Propulsion Measurement Sensor Development Workshop
NASA Marshall Space Flight Center, Huntsville, Alabama
May 12-15, 2003

INITIAL DEVELOPMENT OF A MEMS WALL SHEAR STRESS SENSOR FOR PROPULSION APPLICATIONS

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Abstract

This paper describes preliminary research on the development of a MEMS based shear stress sensor for applications in the hypersonic aeropropulsion wind tunnels at the GASL Division of Allied Aerospace. Typically, when attempting to determine combustor performance (i.e. efficiency) using computer codes, assumptions are made with regards to the skin friction coefficient, required as an input. Obtaining direct shear stress measurements along, for example, the combustor wall will allow engineers to calculate a skin friction coefficient, which may contribute to more accurate combustor performance and thermal load calculations. Development of a MEMS based shear stress sensor may also: (1) allow for calibration of computer code shear stress calculations; (2) help identify when and where flow separation and boundary layer transition occurs in the engine flow path; and (3) allow for direct measurement of vehicle component drag. In the past, bulky, mass-spring-dashpot type skin friction gages have been utilized inside combustors at a single discrete location. MEMS technology employs micro-machining techniques that enable the creation of structures with diameters on the order of microns, fractions of a human hair. A MEMS based shear stress sensor chip may have an array of shear stress measuring elements that can then be embedded inside a combustor wall, or on an airfoil section of a wing. An initial feasibility study was conducted to determine if a MEMS based shear stress sensor can be used to measure the shear stress on engine articles tested in the HYPULSE facility located at GASL. Shear levels ranging from 10 to 10,000 Pa are predicted to be measurable with this device, which utilizes capacitative sensing and active, closed-loop, electrostatic force feedback, and with response times on the order of 10 μsec. Various promising designs are currently under fabrication, using a multi-user silicon carbide (MUSiC) surface micromachining approach.

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Introduction

The goal of this work is to develop a MEMS wall shear stress sensor for application in high-speed aeropropulsion wind tunnels and other "harsh" environments (eg. combustors, rocket nozzles, airfoils). This paper describes preliminary research on the development of a MEMS-based direct shear stress sensor designed for the unique environment and shear levels found in such applications. MEMS (MicroElectroMechanical Systems) is an enabling technology that utilizes surface and bulk micromachining methods, an extension of integrated circuit technology, to create structures on the order of microns. Some of the benefits of using MEMS include: (1) batch fabrication leads to cost reduction; (2) small size allows for minimal disturbance, weight savings; and for integration of sensor, actuator and "smart" electronics in an area the size of a human pupil and (3) very low power requirements.

Initial work has focused on assessing the feasibility of utilizing a MEMS shear stress sensor for application in the HYPULSE Facility at the GASL Division of Allied Aerospace in Ronkonkoma, New York (www.alliedaerospace.com). The GASL Division of Allied Aerospace, originally formed in 1956 by Antonio Ferri and Theodore Von Karman, among others, with primary business areas in RDT&E and design & production relating to high speed, combustion test systems and wind tunnel testing.

Motivation: A measurement that is not readily made and has been absent from our wind tunnel testing is wall shear stress. A MEMS based shear stress sensor can be used to measure the shear stress on articles tested in the HYPUSLE Laboratory and in the Test and Evaluation Laboratory.

Typically, when attempting to determine combustor performance (i.e. efficiency) using computer codes, a value for the skin friction coefficient is assumed, which is required as an input. Obtaining direct shear stress measurements along the combustor wall will allow engineers to obtain a more accurate skin friction coefficient. Development of a MEMS based shear stress sensor: (1) may contribute to more accurate combustor performance and thermal load assessment(using Reynolds Analogy); (2) allow for calibration of computer code shear stress calculations; (3) help identify when and where flow separation and boundary layer transition occurs in the engine flow path; (4) allow for direct measurement of vehicle component drag; and (5) assist in the calibration of hot-wire anemometers.

Requirements: Eventually, the goal is to be able to implement an array comprised of 100's of MEMS shear stress sensors in the harsh environment of a propulsion device (inlet, combustor, nozzle, etc). A "harsh" environment, in this case, includes: (1) a high-temperature, chemically-reacting flowfield, with temperatures ranging from several hundred to several thousand degrees and pressures up to several atmospheres; (2) an environment with characteristics that require fast response measurements of transient events, eg. shock waves, combustor instabilities; and (3) a "dirty" environment that includes liquid jet fuel combustion, combustion products, particulate matter (eg. soot, etc).

