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Development of Direct-Measuring Skin-Friction Gauges for Hypersonic Flight Tests

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A new type of direct-measuring skin-friction gauge was developed for the high-speed, high-temperature environment of turbulent boundary-layer flows in supersonic combustion ramjet (scramjet) engines, with tests progressing from ground tests to an actual hypersonic scramjet-integrated flight vehicle. The skin friction gauge was specifically developed for installation on the Hyper-X flight vehicle (X-43A). The design was nonnulling, with a sensing head that was flush with the model wall and surrounded by a small gap. Unlike previous skin-friction sensor designs, this gauge eliminated water cooling and gap-filling oil, in addition to a radically different flexure design. The design was verified by repeatable tests in a well-documented Mach 2.4 cold flow, with results within 10–15% of C_f estimates from simple theory. The sensor was qualified for flight through a rigorous series of environmental tests, including pressure, temperature, vibration, shock, acceleration, and heat flux tests. Finally, the skin-friction gauge was tested in the Hyper-X engine model (HXEM), a full-scale–partial-width wind-tunnel model of the flight vehicle engine, at Mach 6.5 enthalpy in a freejet facility at NASA Langley Research Center. Successful testing in the HXEM provided the final verification of the gauge before installation in the X-43A flight vehicle engine.

Nomenclature

C_f = skin-friction coefficient
h = enthalpy
I_{sp} = specific impulse
M = Mach number
m = mass
P = pressure
q = dynamic pressure
R^2 = goodness of fit parameter
T = temperature
U_e = edge velocity
u_* = friction velocity
V = voltage
γ = ratio of specific heats
ρ = density
τ = shear

Subscripts

w = wall
0 = stagnation condition

Introduction

BECAUSE of its significant impact in both the practical design of fluid systems and the fundamental scientific understanding of fluid dynamics, skin friction is an important flow quantity. Fundamentally, it is an important part of turbulent boundary-layer correlating parameters, such as friction velocity,[1,2]

$$u_* = U_e\sqrt{C_f/2}$$

In high-speed applications, skin friction helps define aerodynamic performance, and it can make up a large percentage of a vehicle's total drag.[3] Specifically, Moszee and Snyder[4] identified skin friction as a critical, yet poorly understood, quantity in the design and optimization of hypersonic airbreathing engines. To highlight the importance of skin friction in scramjet engines, F. S. Billig (private communication, 1998) performed calculations for a generic Mach 10 hypersonic, scramjet-powered vehicle cruising at 94,000 ft (28,650 m). Figure 1 shows his results. It is easily seen that changes in C_f can significantly impact specific impulse I_{sp}. Therefore, as hypersonic airbreathing engine technology is developed, accurate measurement of skin-friction drag is necessary in assessing engine and vehicle performance.

The techniques for measuring skin friction can be roughly separated into direct and indirect methods. A thorough review of indirect methods was done by Nitsche et al.[5] When other flow quantities, such as heat flux, are measured, indirect methods infer skin friction using an assumed law, for example, the Reynolds analogy (see Ref. 5). However, these methods are not well founded in the highly complex flow in a supersonic combustor. Direct methods, on the other hand, are preferable in such a situation because they require no advance knowledge of the state of the boundary layer regarding laminar or turbulent, separated or reverse flow, or the validity of simple analogies. Early direct measurement designs were documented by Winter.[6] Dhawan[7] first demonstrated skin-friction balances for supersonic cold flow in 1953, and later efforts included those of Hakkinen,[8] Allen,[9,10] and Voisinet.[11]

The major goal of this research was to produce a direct-measuring skin-friction gauge to be installed and flight tested in the scramjet engine of the third Hyper-X research vehicle (HXRV), designated X-43A. This effort required addressing both the extreme environment of the scramjet engine and the necessity of flightworthiness.

Direct-measuring skin-friction sensors have been successfully developed for the extremely hot environment of scramjet combustors in the past. The work of DeTurris et al.[12] and Chadwick et al.[13] is notable for examples of (relatively) long-duration high-enthalpy

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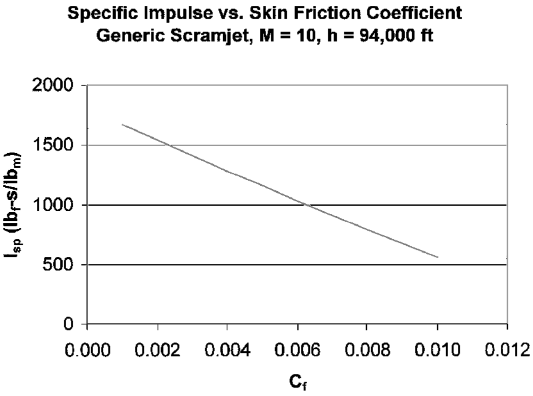

Fig. 1 Impact of skin friction on specific impulse.

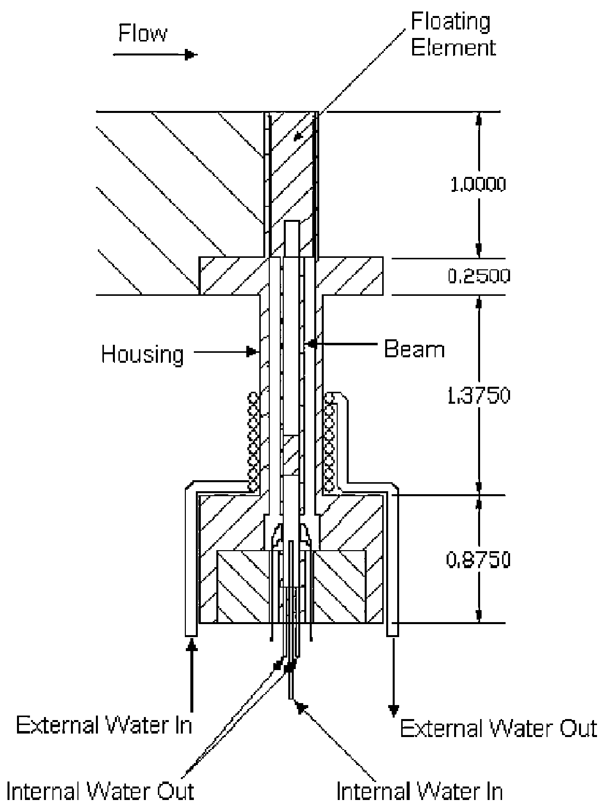

Fig. 2 Legacy skin-friction gauge design for scramjet testing.

tests of gauges in large-scale models. Others researchers, such as Paull,[14] have developed skin-friction sensors for scramjet tests in high-enthalpy impulse facilities. Smith et al.[2] demonstrated a skin-friction gauge in a rocket-based combined-cycle engine operating in the scramjet mode. The sensors developed at Virginia Polytechnic Institute and State University all used piezoresistive strain gauges to measure the strain in a cantilevered beam, to which the floating element was mounted. The temperature sensitivity of the piezoresistive strain gauges made it necessary to incorporate water-cooling systems to maintain constant temperature of the strain gauges. To reduce errors due to the sensor's effect on the flow, water cooling was also used to match the floating element temperature to that of the rest of the wall. In addition, silicon oil was used to fill the gap between the sensor housing and the cantilever beam/floating element assembly. This oil provided both thermal and structural damping and protection from pressure-gradient-induced errors by minimizing unknown pressure forces on the side of the floating element. These gauges were the first to establish the use of the nonnulling, floating-element/cantilevered beam design with actively cooled strain gauges in supersonic combustion flows,[2] although all of these tests were conducted on the ground. This design concept is shown in Fig. 2.

