

Skin-Friction Gauge for Use in Hypervelocity Impulse Facilities

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Introduction

HYPERVELOCITY impulse facilities, such as free piston shock tunnels and expansion tubes, have an important role in the development of technologies for hypersonic flight. They are capable of generating the high-enthalpy flows associated with external aerodynamics of space planes at near orbital velocities and the internal aerodynamics of scramjet propulsion systems. Important model test parameters are drag and skin friction but their measurement is complicated greatly by the very short test times of impulse facilities. Skin-friction measurement is also made difficult because the wall pressure can be an order of magnitude greater than the wall stress generated by skin friction. Skin-friction gauges for use in conventional shock tunnels have been reported.¹ However, their ability to perform satisfactorily in the very short duration flows associated with free piston shock tunnels and expansion tubes does not appear to have been demonstrated. This Note reports the development of a transducer capable of measuring skin friction with a rise time of about 20 μ s. Results prove the effectiveness of the concept when used to measure skin friction on a flat plate.

Gauge Design

The gauge design is shown schematically in Fig. 1. It comprises a thin metal disk or thermal cover (10-mm diam and 0.4 mm thick) mounted flush with the surface of the model and bonded to a stack of two piezoelectric transducer elements (each 7 \times 7 mm and 1.5 mm thick). The material chosen for the elements was the piezoceramic PZT-7A. Its rigidity and density were such that, for the configuration in Fig. 1, gauge natural frequencies were above 300 kHz. In theory, the elements, appropriately orientated and with electrodes on the appropriate surfaces, respond only to the shear force generated by skin friction, but in practice, pressure sensitivity (normal to the disk) was found to be significant. For this reason the two-element gauge was designed, with one piezoceramic element inverted with respect to the other. One element provides an output e_1 proportional to the sum of the effects of skin friction τ and pressure p applied to the disk, and the other provides an output e_2 proportional to the difference [Eqs. (1) and (2) below]. A weighted summation of the two outputs therefore provides a direct measurement of shear stress:

$$e_1 = a_1\tau + b_1p \quad (1)$$

$$e_2 = a_2\tau - b_2p \quad (2)$$

A calibration procedure would involve applying a known transient shear stress, with $p = 0$, to the transducer to determine constants a_1 and a_2 , and a transient pressure, with $\tau = 0$, to the transducer to determine the ratio of constants b_1/b_2 . Hence, an unknown shear stress τ can be determined from Eq. (3) and simultaneous measurements of outputs e_1 and e_2 :

$$e_1 + (b_1/b_2)e_2 = [a_1 + (b_1/b_2)a_2]\tau \quad (3)$$

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Piezoceramics exhibit a Curie temperature above which they begin to depolarize. To avoid this, the thickness of the thermal cover and its material were chosen to prevent unacceptable levels of conductive heat transfer from the hot test gas in the boundary layer. Several materials were evaluated. Invar was finally chosen because it has a very small coefficient of thermal expansion, thereby preventing the transducer elements from being strained due to thermal expansion of the disk.

The impulsive nature of the flow in free piston shock tunnels results in stress waves in the model, with the skin-friction gauge exposed to a vibration-induced acceleration environment. To counteract this, rubber vibration isolation was included in the design (Fig. 1). The technique effectively lowered acceleration induced output from the gauge to a level that could be handled by filtering during signal processing.

The shear stress levels on the model were typically 1250 Pa, but for some of the flow conditions they were as low as 200 Pa. Since the charge produced by the piezoceramic elements is small (of the order of 5 pC for some conditions), amplification of the signal was required. To minimize noise contamination, a charge amplifier was located as close as possible to the site of signal detection. It was housed directly beneath the gauge in a chamber that was vented to atmospheric pressure and completely isolated from the test section flow. This was done to remove the effect the test flow may have had on the electronics.

Results

To determine b_1/b_2 , a small shock tube was used to apply a transient pressure to the gauge. A technique for transient shear stress calibration yielding a_1 and a_2 is being developed. It is based on sudden removal of a weight attached to the disk with a thread and needs further refinement. However, the following results are not dependent on it. They can be viewed as a demonstration of the correct functioning of the gauge, or alternatively, as a calibration of the gauge against a value of skin friction determined from the theory for a simple compressible flat-plate boundary layer and known shock-tunnel test section conditions.

Figure 2 is a typical digitally filtered response from the skin-friction gauge (see Table 1 for test conditions with air as the medium); i.e., it is a plot of $e_1 + (b_1/b_2)e_2$ against time and from Eq. (3) should be proportional to the shear stress on the gauge. The data were sampled at 1- μ s intervals. The flow is established in the test section in about 20 μ s, at which time the gauge registers a constant mean value with small fluctuations superimposed. (Note that the gauge gives a negative output for positive skin friction.) This steady flow lasts for about 200 μ s, after which large fluctuations appear and the response departs from the steady mean value. To prove that these fluctuations

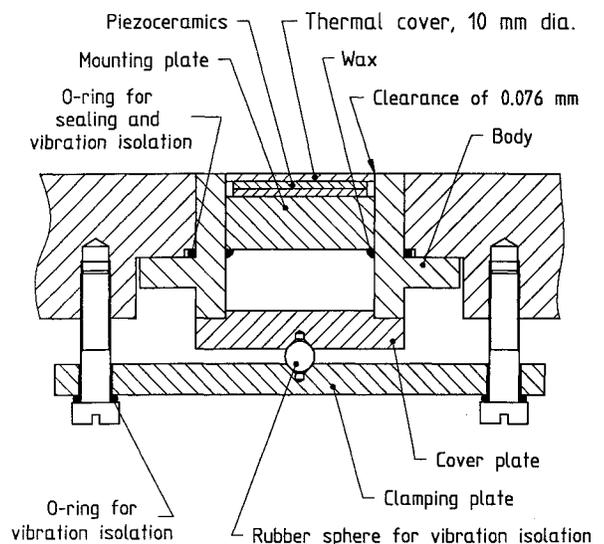


Fig. 1 Schematic of skin-friction gauge.

