample measurements are presented for flow conditions that simulate a flight Mach number 6.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>pressure calibration constant (slope), V/da2</td>
</tr>
<tr>
<td>Cf</td>
<td>local shear-friction coefficient, m/s2/deg2</td>
</tr>
<tr>
<td>e</td>
<td>acceleration calibration constant</td>
</tr>
<tr>
<td>D</td>
<td>diameter of skin-friction transducer sensing disk, m</td>
</tr>
<tr>
<td>d</td>
<td>shear calibration constant (slope), V/da2</td>
</tr>
<tr>
<td>ε</td>
<td>pressure calibration constant (voltage axis intercept), V</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity, m/s2</td>
</tr>
<tr>
<td>h</td>
<td>enthalpy, M•kg</td>
</tr>
<tr>
<td>J</td>
<td>moment, N•m</td>
</tr>
<tr>
<td>M</td>
<td>mainstream Mach number</td>
</tr>
<tr>
<td>m</td>
<td>mass, kg</td>
</tr>
<tr>
<td>P</td>
<td>static pressure, kPa</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number, U•L/μ</td>
</tr>
<tr>
<td>u, v</td>
<td>mainstream velocity, m/s</td>
</tr>
<tr>
<td>w</td>
<td>Cartesian velocity components</td>
</tr>
<tr>
<td>V</td>
<td>voltage, V</td>
</tr>
<tr>
<td>x</td>
<td>Cartesian coordinate and distance from leading edge, m</td>
</tr>
<tr>
<td>y</td>
<td>Cartesian coordinate</td>
</tr>
<tr>
<td>z</td>
<td>length of moment arm, m</td>
</tr>
<tr>
<td>θ</td>
<td>angle in shear calibration technique</td>
</tr>
<tr>
<td>ν</td>
<td>mainstream viscosity, Nm/s</td>
</tr>
<tr>
<td>ρ</td>
<td>mainstream density, kg/m3</td>
</tr>
<tr>
<td>τ</td>
<td>boundary-layer shear stress, Pa</td>
</tr>
</tbody>
</table>

Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>acceleration component</td>
</tr>
<tr>
<td>p</td>
<td>pressure component</td>
</tr>
<tr>
<td>s</td>
<td>stagnation</td>
</tr>
<tr>
<td>sf</td>
<td>skin-friction component</td>
</tr>
<tr>
<td>w</td>
<td>wall</td>
</tr>
<tr>
<td>O</td>
<td>zero-deg orientation</td>
</tr>
<tr>
<td>1</td>
<td>measuring piezoelectric element</td>
</tr>
</tbody>
</table>

Received 8 May 2000; revision received 16 February 2000; accepted for publication 13 June 2001. Copyright © 2001 by the authors. Published by the American Institute of Aeronautics and Astronautics, Inc. with permission. Copies of this paper may be made for personal or internal use, or for the personal or internal use of specific clients, provided that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, include the code 0001-1452/01 $10.00 in correspondence with the CCC. Postgraduate Scholar, Department of Mechanical Engineering, James G. Summey Research Associate, Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA 22904. Member AIAA./displayed Professor, Department of Mechanical Engineering, Associate Fellow AIAA. Senior Research Fellow, Department of Mechanical Engineering.

Introduction

Skin friction drag is expected to limit significantly the performance of vehicles designed for sustained hypersonic flight. For example, estimates indicate that skin friction can contribute around one-third of the total drag of propelled devices such as scramjet engines.1 On vehicle surfaces, the skin-friction component can be expected to be even higher. If one considers a flat plate at incidence at Mach 16, for example, and assumes a turbulent boundary layer with a skin-friction coefficient of 1.7 × 10−4, then it is readily shown that the inviscid drag is equal to the viscous drag when the angle of attack is 3 deg. This angle of surface incidence is of the same order as can be expected for sustained hypersonic flight. Thus, considering the vehicle and propulsive device, it is clear that the total skin-friction drag will be a major component of the overall vehicle drag. Although the skin-friction component is expected to be significant, actual levels are difficult to predict accurately, and this is largely due to the challenges of directly measuring skin friction in hypervelocity facilities.

Hypervelocity impulse facilities, such as shock tunnels and expansion tubes, provide the only practical means of producing the high-Mach-number and high-stagnation-enthalpy flows that correctly simulate hypersonic flight. Test times in these facilities, however, are extremely short. For example, test time lengths for shock tunnels and expansion tubes capable of scramjet testing are typically a few milliseconds and a few hundreds of microseconds, respectively. Hence, skin-friction instrumentation must have an appropriately fast response to shear loads. The transient nature and high levels of heat transfer, pressure, and acceleration in the test section exacerbate this viewpoint. Such factors have contributed to a lack of accurate skin-friction instrumentation for hypervelocity impulse facility testing. This has resulted in a lack of data for high-enthalpy flows and, hence, considerable uncertainty exists in relation to theoretical skin-friction production methods.