Table 1 HYPULSE Facility Operating Characteristics

Facility Characteristic	**Value/Comment**
Avg. Test Time	400 µsec-10 msec
Instrumentation Response Time	20µsec - 100 µsec
Environment	Highly transient, hot air, ~2% NO, 0.5% O-atom, steam, hydrocarbon soot.

Description of GASL Division Test Facilities

The HYPULSE Facility, part of GASL's Shock Tunnel Laboratory, provides aeropropulsion and aerothermal simulation capabilities over the Mach 2-25 flight speed regime. HYPUSLE is a NASA-MSFC facility located on site at GASL**,** Figure 1**,** and has been used as a dual-mode shock tunnel facility: reflected shock tunnel mode and shock-expansion tunnel mode, able to handle test articles up to 2 meters long, Figure 2. This facility has also been used for NASA's HYPER-X Program, with extensive work for HYPER-X scramjet engine design and evaluation. Another shock tunnel, located in the laboratory is the Kinetics and Instrument Shock Tunnel (KIST), used for chemical kinetics, oblique detonation wave studies, Figure 1.

HYPULSE is used for hypersonic aerothermal studies, ramjet/scramjet tests, aero-assist rocket development and boundary- layer transition testing[1-3]. When the facility operates in a blowdown mode (Ludwieg Tube mode of operation), the driver section (Figure 1) is filled with test gas (air, nitrogen) to a specified pressure and the model test section is evacuated to sub-atmospheric pressures with a vacuum pump. These two sections are separated by a thin Mylar diaphragm that is designed to burst at a predetermined pressure[1]. Once the diaphragm bursts, a shock wave travels down the length of the tube and into the test section, where the test article is mounted on a three-component balance. Test times are on the order of milleseconds, and high speed data acquisition equipment record pressure, temperature and heat flux measurements from the model.

The Test and Evaluation Laboratory has six high-temperature aeropropulsion wind tunnels capable of achieving total temperatures up to 5600 °F and total pressures up to 1800 psi, Figure 3. Experiments range from combustor testing (Legs 1 and 2), to materials testing (Leg 3) and scale model testing of freejet engines (Legs 4-6).

Aerodynamic testing facilities also exist in our El Segundo site, where there is a Low Speed Wind Tunnel (up to Mach 0.3) and a TriSonic Wind Tunnel (Mach 0.1 to 3.5).

Shear stress sensors use either direct or indirect for shear stress detection.[4] In the direct method the tangential force, i.e. shear, acts on a surface floating balance, thus giving the shear stress directly.[5,6] The deflection of the floating element is then proportional to the shear. There are several ways to measure this deflection, including: (1) using optical sensors; (2) generating an electric field in the gap between the floating element and the support structure and measuring the change in capacitance; (3) implementing piezoresistors and measuring the change in resistance, proportional to the deflection.

For the indirect shear stress measuring methods, the shear stress is obtained by making measurements that are related to shear stress through some physical principle, eg. heat transfer. Some indirect measuring devices include: Preston tubes[7], Stanton tubes[8], and hot-wire/hot-film surface mounted sensors.[9] Flow sensors based on heat transfer methods have a common problem in that the heat loss to the wall or substrate beneath the sensor limits the performance.

There are many different devices for measuring shear stress, some of which are described below.

Surface Hot Wire Anemometers:

A surface hot wire is made of a tungsten or platinum wire, (~ 2μm in diameter). Hot wire anemometers measure flow velocity indirectly by applying a known current to the hot wire (with a known resistance) and relating the convective heat transfer flux q (dependent on flow velocity) to the i^2R power dissipation in the wire. The power dissipated will vary since the resistance will change with temperature and therefore flow velocity.

Since the wire sensor is extremely fragile, hot wire anemometers are usually used in clean air or gas environments.[10] Hot wire anemometers cannot distinguish between different flow directions, leading to problems if flow reversal occurs.[11] This could especially be a concern in a turbulent boundary layer. An option to hot-wire anemometers is a pulsed hot-wire sensors, which suffers from insufficient time resolution.[12-14]

Hot Film Anemometers:

Hot-film sensors operate on the same basic principle as hot-wire sensors, with the following differences: (1) hot-film sensors are very rugged and can be used in both liquid and contaminated-gas environments;[10] (2) a high-purity platinum film is bonded to a rod and the thin film is protected by an alumina coating or quartz, depending on the flow environment.[10]