Direct-measuring skin-friction sensors for flight tests have also been developed in the past. Lyons[15] developed a sensor that was insensitive to linear and rotational accelerations to be tested on Aerobee-Hi rockets. Direct skin-friction measurements were conducted at NASA at Mach 3.0 on an YF-12 aircraft, both on the surface of the aircraft and on a cylinder suspended beneath the aircraft. These tests were reported by Fisher,[16] and Quinn and Gong,[17] respectively. More recently, Sang[18] developed a skin-friction sensor that was tested on a pylon suspended beneath an F-15 (Ref. 3).

Although skin-friction sensors have been independently developed for scramjet engines and flight tests before, this effort was the first to attempt a sensor for the combined application of a scramjet flight test largely because scramjet flight testing has only now become possible. At first, it was intended to draw the design largely from the previous work on scramjet skin-friction sensors done at Virginia polytechnic Institute; however those sensors were all tested in ground-based facilities. The unique demands of developing a flightworthy skin-friction sensor led to significant departures from previous scramjet skin-friction sensors.

Gauge Design Constraints

The cooling systems that were a part of the previous scramjet skin-friction gauge designs were too difficult to incorporate into a gauge for a flight vehicle. The flight vehicle, as a self-contained entity, has fewer systems and much less space available than the wind-tunnel models in which the previous gauges were tested. Although there was an onboard cooling system planned for the leading edges of the flight vehicle, integrating a skin-friction sensor into this system would have been very difficult and add risk to the flight vehicle.

Another concern was that the skin friction gauges would be mounted in the Hyper-X engine long (months to years) before the actual flight took place, and the gauges would be oriented upside down. During previous tests in which an oil-filled skin-friction gauge was mounted upside down in a scramjet engine, it was found that slow oil leakage before and during testing was a problem. The gauges installed on the flight vehicle would need to remain inverted for far longer before testing, with no prospect of refilling the oil. Keeping oil in an inverted gauge for long periods was simply impractical.

It soon became apparent that the best approach was one of simplicity. Thus, at the outset of the design of the flight vehicle skin-friction sensor, both the oil-fill and water-cooling systems were deleted from the requirements.

Because no cooling system was available, the semiconductor (piezoresistive) strain gauges of the previous scramjet skin-friction gauges were abandoned in favor of the more thermally insensitive metal foil strain gauges. This made the temperature sensitivity of the skin-friction sensor much more manageable. Choosing metal foil strain gauges had a major impact on the design of the scramjet flight vehicle skin-friction sensor. Although metal foil strain gauges are much less temperature sensitive, they are also less sensitive to strain, with typical gauge factors of about 2, compared to about 150 for semiconductor strain gauges. The result was that a much higher amount of strain would need to be induced in the flexible member of the skin-friction sensor to produce a large enough output from the strain gauges. However, the magnitude of the floating element deflection would need to remain about the same as the previous designs. In addition, size constraints within the scramjet engine bay of the flight vehicle limited the depth of the gauge. These requirements eliminated the cantilever beam configuration as a possibility for the Hyper-X flight vehicle skin-friction gauge, departing from all previous Virginia Polytechnic Institute scramjet skin-friction sensors. In the place of the cantilever beam, a very different flexible member design was conceived.

The flexible member design was found in a skin-friction balance designed for tests at the U.S. Naval Ordnance Laboratory in the late 1960s.[19] This balance made use of a "flexure ring" as a frictionless pivot. The sensor was a large nulling design that used a linearly variable displacement transducer to detect deflections and a servomotor to restore the position of the floating element. The only purpose of the flexure ring itself was to pivot under load; it was not instrumented in any way. The flexure ring, as shown in Fig. 3, consists

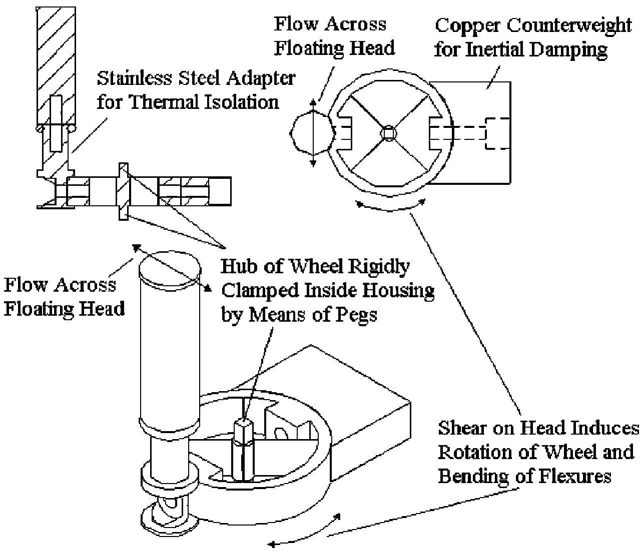

Fig. 3 Internal components of skin-friction sensor final design: floating head, adapter, flexure ring, and counterweight.

of a ring of material connected to a hub at the center of the ring by means of four thin webs. These webs act as clamped–clamped beams of rectangular cross section. Equations to relate the strain in a clamped–clamped web to a transverse force applied to one end are readily obtained from beam theory.[3]

In previous work, the flexure ring was not instrumented. Here, however, it was desired to instrument the flexure ring by placing metal foil strain gauges on the webs. By use of the equations earlier mentioned, a design study was done to find flexure ring geometries that would optimize the conflicting requirements of producing measurable strain in the webs and, at the same time, keeping the deflection to within a tolerable level. In addition to varying the length, height, and thickness of the webs, the placement of the floating element was also a variable in the study. Mounting the floating element at various distances from the hub of the flexure ring made it possible to increase or decrease the effective force seen by the webs due to a moment arm.