A skin-friction transducer is only suitable for use in an impulse facility if its response time is short. Transducers with short response times inherently have light stiff components with large internal damping. This results in a highly resonant gauge that has multiple natural frequencies and has a gain that varies with input frequency. According to Wright,2 such transducers can be used to make valid wave shape measurements up to 25% of the first natural frequency. Up to this point, the amplitude response will vary by a maximum of 5%, and the phase response will be approximately linear. Thus, a skin-friction transducer with high natural frequencies will allow a more accurate reproduction of a high-frequency skin-friction wave shape. The importance of high natural frequencies for an impulse
flow skin-friction transducer can also be demonstrated by considering the length of steady test time available from the facility or the length of a particular event of interest being a test. At least five cycles of the lowest natural frequency is generally regarded as a conservative estimate, if mean level information is to be obtained even a signal. If, for example, the available test time is half a minute, then a lowest natural frequency of at least 10 Hz would reasonably be required. If skin-friction fluctuations with a period of, say, one-fifth of this test time are to be resolved accurately, then the requirement of [Form] would dictate a lowest natural frequency of at least 40 Hz. Although this choice is somewhat arbitrary, experience has shown that a skin-friction transducer with a lowest natural frequency near 40 Hz is suitable for resolving fluctuations resulting from unsteady processes such as combustion or boundary-layer transition.

High-frequency transducers that directly measure skin friction have been used in hypervelocity impulse facilities since the late 1960s. Four different transducers have been employed for the test with mixed success. Vollick[8] and Holdcroft[9] reported early use of skin-friction transducers in shock tunnels. The transducer consisted of two piezoelectric cantilever beams supporting a floating element flush with the model surface. A third cantilever with a meniscus attached, but not exposed to the flow, allowed for acceleration compensation. The arrangement resulted in a natural frequency of approximately 5 kHz (Ref. 9), which in the current context is relatively low.

Jensen et al.[10] described a skin-friction transducer that consisted of a 4-mm-diam floating element attached to a cantilever beam. Two semiconductor sensors gauged the deflection of the beam in two orthogonal axes, and thus enabled the two-component measurement of skin friction. The design resulted in a natural frequency near 10 kHz, and the gauge was applied to a shock tunnel. The authors reported that difficulties were encountered and were not fully resolved. Thermal loads resulted in millimeter gauge drift, and vibration affected the performance.

Dowson et al.[10] reported on a skin-friction transducer that was also applied to shock-tunnel experiments. The gauge consisted of a plastic cantilever that was presented to the flow with a 4-mm-diam floating element head. Two strain gauges were bonded near the head of the cantilever and were combined to cancel out pressure sensitivity. In an attempt to limit pressure gradient, heat transfer, and vibration effects, the cavity surrounding the cantilever was filled with silicon oil. The design resulted in a natural frequency of 10 kHz. Novera et al.[11] later modified the gauge to achieve a natural frequency of 70 kHz. In this transducer, the transducer was used in an expansion tube. Encouraging results were obtained. However, the potential for oil leekage from the sensing cavity via concerned oil collecting requirements and of contamination of other instrumentation. In some tests, silicon rubber was used in place of the silicone oil. The author found to reduce the sensitivity and increase the effects of vibration and pressure gradients. For the present study, the potential for oil or rubber in the gap surrounding the floating element of the skin-friction transducer was, therefore, regarded as detrimental to its operability and performance. It may be argued that the unfilled gap will lead to measurement errors that the transducer is operated in a flow with a pressure gradient; how this translates to a new gauge designed to reduce the induced errors to the point that they are one to two orders of magnitude lower than skin-friction levels.

To achieve higher natural frequencies than obtained with cantilever-type transducers, Kelly et al.[12] developed a skin-friction transducer that employed direct shear of a piezoelectric element. The gauge was applied to shock tunnels. The design consisted of a floating element sensing disk that was directly adhered to a series of piezoelectrics. Early designs resulted in natural frequencies above 300 kHz, although later modifications[13] reduced natural frequencies to the range of 40-60 kHz. Figure 1 illustrates an acceptable shear calibration technique, independent of the shock-tunnel test flow, was not established. This resulted in the need to infer a calibration from the transducer from other measured test flow parameters. The gauge was also severely affected by vibration of the test model.

This paper reports on a new skin-friction transducer that has resulted from further development and development of the gauge to Kelly et al.[14] and Kelly[15]. The new transducer incorporates features to minimize the effects of acceleration, pressure, heat transfer, and electrical interference, while maximizing shear response and maintaining a relatively high first natural frequency, of approximately 40 kHz. The gauge is manufactured at the University of Queensland and has been applied to transonic, transitional, and supersonic boundary layers in a shock tunnel[16] and to supersonic combustion experiments in a shock tunnel[17]. The stagnation enthalpy of the test flows simulated flight Mach numbers in the range of 5-12. The paper begins by describing the design and calibration of the new gauge. Particular attention is paid to the experimental uncertainty inherent in the calibration and measurement techniques. Some sample experimental results are then highlighted before the conclusion.

