Skin Friction Sensor Design Methodology and Validation for High-Speed, High-Enthalpy Flow Applications

Ryan James Meritt

Dissertation submitted to the faculty of the Virginia
Polytechnic Institute and State University in partial
fulfillment of the requirements for the degree
of

Doctor of Philosophy
In
Aerospace Engineering

Joseph A. Schetz, Chair
William J. Devenport
Christopher J. Roy
Roy J. Schulz

November 1, 2013
Blacksburg, VA

Keywords: Skin Friction Measurement, Wall Shear Stress
Measurement, Aerodynamic Instrumentation

Skin Friction Sensor Design Methodology and Validation for High-Speed, High-Enthalpy Flow Applications

Ryan J. Meritt
Dr. J. A. Schetz, Chairman
Aerospace Engineering

Abstract

This investigation concerns the design, build, and testing of a new class of skin friction sensor capable of performing favorably in high-speed, high-enthalpy flow conditions, such as that found in atmospheric re-entry vehicles, scramjets, jet engines, material testing, and industrial processes. Fully understanding and optimizing these complex flows requires an understanding of aerodynamic properties at high enthalpies, which, in turn, requires numerical and analytical modeling as well as reliable diagnostic instrumentation. Skin friction is a key quantity in assessing the overall flight and engine performance, and also plays an important role in identifying and correcting problem areas.

The sensor design is founded on a direct-measuring, cantilever arrangement. The design incorporates two fundamental types of materials in regards to thermal conductivity and voltage resistivity properties. The non-conducting material distinction greatly deters the effect of heat soak and prevents EMI transmission throughout the sensor. Four custom fabricated metal-foil strain gauges are arranged in a Wheatstone bridge configuration to increase sensitivity and to provide further compensation for sensitivity effects. The sensor is actively cooled via a copper water channel to minimize the temperature gradient across the electronic systems. The design offers a unique immunity to many of the interfering influences found in complex, high-speed, high-enthalpy flows that would otherwise overshadow the desired wall shear measurement.

The need to develop an encompassing design methodology was recognized and became a principal focus of this research effort. The sensor design was developed through a refined, multi-disciplinary approach. Concepts were matured through an extensive and iterative program of evolving key performance parameters. Extensive use of finite element analysis (FEA) was critical to the design and analysis of the

sensor. A software package was developed to utilize the powerful advantage of FEA methods and optimization techniques over the traditional trial and error methods.

Each sensor endured a thorough series of calibrations designed to systematically evaluate individual aspects of its functionality in static, dynamic, pressure, and thermal responses. Bench-test facilities at Virginia Tech (VT) and Air Force Research Laboratory (AFRL) further characterized the design vibrational effects and electromagnetic interference countermeasure effectiveness. Through iterations of past designs, sources of error have been identified, controlled, and minimized. The total uncertainty of the skin friction sensor measurement capability was determined to be ±8.7% at 95% confidence and remained fairly independent of each test facility.

A rigorous, multi-step approach was developed to systematically test the skin friction sensor in various facilities, where flow enthalpy and run duration were progressively increased. Initial validation testing was conducted at the VT Hypersonic Tunnel. Testing at AFRL was first performed in the RC-19 facility under high-temperature, mixing flow conditions. Final testing was conducted under simulated scramjet flight conditions in the AFRL RC-18 facility. Performance of the skin friction sensors was thoroughly analyzed across all three facilities. The flow stagnation enthalpies upward of 1053 kJ/kg (453 Btu/lbm) were tested. A nominal Mach 2.0 to 3.0 flow speed range was studied and stagnation pressure ranged from 172 to 995 kPa (25 to 144 psia). Wall shear was measured between 94 and 750 Pa (1.96 and 15.7 psf). Multiple entries were conducted at each condition with good repeatability at ±5% variation. The sensor was also able to clearly indicate the transient flow conditions of a full scramjet combustion operability cycle to include shock train movement and backflow along the isolator wall. The measured experimental wall shear data demonstrated good agreement with simple, flat-plate analytical estimations and historic data (where available). Numerical CFD predictions of the scramjet flow path gave favorable results for steady cold and hot flow conditions, but had to be refined to handle the various fueling injection schemes with burning in the downstream combustor and surface roughness models. In comparing CFD wall shear predictions to the experimental measurements, in a few cases, the sensor measurement was adversely affected by shock and complex flow interaction. This made comparisons difficult for these cases. The sensor maintained full functionality under sustained high-enthalpy conditions. No degradation in performance was noted over the course of the tests.

This dissertation research and development program has proven successful in advancing the development of a skin friction sensor for applications in high-speed, high-enthalpy flows. The sensor was systematically tested in relevant, high-fidelity laboratory environments to demonstrate its technology readiness and to successfully achieve a technology readiness level (TRL) 6 milestone. The instrumentation technology is currently being transitioned from laboratory development to the end users in the hypersonic test community.