Collaboration with the designers and manufacturers of the Hyper-X scramjet engine was required from the earliest stages of the sensor design process. This was necessary to ensure that the sensor would fit into the available space in the engine bay. The feedback from this process of collaboration had significant impact on the final design, as size and shape constraints were added to the design parameters. Also, there were many qualifications and requirements for equipment to be mounted on the Hyper-X flight vehicle. These requirements addressed many different issues, from sealing against hot gas leakage, to vibration tolerances, to electromagnetic interference susceptibility. Also, the requirement for integrating a flight-qualified electrical connector into the skin-friction gauge was a major factor in the design.[3]

Gauge Description

The design of the skin-friction gauge for the Hyper-X flight vehicle developed after several iterations. Figure 3 shows the design of the internal components, which form the heart of the sensor. The flexure ring design was critical, being the first part of the skin-friction gauge to be finalized, with the rest of the skin-friction gauge components designed around the flexure ring.

The flexure ring was made of aluminum and was machined by an electrical discharge machining method due to the very thin webs, 0.005 in. (0.0127 cm) thick. The outer diameter of the ring was 1.000 in. (2.54 cm). In the center of the ring was a hub. The ring, webs, and hub were all 0.250 in. (0.635 cm) wide. Two pegs of square cross section extended from either side of the hub, which were used to clamp the ring into the housing. Also, two bosses were machined into the ring on opposite sides. These were drilled and tapped so that the floating element and/or other components could be fastened to the ring.

The flexure ring was mounted horizontally to minimize the total height of the gauge so it could fit into the engine bay of the Hyper-X flight vehicle. The floating element was then mounted perpendicularly to the ring by means of the stainless steel adaptor. The counterweight was added for inertial damping of the sensing structure.

The floating element was made of copper and was 1.030 in. (2.616 cm) long. The diameter at the top of the floating element was 0.348 in. (0.884 cm), before tapering down to 0.338 in. (0.859 cm) at a distance of 0.030 in. (0.076 cm) from the top. This creates a gap of 0.010 in. (0.0254 cm) between the floating head and the surrounding engine wall. The material and geometry of the head were designed to match as closely as possible those of the surrounding engine model. This is important to ensure the same conditions exist at the gauge location as over the surrounding engine wall. Changes in material properties and/or geometry can alter the heat flux and temperature characteristics, causing the gauge to measure an incorrect skin-friction value.

To act as a thermal barrier, the adapter was made of stainless steel due to its relatively low thermal conductivity (compared to the conductivity of copper or aluminum). The adapter is critical because it is directly in the heat flowpath between the floating element, which is subject to the high heat loads of the flow, and the flexure ring, which has the strain gauges mounted on it. Because no active cooling was available for the skin-friction sensor, this type of passive thermal protection became even more important. The adapter was threaded to the floating element by a setscrew in the top and to the flexure ring by means of a screw that passed through the bottom of the adapter and threaded into the flexure ring.

A high-temperature O-ring was placed over the adapter and seated against the bottom of the floating element. This acted as a mechanical "stop" to prevent extreme deflections of the ring in the case of unexpected loads during testing, improper handling, vibrational loads, etc.

A copper counterweight was mounted onto the opposite side of the flexure ring. This counterweight was designed to match the mass-times-moment-arm of the floating element and adapter. This type of counter balancing is important in flight tests of force balances such as this skin-friction sensor. The skin-friction balance design of Lyons incorporated extensive systems to make the balance insensitive to the accelerations that occur on a flight vehicle.[15] That sensor was made to be insensitive to both linear and angular accelerations. The flexure ring has only one degree of freedom, which is a rotation about the hub, so that the only accelerations that should be of concern are linear accelerations in the direction of the flow and angular accelerations in the plane of the flexure ring. Because of the way in which the skin-friction sensor is to be mounted on the flight vehicle, these would correspond to axial force changes (such as due to changes in thrust and/or drag) and yaw rate changes. The counterweight on the flexure ring reduces sensitivity to the linear axial acceleration. The yaw rate changes are assumed to be small during the engine-testing phase of the flight, which should follow a nearly straight flight path. Therefore, the skin-friction gauge is expected not to give output due to accelerations on the flight vehicle during the engine test.

When only one flexure ring is used in the skin-friction sensor, only one axis of motion could be measured. It would be possible to measure two perpendicular directions of wall shear, but that would require integrating a second flexure ring into the design. Goldfeld et al. recently studied a similar scheme for a different type of structure.[20] There was neither enough space in the flight vehicle nor enough time to develop this more complicated configuration. These skin-friction gauges were designed to be aligned with the direction of flow, which should be mostly two dimensional. This configuration allowed the most important component of skin friction to be measured in the engine of a scramjet flight vehicle, something never before done, and remained simple enough to build and test.

Figure 4 shows a gauge partially and fully assembled. The housing was made of brass and was designed in two pieces to fit around the internal components. A commercial six-pin connecter

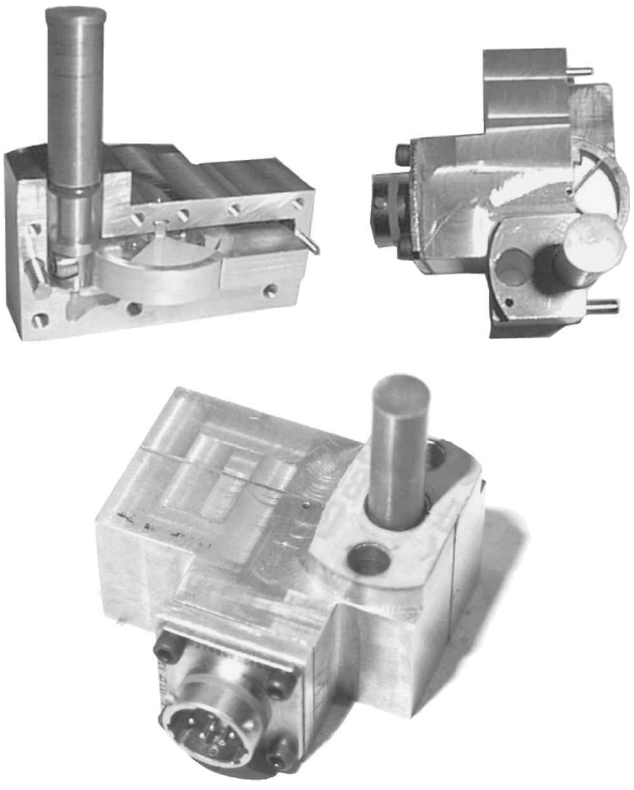

Fig. 4 Hyper-X skin-friction sensor assembly.