**Design**

**A. Piezoelectric Effect**

The piezoelectric effect is a most appropriate method for sensing shear stresses in hypervelocity impulse facilities. Piezoelectric elements are relatively stiff and result in high transducer natural frequencies with minimal distortion under load. More recently, the shear response of such elements can be effectively decoupled from other forces such as tension, compression, and transverse shear. Piezoelectric transducers also typically have a large dynamic range and exhibit very little hysteresis.[18]

Iaffe et al.[19] define piezoelectricity as the ability of a certain crystal-like material to develop an electrical charge that is proportional to a mechanical stress. Conversely, the mechanical charge shaper when an electric field is applied. The piezoelectric material need for the present transducer is lead zirconate titanate ceramic (PZT), and six or all piezoelectric elements, PZT is highly anisotropic. From crystallographic considerations, it can be shown that PZT will produce a charge on an electrode surfaces that is linearly proportional to an applied shear force. Further, the charge output is not a function of tension, compression, hydrostatic forces (pressure), or orthogonal shear forces.[20]. This is precisely what is required as the material is operated in a fashion referred to as shear mode. Here the electrodes are located on a pair of parallel surfaces that are on a plane parallel to the poling axis of the material. Thus, a skin-friction gauge incorporated into a shock tunnel will have a defined axis of maximum sensitivity to shear and zero sensitivity to pressure and cross-axis shear. However, manufacturing deficiencies introduce some sensitivity to pressure and cross-axis shear, and as discussed later, calibration techniques can be used to quantify these effects.

**B. Transducer**

The gauge of the present study is schematically depicted in Fig. 1. The layout consisted of a measuring element that was exposed to the flow and its acceleration compensating element that was located within the gauge housing. The measuring element was passively subjected to shear, pressure, heat transfer, and acceleration, while the compensating element, exposed to the flow, experienced only acceleration forces. Each element incorporated one ring of PZT piezoelectric operated in shear mode. The use of one ring

Fig. 1 Schematic of skin-friction transducer.
in each element, rather than multiple rings, limited the transducer to the measurement of one component of skin friction.

The piezoelectric rings were 1.5 mm in thickness and the outer diameter was 8 mm. 0.2-mm-thick stainless steel tubing was located next to the electrode contact leads. The poling axis of the piezoelectric device was set parallel to the tangential flow. The duration of the probe was made to be sufficient for all the data to be collected, parallel to the axis of the piezoelectric probe. The piezoelectric ring was mounted flush with the model surface and formed the shear sensor of the gauge. The ring dimensions and model were similar to those chosen by Kelly et al. M and Kelly.5

Coatings of acrylic and polyurethane insulation and electrically conductive paint protected the sides of both ceramics (the conductive paint was applied over the acrylic and polyurethane and, hence, was electrically isolated from the piezoelectric). The sensing ceramic was also wrapped in approximately 11 layers of fine brass mesh. This acted to cool the freestream air that entered the cavity formed between the piezoelectric-shear sensor and the brass housing. Significant quantities of freestream air were expected to enter the cavity only up to the point of 20-50 μs after arrival of the test flow. This was determined by treating the invar-housing gap as a toric throat that vented into the known volume of the transducer cavity. Theoretical analyses indicated that the combination of insulation coating, and mesh were able to effect adequate thermal protection of the measuring piezoelectric for boundary-layer heat transfer loads of up to 7.5 MW/m² for a period of at least 5.3 s.

The sensing invar disk and the gauge housing defined a clearance gap of 0.16 ± 0.01 mm. Maximum displacement of the measuring element at the sensing disk was estimated to be 5 x 10⁻⁶ m. This was based on the total bending and sheath deflection of a PZT element for a 3000-Pa skin-friction load on the sensing disk. Each piezoelectric was adhered to a brass base, which was in turn located within the brass housing of the gauge. Component size and shape were optimized to maintain a possibility to maximize resonant frequencies of the piezoelectric assembly. As discussed later, the arrangement resulted in a first natural frequency of approximately 60 kHz.

To stimulate the acceleration response of the measuring element, the gauge housing was moved in a manner identified to the measuring element. Thus, the acceleration piezoelectric was also operated in shear mode, with the poling axis aligned along the same axis as that of the measuring element. Both ceramic were of the same dimensions and were coated with insulation and fasteners to prevent the gauge disk in the same manner. Brass mesh, however, was not applied around the acceleration element; instead, this was grounded. It was revealed that this did not degrade the accuracy of the accelerometer compensation method. Because the ceramics were exposed in shear mode, both elements were nominally only sensitive to acceleration in the poling axis. By monitoring the output of the acceleration element and the measuring element during test, the gauge could be compensated for acceleration by subtraction of one signal from the other.