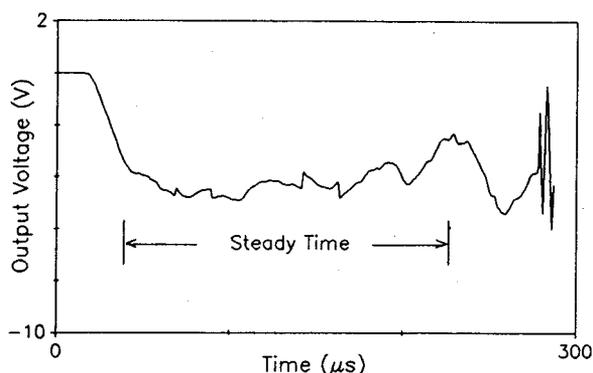


Fig. 2 Uncalibrated time history of filtered gauge output for the following test section conditions: Mach number = 3.1; velocity = 3486 m/s; static pressure = 114 kPa; stagnation enthalpy = 12.1 MJ/kg; temperature = 3383 K.

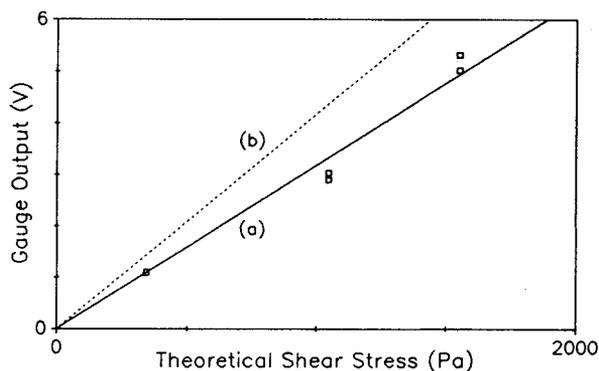


Fig. 3 Measured gauge output in volts (line a) and predicted gauge output (line b) vs theoretical shear stress for test section stagnation pressure from 0.77 to 5.88 MPa; line b is determined from nominal manufacturer's sensitivities for the piezoceramics.

were associated with the flow and not with the gauge, a commercial piezoelectric pressure transducer was mounted in a second flat-plate model to measure static pressure on the surface. The second flat-plate model had substantially different geometry and different flow-induced stress wave reflection times, but the onset of large fluctuations occurred in the unfiltered outputs from both the pressure transducer and one piezoceramic element at the same time, about 250 μ s after the start of the flow. We conclude that the large-scale unsteadiness after 250 μ s is due either to shock wave reflections resulting from the impulsive flow meeting the back face of the dump tank or to the arrival of the helium driver gas. However, in the available 200 μ s of useful test time, the skin-friction gauge indicated steady boundary-layer flow (Fig. 2).

Figure 3 displays the skin-friction gauge averaged output voltage in the 200- μ s test time plotted against theoretical shear stress values obtained using the method of van Driest.² The test section stagnation pressure ranged from 0.77 to 5.88 MPa. The flow Mach number was nominally 3.2. The relationship is linear, confirming the fact that shear stress has effectively been isolated from the unwanted contributions due to pressure, temperature, and flow-induced vibration. One of the major problems encountered in the development of the gauge was the decoupling of pressure and shear stress. For the range of conditions considered, pressure varies as a nonlinear function of shear stress. Hence, if the gauge were responding to pressure, the linear relationship in Fig. 3 would not occur. Using the nominal manufacturer's sensitivities for the piezoceramic material, calculations indicate that the gauge outputs for the theoretical shear stresses should lie along the second straight line in Fig. 3. This small difference is not surprising and further confirms the proper functioning of the gauge.

Table 1 Four test conditions

	1	2	3	4
Stagnation enthalpy, MJ/kg	12.07	9.507	7.34	5.76
Stagnation temperature, K	6348	5287	4373	3763
Stagnation pressure, MPa	5.88	3.62	1.63	0.77
Temperature, K	3383	2262	1952	1463
Pressure, kPa	114	65.8	27.4	12.1
Density, kg/m ³	0.107	0.079	0.046	0.027
Velocity, m/s	3486	3134	2789	2444
Mach number	3.10	3.13	3.20	3.22

Conclusions

Tests of a prototype skin friction gauge at Mach 3.2 in a small free piston shock tunnel have demonstrated the effectiveness of the design concept and the calibration against theoretical skin-friction values in a simple flow. The gauge has a rise time of about 20 μ s, sufficiently short for most shock-tunnel applications and approaching the rise times needed for expansion tube applications.

Acknowledgments

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Large Deflections of Sandwich Plates with Orthotropic Cores—A New Approach

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Introduction

THE problem of large deflections of isotropic sandwich plates has been investigated by several authors.¹⁻⁶ Kamiya⁵ presented governing equations for large deflections of isotropic sandwich plates following Berger's approximation. Accuracy of his solution depends on a correction factor. Dutta and Banerjee⁶ have offered a simplified approach to investigate the nonlinear static as well as dynamic behaviors of sandwich plates. The literature on large deflection analysis of sandwich plates of orthotropic materials is scarce.^{7,8} The present study investigates the large deflections of rectangular sandwich plates with a core as an orthotropic honeycomb-type structure. It is felt that this type of core corresponds more

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