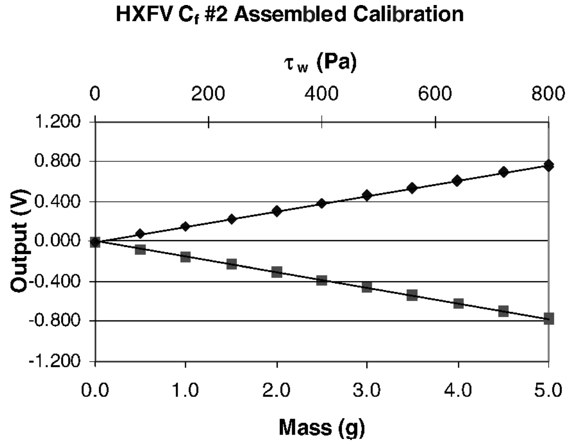

Fig. 5 Sample calibration for Hyper-X skin-friction sensor.

was integrated into the design and fastened to a large extension on the side of the housing. High-temperature gaskets were used to seal between the two housing pieces and between the housing and the connector. A third gasket was used to seal between the upper surface of the housing and the engine wall. Two dowel pins were used to align the two housing pieces with each other, and two more dowel pins were used to align the skin-friction sensor in the engine wall.

In addition to the four leads from the strain gauges, the connecter also accommodated the connections for a type K thermocouple that was built into the housing of the skin-friction sensor directly beneath the floating element. This thermocouple made it possible to monitor the temperature of the skin-friction gauge during testing. Measuring this temperature would help in diagnosing thermal drift in the strain-gauge signal, should it arise.

Experimental Facilities and Procedures

For the ground tests of the skin-friction sensor, the excitation and balance for the strain gauges, as well as amplification and filtering of the signal, were all provided in one unit with Measurements Group 2310 signal conditioning amplifiers. A dc excitation voltage of 0–10 V was used to power the strain gauges, and the signal was filtered at 10 Hz. For tests in the Virginia Polytechnic Institute supersonic wind tunnel, data were recorded on a personal computer with a 12-bit A/D card at a rate of 100 Hz. For the HXEM scramjet tests at the NASA Langley Research Center freejet facility, the signal was acquired at 50 Hz and filtered at 1 Hz on facility equipment. For the flight test on the Hyper-X RV, the gauge will be excited by a $\pm$5-V source, with sampling at 100 Hz and signal filtering at 14 Hz.

Calibration

The skin-friction gauge was calibrated by applying a direct force to the floating element along the axis of measurement. The gauge was first clamped in a horizontal position, and then weights were hung vertically by thread from the surface of the floating element. Output in millivolts was recorded from a multimeter, and a linear regression was done to obtain a calibration curve. A sample calibration curve is presented in Fig. 5.

Flight Qualification Tests

To qualify the skin-friction sensor for installation on the Hyper-X flight vehicle, the sensor was subjected to a series of environmental tests.

First, to meet the vibrational requirements, the skin-friction sensors were shaken in the Virginia Polytechnic Institute Modal Analysis Laboratory. The skin-friction gauge was fastened to a shaker (Vibration Test Systems VG 100-41), and an accelerometer (Kistler 8630B50) was mounted onto the skin-friction gauge. The 2310 signal-conditioning amplifier powered the skin-friction gauge. An Hewlett–Packard Company HP 35665A digital signal analyzer (DSA) was used to supply the source signal for the shaker and to acquire and process the signals from the accelerometer and the skin-friction gauge. An Onkyo Integra M-504 stereo power amplifier amplified the source signal from the DSA.

The skin-friction sensor was first shaken at extremely high loadings (20–50 g rms) to determine the failure modes of the skin-friction gauge and whether failure would pose risks to the flight vehicle. Then, the sensor was shaken to a curve of specified frequencies and amplitudes that represented the expected loading during flight. Last, simple sine wave sweeps were done to determine the frequency response of the skin-friction sensor.

The sensor was also tested in an altitude/pressure chamber at NASA Dryden Flight Research Center. These tests examined the survivability and response of the sensor to the pressures expected during flight at altitude. The sensor was placed in the altitude chamber, and the pressure was reduced incrementally to simulate altitude. Data were taken at several different altitudes, up to 96,000 ft (29,260 m). (Higher altitudes were not possible due to the limitations of the altitude chamber.)

The skin-friction gauges were also required to pass temperature environmental qualification tests. These tests were to examine the ability of the gauges to function at the temperatures expected during the flight test. Those temperatures range from a low of -40°F (-40°C) to a high of 160°F (71°C).

Steady-state temperature tests were conducted at Virginia Polytechnic Institute using a Blue M Electric ETC-04D-C environmental test chamber with a Pro-550 controller. The gauge was placed in the chamber with wires routed through a passthrough to the 2310 signal conditioning amplifier and an Omega thermocouple dc millivolt amplifier. Multimeters read the output from the 2310 and the thermocouple amplifier.

To determine the response of the sensor to heat loads close to those expected in-flight, it was necessary to reproduce the wall heat flux that was estimated for the engine near the location of the sensors. This was done with a radiative heat flux source because methods for accurately reproducing high levels of convective heat fluxes are not available.

These tests were performed at Vatell Corp. in Christiansburg, Virginia, using a flat plate heater facility to reproduce the predicted heat flux of the Hyper-X scramjet engine during the flight test. The furnace provided a high-power voltage across a thin, flat graphite plate. The current flowing through the flat plate causes it to heat to extreme temperatures. At these extreme temperatures, the plate glows and radiates heat flux values up to 400 Btu/ft$^2 \cdot$ s (4539 kJ/m$^2 \cdot$ s). A calibrated Gardon-type heat flux gauge was placed on one side of the flat plate to monitor the heat flux level. The test article was placed on the opposite side and at the same distance from the flat plate to be exposed to the same heat flux. The test article was traversed on rails toward and away from the flat plate heater during testing, and this allowed the skin-friction gauge to be pulled away from the heater plate and shielded during the rampup and shutdown periods. In this way, the skin-friction gauge could be exposed to the heat flux only for the brief amount of time expected during the flight test. The sensor was mounted in copper block that simulated the scramjet engine wall. To ensure that the sensor absorbed the entire amount of radiated heat flux, the surface of the gauge and the copper block were coated with soot, giving them an emissivity very near 1.0.

The skin-friction sensor was tested at 30 and 70 Btu/ft$^2 \cdot$ s (340 and 794 kJ/m$^2 \cdot$ s). The output from the Wheatstone bridge and the type K thermocouple in the housing were recorded on a personal computer via a National Instruments A/D board using LabView data acquisition software. While the heater plate reached the test condition, the skin-friction gauge and copper mounting block were shielded and traversed away from plate. Once the heater reached the designated heat flux, the shielding was removed, and the gauge was traversed up to the flat plate for several seconds. Then, the gauge was traversed away from the plate again as the power to the heater plate was cut.