Two purpose-built charge amplifiers were located within the gauge housing, and each amplifier was connected to one ceramic. When the gauge was subjected to a change in voltage that was proportional to the change in charge to the piezoelectric electrodes. The amplifiers had a rise time of 2 μs and a decay time constant of 47 μs. All metalic components of the gauge, including the electrically conductive piezoelectric and the polyurethane, were adequately earthed via coaxial connectors on the rear of the gauge housing. This resulted in a metallic sheath that fully encased the piezoelectric ceramics, electrodes, internal leads, and charge amplifiers. Hence, these elements were protected from background electromagnetic fields and any effects of ionization of the impinge facility test gas.

C. Mounting System

The mounting system was designed to maximize vibration and acceleration isolation of the skin-friction transducer while adequately locating the gauge and preventing test flow leakage. As shown in Fig. 2, a felt isolator system was adopted for the present transducer. Felt is a popular choice for high-frequency applications because of its high internal damping and a mechanical impedance that is similar to that of many engineering materials.1,2 (Hence, transmissibility of a felt to metal interface, for example, is low.) For the present system, felt washers were used on the front and back faces of the transducer base housing, and a smaller washer was mounted on the back of the electronics housing. This two mass housing washers located the gauge axially, and the rear washer located the gauge within the center of the tapping hole in the model. The use of paper shims and a threaded brass mounting sleeve enabled the mounting of the felt compressor to the rear of the sensor. This allowed flexibility of the sensing face with the model surface to be maintained; however, the arrangement resulted in the need to adjust the mount before every run in the impeller facility. The mount could be operated with the gauge mounted face down or face up, that is, mounted in the lower or upper wall of a test, etc.

Applied shear and pressure forces were expected to displace the transducer during the test time, and hence, appropriate amounts of mass were incorporated into the gauge housing to limit the effect. Based on the expected stiffness of the felt washers and a 3-mm diameter lip of 0.646 m, the gauge shear and pressure on the sensing face of the gauge, calculations indicated that transducer displacements would be significant. A 3000-Pa skin-friction load on the sensing face of the disk was expected to produce only 1.3 μm translation in the flow direction and 0.08° deflection about the center of mass. For static pressures in the range of 10–100 kPa, maximum axial translation away from the test flow was expected to be near 50 μm.

Because of the porosity of the felt washers, a finite amount of test gas was expected to leak through the skin-friction gauge mount. As a result of a lack of compressible flow data on felt leakage, a simple experiment was devised to measure the amount of leakage through the gauge mount. A skin-friction transducer was mounted in a test section calibration block, using the mount of Fig. 2, and a pressure differential was applied across the end gauge using a pressure calibration rig.7 The apparatus enabled known pressure to be applied to the test flow side of the skin-friction gauge mount. The pressure and temperatures at the rear of the mount remained at ambient room values. The velocity of air issuing from the rear of the mount was measured using a commercial air velocity meter. The point of measurement was at the exit of the gap between the skin-friction gauge and mounting sleeve. From knowledge of the air velocity, the dimensions of the gap and assuming ambient room density of the existing gas, the mass flow rate of air leakage was established to be (2.92 × 10⁻³) + (12.5 × 10⁻³) x 10 kgs for a pressure differential of 10 and 100 kPa, respectively.

To quantify the effect of these leakage levels on the instrumented boundary layer of an experiment, estimates were made of the mass flux in the boundary layer that were expected to pass over the transducer for a typical application. The experimentally determined leakage levels were found to be of the order of a few percent of the boundary-layer mass flux. Effects of such leakage can be regarded
as negligible when it is considered that actual test flow leakage will involve gas that is supplied by a high-enthalpy boundary layer. Gas temperatures in the vicinity of gauge to test model gap would be expected to be 2-6 times greater than that of the test device. Hence, actual leakage mass flow rates will be very low because of low flow density and high viscosity. Although the leakage rates are expected to be low, White et al. shows that even small amounts of water-layer leakage, or suction, can affect the local skin friction. To experimentally assess the effect of mount leakage on measured skin-friction levels, tests were conducted in the T4 shock tunnel in which the test mounting washers were replaced with impervious rubber O-rings. The measurements were conducted during testing of an early prototype skin-friction gauge and were obtained on a flat plate in air $Re = 3 \times 10^6$, $M = 0$, and $V = 3.0$ Mach ($V_w = 0$). Rubber O-rings were found to increase vibration and acceleration transmission to the skin-friction gauge and shorten the duration of useful signal from the transducer. However, up to 0.3 ms after the onset of the test flow, the skin-friction gauge was capable of functioning adequately while mounted using O-rings. When the transducer was mounted using rubber O-rings, the measured level of skin friction during the 0.3 ms period was the same as when mounted using felt washers. The tests, therefore, demonstrated that in the developing boundary layer of the test flow, the measured level of skin friction was the same with and without a small amount of leakage into the skin-friction gauge mount. Such a limited effect of mount leakage was expected because the boundary-layer momentum equation is considered for the case of localized suction. If the normal velocity of flow at the wall, $V_{w}$ is finite and there is no pressure gradient in the flow, then the momentum equation dictates that $\frac{\partial}{\partial y}V_{y}$ is finite very close to the wall. Hence, at the point of leakage to the felt mount, $V_{w} = 0$, and the distribution of $t_{u}$ and hence $t_{m}$ is affected. However, referring to Figs. 1 and 2 it is noted that the point of leakage is through the gap between the gauge mounting and model, as area that is removed from the shear-sensing surface of the skin-friction gauge. At the sensing surface itself there is no leakage, and $V_{w} = 0$, thus, $\frac{\partial}{\partial y}V_{y}$ is zero, and the skin-friction remains unaffected. On the model test surface, $V_{w}$ is also zero, and $\frac{\partial}{\partial y}V_{y}$ is zero. Noting that $\frac{\partial}{\partial y}V_{y}$ is low, it is apparent that there is a thin layer of fluid at that position and the skin-friction gauge is removed, and one constant shear layer is replaced by another in which the shear stress, and hence $t_{m}$, has the same value. Given that the level of skin friction was measured in a developing boundary layer with and without mount leakage, the shear layer thickness would appear to have no downstream effect on the level of skin friction encountered by the sensing surface of the gauge.

Calibration
The skin-friction transducer was calibrated for shear and acceleration in separate bench tests. Natural frequencies of the gauge and sensitivity versus mount orientation face were explored in bench tests. Pressure calibrations were obtained in situ, within the shock-tunnel flow, during the experimental program.

1. Shear Calibration
Shear calibrations were performed by monitoring the skin friction transducer output following the sudden release of a known shear load. The gauge was supported in a cast iron block using the mounting system of Fig. 2. As shown in Fig. 3a, the block was oriented so that the gauge-sensing disk was in the vertical plane, with the sensing axis horizontal. A cotton thread arrangement was then directly attached to the gauge-sensing disk using nylon string. The thread was approximately 0.2 mm in diameter. This arrangement, with a weight of known mass $m$, then produced an effective static shear stress, aligned with the sensing axis, according to

$$t_{m} = \frac{4mg}{\pi D^2 \cos(\theta)}$$

Here $t_{m}$ is based on the force applied through thread $A$ divided by the area of the sensing disk $D$ is the angle between the horizontal thread and, $g$ is the acceleration of gravity, and $D$ is the diameter of the sensing disk. The load on the gauge was then impulsively

released by striking the weight from below with a hard metal object. Shown in Fig. 3b, the output from the measuring piezoelectric $V_{1}$, typically had a 10-90% rise time near 1 ms. The relatively long rise time was confirmed to be an elastico-liquid trait of the cotton thread arrangement within the transducer and not a function of the skin-friction gauge rise time. In the confirmation test, thread $A$ was adhered to the center of the sensing diaphragm of a PCB 149C10 piezoelectric pressure transducer. The thread and transducer were arranged such that the sensing diaphragm plane was perpendicular to the applied force. The gauge had a manufacturer specified rise time of 2 μs. The pressure transducer output, resulting from load release, was found to have a rise time near 1.5 ms and was similar in shape to that of the skin-friction gauge. Sensitivity of the skin-friction transducer to a given shear load was established by determining the average level of the measuring element output $V_{1}$ over a given test time (as shown in Fig. 3b). To minimize errors introduced because of the charge amplifier decay time constant, the test time was chosen to resemble the shock-tunnel test time in terms of duration and time from load application. As evident in Fig. 3b, the acceleration piezoelectric response, $V_{2}$, was negligible during the calibration tests.

Calibrations were performed over a skin-friction range of 0-100 Pa and 0-4000 Pa. Gauge output was found to be very linear because the maximum deviation of the calibration points, from a zero-based best straight line, was less than 1.5% of full scale. A typical calibration and resulting linear regression are presented in Fig. 4. The coefficient of determination (coefficient of squared regression) was typically near 0.9998; indicating a highly significant linear correlation. Deviation of the regression line from the origin was neglected during subsequent gauge use, and this represented an error of 1% or less for typical measuring levels. For each of the calibration ranges, the calibration was checked by repeating the procedure with the gauge routed by 180°. Typical agreement for the calibration slope was near 1% for the two orientations of the average slope or shear sensitivity, $d$, was typically near 0.8 $10^{-3}$ V/Pa, and individual gauge calibrations were found to be very stable with age.
The total experimental uncertainty in $d$ was established to be near ±1%. This followed consideration of the random error introduced by the calibration method and systematic errors of establishing the mass of the calibration weights, the angle of thread C, and the diameter of the sensing disk. The systematic errors introduced through data recording and through possible misalignment between the sensing axis of the transducer and the calibration force applied through thread A were also considered.