Cold-Flow Tests

To verify the ability of the gauge to measure skin friction accurately and reliably, tests were conducted in the Virginia Polytechnic Institute 23 × 23 cm supersonic blowdown wind tunnel. This facility provided a well-understood flow to compare the gauge results against. Nominal tunnel conditions were set at Mach 2.4, with $P_0 = 50$ psia (345 kPa) and $T_0 = 540°$R (300 K). Run times were typically 5–10 s long. The turbulent boundary-layer characteristics of the tunnel floor plate had been previously measured, allowing the skin-friction coefficient to be calculated.

For these tests, the skin-friction gauge was located in a section of the flat wall about 7 in. (17.78 cm) downstream of the diverging section. The gauge was installed in a copper insert so that the tunnel wall would share the same material properties as the floating element. The Reynolds number based on distance from the leading edge of the copper insert to the floating element was 4.8×10^6. Reynolds number Re_δ was about 3.75×10^5. Data were recorded at 100 Hz on a personal computer via a 12-bit A/D card. The signal was filtered at 10 Hz.

HXEM Tests

The final step was to verify that the skin-friction gauge was capable of measurement in a scramjet flow environment. Therefore, before installation on the Hyper-X Mach 10 flight vehicle, it was tested in a wind-tunnel ground test of the HXEM. This was a full-scale–partial-width model of the Hyper-X engine.

The facility used for these tests was the NASA Langley Research Center Arc-Heated Scramjet Test Facility (AHSTF). For these tests NASA's test program called for Mach 6.5 flight enthalpy. The nozzle area ratio produced a Mach 6.0 freejet at the nozzle exit. The nominal total pressure was 555 psia (3827 kPa), and the total enthalpy was 900 Btu/lbm (2093 kJ/kg).

The gauge was mounted on a flat portion of the inlet ramp (rather than in the combustor) of the engine because there was no room for the gauge in the internal compartments of the engine. A boundary-layer trip ensured a turbulent flow. A photograph of the HXEM in the AHSTF test section is shown in Fig. 6.

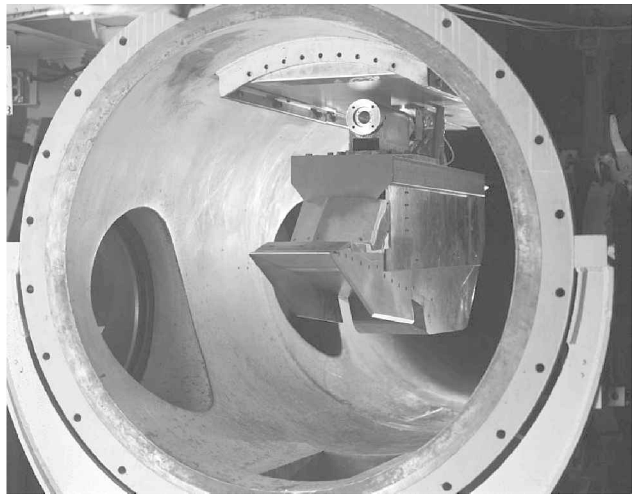

Fig. 6 HXEM installed in AHSTF (obtained from NASA Langley Research Center's website).

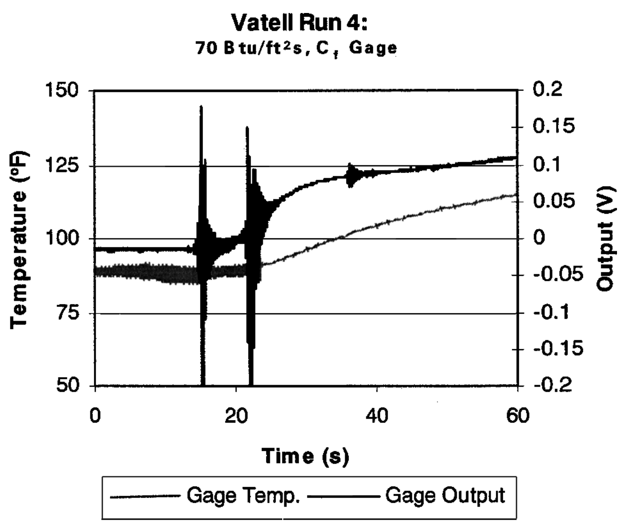

Fig. 7 Heat load test results: 70 Btu/ft$^2 \cdot$ s (794 kJ/m$^2 \cdot$ s).

Experimental Results

Flight Qualification Tests

The skin-friction gauge qualified for flight tests. The vibration tests showed the ability of the sensor to withstand the vibration loads expected during flight. In addition, the natural frequency of the sensor was found to be about 40 Hz.

As expected, pressure/altitude was not an issue for the skin-friction gauge. There was no effect of pressure on the integrity of the sensor, and the output from the gauge did not change when the pressure was reduced to simulate altitude.

The temperature tests proved that the sensor could easily survive the temperature extremes required. However, without temperature compensation or cooling systems, some thermal drift was seen in the output from the strain gauges. The magnitude and behavior of this temperature sensitivity was accepted to be within manageable limits.

The heat loads tests were used to determine the ability of the skin-friction gauge to withstand the high heat fluxes expected in the Hyper-X scramjet engine during flight and also to determine the response of the strain gauges to a heating environment similar to the actual flight test. The earlier temperature tests allowed the sensor to reach a steady temperature over a long period of time. On the flight vehicle, however, the heat flux would be a much more transient event, with the heat load coming on quickly and then going away after only a few seconds of engine operation.

A sample output from the heat loads tests is shown in Fig. 7. The output from the strain gauges is shown in volts, and the temperature measured inside the housing of the skin-friction gauge is shown in degrees Fahrenheit. The large excursions in the strain-gauge signal mark the beginning and end of the heat flux exposure at about 15 and 22 s, respectively. These excursions were the result of forces on the gauge as it was traversed toward and away from the heat source.

It was clear from these tests that the major portion of the gauge temperature rise and thermal output occurred well after the window of exposure. The thermal mass of the sensor delayed the propagation of the high temperatures into the sensor. Because the test window in the flight vehicle will also be relatively short (7–15 s), this result indicated that thermal drift during scramjet operation should be manageable.

Cold-Flow Tests

Four tests were conducted in the Virginia Polytechnic Institute supersonic wind tunnel. A sample result from one of the runs is shown in Fig. 8. The gauge directly measures the shear on the flow surface. The skin-friction coefficient C_f is obtained by normalizing the wall shear τ_w by the dynamic pressure q. A summary of the results from all of the tests is given in Table 1. The tunnel was shut down before the end of the data record, which made it possible to confirm that the output returned to zero after the test.