Cross axis sensitivity, at 90°- and 270°-degree orientation, was explored for the 0-800-Pa calibration range. Sensitivity to transverse shear was typically near 6% of the measuring axis sensitivity. As example linear regression of cross axis calibration data is presented in Fig. 4.

B. Acceleration Calibration

Acceleration calibrations were performed by vibrationally exciting the gauge, along the sensing axis, using an electrodynamic vibra-
tor. The gauge was mounted rigidly to the vibrator drive spindle, and a reference accelerometer was mounted on the spindle centerline. A nominal excitation frequency of 300 Hz was used for the calibration. This frequency approximately matched the dominant frequen-
cy of acceleration experienced by gauges during early prototype

testing in the shock tunnel. A shock tower mounted at 1 kHz was also obtained, and it was established that the effect of altering excita-
tion frequency was small. Figure 5 presents typical outputs of the measuring $V_a$ and the acceleration, $V_a$, elements of the skin-friction

gauge and the accelerometer during electrodynamic vibra-
tor operation. The three signals can be seen to be in phase. A typical linear

regression of gauge rms output against accelerometer rms output is presented in Fig. 5. Acceleration of the ratio of measuring element
output to accelerometer element output allowed for routine subtrac-
tion of the acceleration component of the measuring element signal

during service. The mean acceleration calibration constant $c = (V_a/

rms \sqrt{rms})_{mean}$ was typically 1.1.

An uncertainty analysis of the calibration method indicated that the constant $c$ could be determined to within ±3%. This estimate was based on a root square sum of the systematic uncertainty of data recording and a 95% confidence interval for the uncertainty of the mean of four calibration points.

C. Pressure Calibration

Pressure calibrations were obtained through a series of paired runs, in the shock tunnel, during the experimental program. The technique was found to produce more reliable and repeatable results than other bench top methods trials by Kelly. For the present tech-
nique, measurements were obtained for one condition in the impulse facility and then repeated with the skin-friction transducer rotated by 180 deg relative to the test flow. The shear component of the gauge output, $V_{ac}$, changed sign once rotated; however, the pressure output did not. With the assumption of a flat signal, as compared with the average static pressure measured adjacent to the transducer, the pressure sensitivity of the transducer was established. This technique is represented by

$$ V_p = (V_{ac} + V_{ad})/2 $$

where $V_{ac} = V_{ac} + V_{ad}$ and $V_{ad} = V_{ac} - V_{ad}$. Here $V_p$ and $V_{ac}$ are the acceleration compensated outputs of the skin-friction gauge for the two orientations. Calibration runs were conducted in the shock tunnel using the same test models that were used for the experimental program.

An example of a linear regression of $V_p$ as a function of the mean measured static pressure is presented in Fig. 7. Even though the data were obtained for a broad range of flow conditions, the correlation with average pressure is found to be highly significant. The data

represent tests with laminar and turbulent boundary layers, over a range of stagnation enthalpies, and tests with and without hydrogen

combustion in the freestream. Linear regressions, in the form of $V_p = bV_p + a$, were performed over a low- and high-pressure range for each skin-friction transducer. In general, the correlations were found to be significant. Absolute values of the pressure calibration constants, $b$ and $a$, were typically $4 \times 10^{-7}$ VPa and $10^{-5}$ V, respectively.

An uncertainty analysis for the pressure calibration technique was performed. The analysis accounted for factors such as systematic uncertainties in pressure measurement and data recording, repeata-

bility of static pressure and skin-friction levels between pairs of

calibration tests, and overall random error introduced by the tech-
nique. It was established that the total uncertainty in the constants $b$ and $a$ was approximately ±30% and ±200%, respectively. Such large uncertainty levels resulted from large random errors and reflected an inherent weakness of the current technique and a lack of com-

petitive calibration data for some gauges. However, for the flow

conditions of the experiments of Refs. 5 and 6, the pressure compo-
nent of the transducer signal, $V_{ac}$, was typically 10 and 30%, respec-
tively, of the shear component, $V_{ad}$. Therefore, as discussed later, the

resulting levels of total uncertainty in measured skin friction were acceptable, particularly for high Reynolds-number measurements.

D. Natural Frequency Determination

To circumvent a complex theoretical analysis, an empirical tech-
nique was devised to assess the resonant behavior of the skin-friction transducer. The technique provided an impulse input to the skin-

d fringe gauge sensing disk and, hence, excited a state of free-damped

vibration. The method involved rolling a 4-mm-diam., stainless-steel

ball bearing off a 25-deg ramp and onto the sensing disk. The ramp

was aligned with the transducer measuring axis, and the gauge was

supported in a cast iron block using the mounting system of Fig. 2.

The ball obliquely struck the disk on the measuring axis; however,

the impact point was away from the gauge axial center. This arrange-

ment was aimed at simultaneously exciting shear, translational,

and rotational modes of vibration. The ball bounced off the face of

the gauge and did not strike the transducer a second time. The output from the gauge measuring element indicated an impulse of approxi-

mately $40 \mu$s in duration was applied. Fast Fourier transforms were performed on the measuring and acceleration element outputs to
determine the spectral response of the gauge. In general, three to four
dominant resonant frequencies were identified for both the measur-
ing and acceleration elements. For the group of transducers tested, resonant frequencies were in the range of 30-60 kHz. The group
momentum is negligible, and hence, the effect is omitted from the calculation summary equations that follow. The resulting bias of this omission, however, is incorporated into the systematic uncertainty of the experimental measurements of skin friction.

E. Calibration Summary

The established skin friction constant can now be combined to determine the incident skin friction acting on the transducer during the experiment. The output of the transducer is related to the output of the expanding measuring element \( V_1 \) can be represented by

\[ V_1 = V_{O} + V_{P} + V_{C} \]  

where \( V_{O}, V_{P}, \) and \( V_{C} \) are the components of voltage output due to shear, static pressure, and experienced acceleration, respectively. The output of the protected acceleration element \( V_2 \) can be represented by

\[ V_2 = V_{P} + V_{S} \]  

where \( V_{S} \) is the voltage output due to experienced acceleration. Because the element is not exposed to the flow, the shear and pressure components of the signal are equal to zero. The calibration techniques have established the following:

1. acceleration, \( V_{A} = V_{A} \times 2 \); shear, \( V_{S} = \frac{dV}{dt} \); and pressure, \( V_{P} = -BP + \beta \Delta d \)

Combining these linear relationships with Eqs. (4) and (5) reveals the skin friction acting on the sensing disk of the gauge is given by

\[ \tau_s = \sqrt{\left| V_{O} - V_{1} - \frac{(BP + \beta \Delta d)}{2} \right|^2} \]  

Before estimates of the total uncertainty in determining \( \tau_s \) were made, consideration was given to errors introduced through transducer design and operation. According to the work of others,22,23 skin friction Preston pipe and flow disturbances to the boundary layer will be minimal for the transducer dimensions and boundary-layer conditions of interest. If the transducer is to be operated in a pressure gradient, consideration must be given to flow and tube wall effects on the measuring element because of unequal pressure around the edge of the sensing disk. As discussed earlier, moment sensitivity must also be considered. Further consideration of the uncertainty of the quantities in the right-hand side of Eq. (5), that is, uncertainty in the calibration constant and in pressure and voltage measurement, the total experimental uncertainty in measured skin friction was determined.24 The total uncertainty is dependent on test flow conditions and skin friction levels. However, for an experiment of Ref. 6, \( \tau_s \) could typically be measured to within ±5% for a laminar boundary layer, to within ±10% for a transition boundary layer, and to within ±20% for a turbulent boundary layer. Whereas, for the sparkrew combustion experiment of Ref. 5, \( \tau_s \) could typically be measured to within ±12%.

Table I provides a summary of the characteristics of a typical skin-friction transducer.

Measurements

The experiments were performed in the F4 free piston shock tunnel at the University of Queensland. The measurements reported here were obtained on a 1.5-m-long flat plate that formed one of the inner walls of a rectangular duct. The duct had a 120 × 60 mm inlet, which captured air issuing from the 260-mm-diam exit of the facility's hypersonic nozzle. Skin-friction transducers, thin-film bend flux gauges, and pressure transducers were mounted at a series of locations that extended axially along the instrumented plate. Measurements in laminar, transitional, and turbulent boundary layers were obtained. The experiment, results, and analysis are fully described in Ref. 6.