These tests were very successful. The output was very consistent from run to run, as seen in Table 1. The output began and ended at zero with no shift due to temperature or to anything else. Simple estimates of the skin-friction levels to be expected in these tests were made for reference by assuming flat plate flow. Using skin-friction formulas for incompressible flow over a flat plate based on local boundary-layer thickness or plate length and applying the Van Driest II compressibility correction yielded estimates of C_f from 0.0014 to 0.0021.

Because this gauge was very different from previous Virginia Polytechnic Institute skin-friction sensors, this test was crucial in determining whether the new features would work. The flexure ring proved to be capable of functioning as the flexible member in a direct-measuring skin-friction gauge. It was also important to verify that a skin-friction gauge could operate without gap filler. This skin-friction sensor was not filled with oil or any other substance; neverthless it was able to measure the skin-friction coefficient within 10–15% of the estimated range of values. The higher C_f of the experiment may be due to the location of the sensor not far downstream of the diverging section of the nozzle, where the positive pressure gradient causes higher skin friction. Also, the gauge was mounted in a copper insert to match locally the gauge head material needed for Hyper-X and that was in a large aluminum plate forming the floor of the tunnel resulting in a wall temperature mismatch near the gauge, increasing the uncertainty. The results were also in good agreement with the measurements of the earlier skin-friction sensor designs of Smith et al.,[2] which previously measured skin friction coefficients from 0.0017 to 0.0023, as well as others within the research group.

Table 1 Supersonic wind-tunnel results

	$\tau_{w,\text{av}}$, Pa		$C_{f,\text{av}}$	
Run	Average	±5%	Average	±5%
0	236	248/224	0.00228	0.00240/0.00217
1	245	257/233	0.00220	0.00231/0.00209
2	225	236/214	0.00222	0.00233/0.00211
3	237	249/225	0.00221	0.00232/0.00210

HXEM Tests

A total of six high-enthalpy runs were performed with the Hyper-X skin-friction gauge installed in the HXEM in the NASA Langley Research Center AHSTF. Sample results from these tests are shown in Fig. 9 and Table 2. All of the hot runs, except for the first trial run, operated with the arc on for a total of about 30 s. There was an interval of roughly 30–60 min between most of the runs, with a longer interval between the third and fourth hot runs. This test procedure resulted in a relatively long exposure to the high-enthalpy,

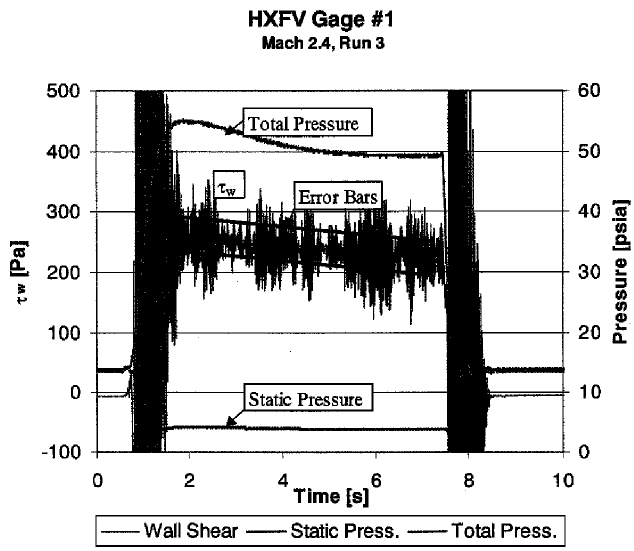

Fig. 8 Supersonic wind-tunnel test results: run 3.

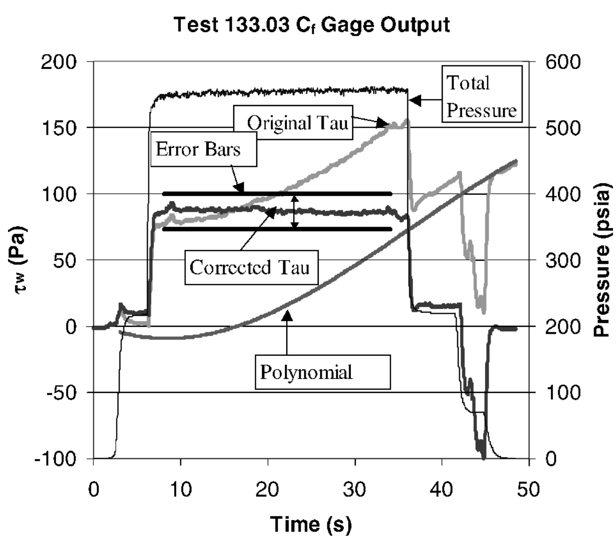

Fig. 9 AHSTF test results: run 133.03.

Table 2 HXEM AHSTF test results summary

	$\tau_{w,\text{av}}$, Pa		$C_{f,q\text{ nozzle}}$		$C_{f,q\text{ local}}$	
Test	Average	±15%	Average	±15%	Average	±15%
133.01	74.9	86.1/63.7	0.0016	0.0018/0.0013	0.0009	0.0011/0.0008
133.02	82.2	94.5/69.9	0.0017	0.0020/0.0015	0.0010	0.0012/0.0009
133.03	87.3	100.4/74.2	0.0018	0.0021/0.0016	0.0011	0.0012/0.0009
133.04	72.0	82.8/61.2	0.0015	0.0017/0.0013	0.0009	0.0010/0.0008
133.06	87.3	100.4/74.2	0.0018	0.0021/0.0016	0.0011	0.0012/0.0009
133.07	77.0	88.6/65.5	0.0016	0.0019/0.0014	0.0010	0.0011/0.0008

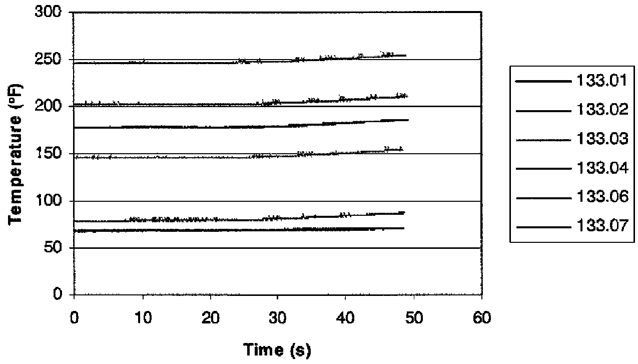

Fig. 10 AHSTF test results: gauge temperature history.

high-heat-flux flow. The flight test, in comparison, is only planned to expose the engine to 7–15 s of hot flow.

The output from the skin-friction sensor was extremely repeatable for all of the runs. The output clearly followed the tunnel events, with jumps in output as the tunnel came on and again as the arc came on. There was also repeatable thermal drift late in all of the runs. However, the magnitude of the thermal drift was not so great as to overwhelm the shear signal. It was still quite easy to determine the changes in the signal due to the shutting down of the arc and the air. The thermal drift was minimal early in the run and increased during the run. Instead of returning to zero, there was an offset in the output that continued to rise as the heat soaked into the engine after the end of the run. This delay can also be seen in the temperature history of the gauge shown in Fig. 10. The temperature of the gauge remained nearly constant well into the run, with an increase of a few degrees near the end. The temperature of the gauge at the start of each consecutive run was higher than the previous run. This indicated that the temperature continued to rise after each run as the heat soaked through the engine walls.

Earlier results of the temperature tests had shown that temperature changes caused output from the strain gauges but did not affect the sensitivity of the gauge. This was verified by the experience in the HXEM. Though there was thermal drift between the start and the end of each run, the voltage changes at the startup and shutdown were the same magnitude.

The delay in the temperature rise and drift made it possible to determine the shear level from the data early in each run. Also, that the sensitivity remained constant meant that the signal due to shear could be obtained by simply subtracting out the part of the signal due to thermal drift for the later portions of the run. Because the flow on the inlet was steady (due to constant total and dynamic pressure), any change in the signal during the steady portions of the run could be attributed to thermal drift. Thus, by the assumption that the signal should have been constant between facility events (startup, arc on/off, shutdown), the thermal drift portion of the signal was separated out by subtraction. A third-order polynomial was then fit to the thermal drift, and this was then subtracted from the original signal. For example, in test 133.03, the initial shear value after the arc came on and before drift was about 80 Pa. This value was subtracted from the signal for the entire hot portion of the run, and the remaining signal level was attributed to thermal drift. (Negative drift at the beginning of the run is due to cooling from the expanded unheated air.) A polynomial was then fitted to the drift and subtracted from the original signal.

In Fig. 9, the original signal, the polynomial drift curve, and the corrected signal are shown, along with the total pressure. The skin-friction gauge gave very similar results in each run. The signals early in the run and the corrected signals consistently showed steady shear levels of about 75–85 Pa during the hot-flow test time, and the corrected signals all returned to zero. In every run there was interference in the signal between about 8.5 and 10 s and again between about 34 and 36 s. The cowl actuation motor that opened and closed the engine cowl at the beginning and end of each hot test period caused this. This was quite a large motor, and it produced electromagnetic interference during operation. In each run, there was also a period during the shutdown phase between the cutoff of the bypass air and the cutoff of the main air. During this period, the output of the gauge was generally erratic. The flowfield over the model during that part of the facility operation has not been studied. However, it certainly is not hard to imagine reverse flow and/or separation as the inlet and the facility Mach 6 nozzle unstart at low enthalpy.

The shear levels were normalized by dynamic pressure to calculate the skin-friction coefficient. This was done with two different methods. For the first calculation, the dynamic pressure at the exit of the facility nozzle was used. For the second calculation, the local dynamic pressure (obtained from pressure measurements and oblique shock calculations of Mach number) was used. The results are summarized in Table 2, which shows the shear level and the skin-friction coefficient for each run. The values of C_f based on the tunnel nozzle dynamic pressure ranged from 0.0015 to 0.0018. When the local dynamic pressure was calculated, the C_f range was 0.0009–0.0011. When the same simple method is used as for the cold flow, an estimate of C_f was calculated to be 0.0013. In addition, a Spalding–Chi correlation gave a rough estimate of 0.0015.

Measurement Uncertainties

The errors and uncertainty in these direct measurements of skin friction are due to three basic sources. The first of these sources is the uncertainty in the calibration of the sensor and repeatability issues in wind-tunnel tests. The second major source is the uncertainty due to thermal drift in the output. Errors caused by the floating head factors such as pressure gradients and misalignment make up the final source.

Calibration and Repeatability

The calibrations performed on the skin-friction sensors of this study showed good linearity and repeatability. A statistical analysis of all of the calibration data for this skin-friction gauge produced a standard deviation from a perfectly linear relationship s of 0.80% full-scale output (FSO). For a Gaussian distribution, 95% of all samples fall within $\pm 2s$ of the mean. Therefore, the true load for a given output should be within 1.6% FSO of the indicated load 95% of the time.

Quantifying the repeatability of the results from the HXEM tests was more complicated. The standard deviation of the average local C_f results from run to run was 3.33%, with a maximum scatter of 16.7% (Table 2). The measured local C_f for any given run could be expected to fall within ±6.66% of the average C_f for all runs 95% of the time. The tunnel conditions were intended to be identical from run to run, and the gauge was mounted on the inlet, where the fuelling did not alter the flow. The repeatability of the gauge itself, however, was not the only factor in these tests; there was the added variable of thermal drift in these tests. Accounting for the thermal drift was not perfect and likely is to blame for some portion of the scatter.

Thermal Drift

There was thermal drift in the output from this sensor during the latter part of tests in the high-enthalpy scramjet wind-tunnel tests. One can simply use the data from early in a run or attempt to correct for the thermal drift observed late in the runs. A relatively simple method was developed to subtract out the thermal drift portion of the signal late in the tests, and the results looked good. However, there was still an increased amount of run-to-run scatter in those results (16.7%) compared to results from the cold-flow tests in the Virginia Polytechnic Institute supersonic wind tunnel (4.5%). Certainly, the thermal drift and the subsequent postprocessing must play a major part in contributing to this increased uncertainty.

It was attempted to calibrate the final skin-friction sensor with temperature. Unfortunately, the temperature sensitivity of the final skin-friction gauge was nonlinear and hard to interpret. Therefore, it is difficult to quote an error estimate per degree of temperature change. Rather, when the uncertainty in the cold-flow tests and the calibration is taken into account, a conservative estimate of the uncertainty due to temperature effects would be 10–15%, with the effect being the largest in hot, high-enthalpy flows.

Floating Element Errors

Misalignment Errors

Allen's[9,10] work showed that for a perfectly aligned floating element there was no error introduced into the measurement of skin friction. O'Donnell and Westkaemper[21] similarly showed small errors for small misalignment: less than 2% for protrusions of 0.0005 in. (0.00127 cm). Hakkinen[22] discussed a method for estimating the error caused by the protrusion of a two-dimensional, rectangular floating element.