A time-averaged skin-friction transducer output for a laminar boundary-layer measurement is presented in Fig. 9. Figure 3a shows the raw output from the measuring and acceleration elements \( V_1 \) and \( V_2 \) respectively. The highly undamped, high-frequency moment behavior of the transducer is clearly evident. A 30-μs moving time average of the gauge output is presented in Fig. 9b. The measuring element signal shows a sudden positive increase following tests.
Table 1 Specification summary for a typical skin-friction transducer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum calibrat. range</td>
<td>6 to 6,000 Pa</td>
</tr>
<tr>
<td>Resolution (with 50-μs time average)</td>
<td>1 μV</td>
</tr>
<tr>
<td>Sensitivity (calibrated at 79°F)</td>
<td>0.8 x 10⁻⁷ V/Pa</td>
</tr>
<tr>
<td>Linearity (zero-based straight-line)</td>
<td>±5%</td>
</tr>
<tr>
<td>Cross sens. shear sensitivity</td>
<td>68</td>
</tr>
<tr>
<td>Pressure sensitivity</td>
<td>4 x 10⁻³ V/kPa</td>
</tr>
<tr>
<td>Linear response, frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Frequency range, 5%</td>
<td>30-100,000 Hz</td>
</tr>
<tr>
<td>(approximate ±10%)</td>
<td>15-12,000 Hz</td>
</tr>
<tr>
<td>Decay time constant</td>
<td>47 ms</td>
</tr>
<tr>
<td>Polarity (+ or -)</td>
<td>Positive</td>
</tr>
<tr>
<td>Mass (operating temperature)</td>
<td>380°C</td>
</tr>
<tr>
<td>Temperature sensitivity</td>
<td>-0.014°/K</td>
</tr>
<tr>
<td>Maximum linear pressure</td>
<td>-14 MPa</td>
</tr>
<tr>
<td>Sensing element diameter</td>
<td>10 mm</td>
</tr>
<tr>
<td>Element to bisingal gap (nominal)</td>
<td>0.16 mm</td>
</tr>
<tr>
<td>Prestress, nominal</td>
<td>-57.3 N</td>
</tr>
<tr>
<td>Maximum capac. pressure</td>
<td>14 MPa</td>
</tr>
<tr>
<td>Sensing element material</td>
<td>Foam</td>
</tr>
<tr>
<td>Density</td>
<td>98 ± 10⁻⁶ g/m³</td>
</tr>
<tr>
<td>Viscosity</td>
<td>4 mPa</td>
</tr>
<tr>
<td>Voltage to current regulator</td>
<td>12-24 V ± 5</td>
</tr>
<tr>
<td>Connector</td>
<td>BAK™ microA &lt; 2</td>
</tr>
</tbody>
</table>

![Fig. 9 Skin-friction transducer in laminar boundary layer: (a) raw output and (b) output with 30-μs moving time average.](image)

The measured skin-friction coefficient and static pressure for a turbulent boundary layer are displayed in Fig. 12. The data are identified in Fig. 12 in terms of the skin-friction transducer orientation to the test flow. Absolute values of skin-friction coefficient are displayed for the 90° deg measurement, and the general agreement of these values with the 0° deg data provides evidence of correct operation of the skin-friction transducer.
The magnitude of scatter in measured skin-friction coefficient was of the same order as in measured Stanton number. Theoretical laminar[9] and turbulent[10,11] predictions are all presented in Fig. 12. It can be seen that there is generally good agreement between theory and experiment. However, the high-Reynolds-number data do not agree with one turbulent boundary-layer correlation. Reference 6 identified a strong unit Reynolds-number trend in the difference between experiment and theory for these data and for other data at different stagnation enthalpies and Mach numbers. It was established that the correlations of van Driest[12] and Ekerdt[13] were in better agreement with the data at low unit Reynolds numbers. However, the Spalding and Chiu[14] correlation performed better at high unit Reynolds numbers. The unit-Reynolds-number trend was attributed to nonequilibrium turbulent boundary-layer flow at low unit Reynolds numbers, even though the measurements were obtained well downstream of a transition region defined using the heat flux data. The trend is somewhat reflected in the Reynolds number plot of Fig. 12. The results are discussed further in Ref. 6.

Conclusions

The design, calibration, and operation of a new acceleration compensated piezoelectric skin-friction transducer have been reported. The gauge is particularly suited to use in high-velocity impulse facilities because its lowest natural frequency is near 40 kHz.

The transducer design incorporated a measuring element that was exposed to the test flow and an acceleration element that was mounted internally. Each element contained a piezoelectric material that was operated in shear mode, and the ceramic's anisotropic characterization enabled pressure, transverse shear, and moments to be decoupled effectively from the skin-friction shear force. Thermal insulation, heat conduction control, electrical shielding, and vibration isolation were also important features of the new gauge design and mounting configuration.

The skin-friction transducer was calibrated for shear, acceleration, and moment inducing forces in separate bench tests. For these calibration tests, linear correlations between input and response were developed, and these correlations are used to calibrate this linearly over a wide operating range, (0-4000 ps I wall shear stress). Pressure calibrations were performed in situ, during the experimental facility. For this technique, the expressions of the results typically exhibited a significant linear correlation.

The design was optimized for the correction, compensation, and measurement methods. The inherent uncertainty in the pressure calibration technique introduced a large systematic relative error in skin-friction measurements for operating conditions typical of laminar boundary layers. It was established, however, that for more complex, less understood flows such as turbulent boundary layers and serrated combustion fields, skin friction could be measured to within a typical uncertainty of 5% to 12%.

Simple measurements from a shock tunnel were presented, and the results demonstrated reliable operation of the skin-friction gauge. The successful development of the new transducer has allowed further exploration of viscous drag trends encountered in hypersonic flight. Further investigation to reduce experimental errors, in particular, will allow even more accurate data.

Acknowledgments

The authors are thankful for the financial support provided by the Australian Research Council for operation of the T4 shock tunnel and for the financial support of the NASA Langley Research Center through NASA Grant NAGW-674, during early stages of the project. The authors are appreciative of the technical assistance provided by J. Brennan and R. Allsup in the development of the skin-friction transducers.

References


R. F. Lucht
Associate Editor