All of the checkout tests of the skin-friction gauge took place on flat surfaces in supersonic flows, where there should have been no pressure gradient present. In this case, the error should be zero. Still, it is useful to provide a predictive estimate of the error that could be seen in a scramjet flow with a pressure gradient. Therefore, a pressure gradient that was observed by Chadwick et al.[13] was used in Hakkinen's[22] equation. They quoted a pressure gradient of 1.5 psi/ft (34 kPa/m) in a supersonic combustion wind-tunnel experiment. When this pressure gradient is substituted across the diameter of the floating element, and the wall shear seen on the inlet of the HXEM tests is used, an error of less than 0.5% is predicted for a maximum protrusion of 0.0005 in. (0.00127 cm).

Pressure Gradient Errors

Pressure gradients can also induce errors even for a perfectly aligned floating element. To prevent this, the gaps of earlier Virginia Polytechnic Institute skin-friction gauges were filled with oil. Because the oil is an incompressible fluid, it makes it very difficult to establish a pressure difference from one side of the floating element to the other. The present skin-friction gauge, however, had no oil fill. It is more likely that a pressure gradient across the floating element could have induced errors in this configuration. As already stated, the checkout tests of the final skin-friction sensor were conducted in zero pressure-gradient environments. However an estimate of the error that could be introduced due to a pressure gradient typical of a scramjet combustor was desired.

Hakkinen[22] also discussed a simple method of estimating the error caused by a pressure gradient acting on a floating element. A pressure gradient considerd representative of a scramjet combustor (34 kPa/m) was entered into Hakkinen's equation along with a range of shear levels (150–800 Pa) that might be experienced in a scramjet engine. The geometry of the present skin-friction gauge was used, producing a range of estimated errors of 3–17%, depending on the severity of the ratio of pressure gradient to shear level. Two assumptions about Hakkinen's equation make it a very conservative estimate. The first is that it assumes the floating element to have infinite width, isolating the upstream and downstream pressures. The three-dimensional cylindrical shape of the actual floating element provides significant pressure relief. The pressures upstream and downstream of the floating element are not isolated, but instead can equalize around the gap. The other assumption is that the pressure acting on the floating element remains constant across the entire height of the lip. MacLean and Schetz[23] have undertaken a numerical study of the flow in and around floating elements and the resulting errors. Results indicate that the pressure varies around and across the cylindrical lip, which supports the conclusion that a smaller lip height greatly helps to reduce pressure forces on the floating element. In addition, the pressure distribution was found to be nonlinear, even for floating elements without a lip, casting further doubt about the accuracy of error estimation methods that assume a constant or linearly varying pressure distribution down the floating element.

For the wind-tunnel tests conducted with this skin-friction gauge, the error from pressure gradients is believed to be very small (less than 3%). An estimate of the errors for the scramjet flight test is desired, which take into consideration the preceding estimates and their limiting assumptions. It is believed that a worst-case estimate would indicate possible pressure-gradient errors of up to roughly 15%, with more likely moderate errors between 5 and 10%.

Uncertainty Summary

Calculating the errors in direct measuring skin-friction sensors is difficult. The uncertainty in the measurements reported here due to the calibration and misalignment effects has been shown to be small (1.6 and 0.5%, respectively). The results of the tests of this skin-friction gauge in the supersonic wind tunnel were repeatable within ±2% and were within 10% of previous tests and 10–15% of the integral method estimate. Differences in the test conditions and the estimated accuracy make these differences less worrisome. The pressure-gradient effects for the tests conducted to date are believed to be less than 3%. The largest source of uncertainty for the tests of the skin-friction gauge is the thermal drift, which is believed to be 10–15% late in a short-duration test with high-heat-flux conditions. Calculating the root of the sum of the squares of these values gives an estimated error range of 11–16% for the high-enthalpy scramjet wind-tunnel tests. When the same is calculated with a larger pressure gradient that could be seen in the flight vehicle scramjet engine, the uncertainty range increases to 12–22%. The errors encountered in flows without thermal effects and/or without pressure gradients, such as the supersonic cold-flow tests, will be much smaller.

Conclusions

This work was begun with the goal of designing a skin-friction sensor to be installed in the scramjet engine of the X-43A. The process included developing a new design very different from previous sensor designs, including the elimination of cooling water and oil fill. The gauge was subjected to a series of environmental tests including shock, vibration, steady-state temperature, pressure, and extreme heat loads, and the sensor proved flightworthy by passing through all of these in good working order. The ability of the sensor to measure skin friction in a relatively benign flow was demonstrated by testing in a Mach 2.4 cold flat plate flow, in which the sensor gave results in good agreement both with simple estimates and previous skin-friction sensors in the same flow. Last, the sensor was tested in a high-enthalpy wind tunnel test of the Hyper-X scramjet engine.

The tests in the HXEM were an important milestone in the development program for the Hyper-X flight vehicle skin-friction sensor because the HXEM provided a much closer simulation of the flight vehicle environment. In these tests, it was determined if the new design features of the gauge would work in the high-speed, high-enthalpy supersonic flow of the scramjet engine.

The HXEM tests showed that an uncooled skin-friction sensor without oil fill could be used for testing on a scramjet engine. This was made possible largely by the metal foil strain gauges in conjunction with the flexure ring. Although it was not possible to entirely eliminate thermal output from this gauge late in a hot run, the thermal output was small enough to be accounted for with relative ease. This would not have been possible with semiconductor strain gauges. Experience with the semiconductor strain gauges showed much greater sensitivity to temperature than the foil strain gauges. The design of the gauge, with its thermal barriers, also helped to delay the onset of thermal drift until well into the hot-flow test time. This is important because the flight vehicle test will be much shorter than the wind-tunnel test.

The HXEM tests also provided insight into the response of the skin-friction gauge to axial accelerations. Fueling during the HXEM tests produced sudden changes in the axial force of up to 50 lbf (222 N). There was no response from the skin-friction gauge due to these force changes. The counterweight of the gauge, coupled with effective filtering, reduced the response of the gauge to such accelerations.

After the HXEM tests, the skin-friction gauge was inspected, and no visual damage was seen. The gauge was calibrated to see whether any change in the sensitivity had occurred. The result of the calibration after the test was within 3% of the pretest calibration, and so the sensitivity of the sensor was not significantly changed by the very hot wind-tunnel tests.

It has been effectively demonstrated that this skin-friction sensor design is suitable for testing on the Hyper-X Mach 10 flight vehicle. The environmental pressure and temperature tests, the vibrational tests, the heat loads tests, and the HXEM tests were all successfully performed with this gauge design. The primary goal of the project was achieved by developing a very different skin-friction sensor than previous scramjet skin-friction gauge designs. The new key features, foil strain gauges and flexure ring, no water cooling, and no oil fill, made the gauge more robust, a prerequisite for flight testing.

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