MEMS Based Shear Stress Sensors

Other devices for measuring shear stress include a MEMS, silicon-based fence sensor that is flexible and contains piezoresisters, connected to a Wheatstone bridge. A pressure difference across the fence causes it to deflect, leading to a mechanical stress in the fence which then alters the resistance of the piezoresisters. This direct measuring fence can only be used for wall-shear stresses below 1 Pa.[11]

Liu, *et.al.*,[15] developed a surface micromachined thermal shear stress sensor, that mitigates heat losses to the substrate beneath by positioning the hot-wire on a free-standing silicon nitride diaphragm, which is placed above a vacuum cavity, thus minimizing heat losses, thus improving thermal isolation. Shear stress levels between 0.1 to 1.4 Pa are measurable with this device.

Zhe *et.al.,*[16] developed a microfabricated floating-element shear stress sensor capable of directly measuring, via capacitive methods, shear stress as low as 0.05 Pa ± 0.005 Pa.

The micromachined devices mentioned above[11,15,16] measured in the range of shear stress levels that are far below the range calculated in the supersonic/hypersonic flowfield environments tested in the wind tunnels at the GASL Division of Allied Aerospace. This is the primary reason for developing the MEMS shear stress sensor discussed in this paper.

Approach

The proposed approach consists of directly monitoring the shear force applied by the flow on a freely suspended sensing element flush with the wall. The proposed device is implemented using microfabrication techniques developed for microelectromechanical systems (MEMS) and integrates the exposed sensing element, mechanical compliance, capacitive sensing, and electrostatic force feedback on a chip.

The configuration of the proposed device and its operating principles are illustrated in Figure 4-Figure 6. A lateral force is applied on the sensing element proportional to the local shear stress. This force is transmitted to a free-floating shuttle supported on springs. The springs consist of pairs of folded cantilever beams at each end of the shuttle. When the shuttle translates, the gaps between electrodes attached to the shuttle and stationary electrodes varies, leading to a change of electrical capacitance between the two structures. This change of capacitance is then measured with external circuitry, and converted into a voltage signal. In order to increase the range of shear applied before the movable shuttle contacts the stationary structures, an electrostatic counter force is applied to the shuttle by applying a potential difference between the stationary and movable electrodes. The device is then maintained in the central position (i.e. the "null" condition) and the actuation voltage becomes the output quantity. The device design will be described further in the next section.

Since the device is directly exposed to the harsh environments, its fabrication must be based on materials and operating principles that maintain functionality at elevated temperatures and are chemically stable. Silicon carbide appears as a material of choice, especially given the recent development fabrication techniques for SiC MEMS, such as the multi-user silicon carbide (MUSiC) surface micromachining service offered by FLXMicro[17] and supported by the Glennan Initiative.[18] The process consists of depositing and patterning multiple thin layers of silicon carbide, interlayed with sacrificial layers removed at the end. The approach is similar to the polysilicon surface micromachining process developed at Sandia National Labs (SUMMIT V), but with SiC as the structural material instead of polycrystalline silicon. Chemical vapor deposited silicon carbide offers the advantages of maintaining its structural integrity up to 2100 °C, being chemically inert, and providing good mechanical properties.

Multiple sensing principles are possible in order to convert the displacement of the sensing element into an electrical signal, such as opto-electronics using photodiodes, piezo-resistance using doped resistors, or capacitive sensing. The latter was used since it is easily implemented, does not rely on temperature sensitive materiel properties, and the sensing component can also be used for force feedback.

Typically, MEMS sensors, such as pressure sensors and accelerometers are packaged in vacuum sealed enclosures with limited exposure to the environment. Direct shear flow measurement however requires the device to be exposed to the flow, and to be subjected to the harsh environments, with minimal disturbance of the flow field. These constraints require appropriate device design and packaging. Possible scenarios for the MEMS shear stress sensor may be to package it in a structure that is easily installed flush to an engine wall, either as a thin layer bonded to the wall surface or at the end of a probe tip inserted through the wall with the electrical leads proceeding along the wall or through the probes, respectively, as shown in Figure 4. Electrical connections to the sensor components can be done through the substrate, leaving the front side of the device undisturbed.

It is conceivable that an array of MEMS shear stress sensors will incorporate a fraction of the floating elements able to translate in one direction and another set of floating elements able to translate in another direction. This will allow the sensors the ability to measure shear stress in two different, in-plane, directions.

MEMS Shear Stress Sensor Design

The design process consists of defining a device geometry which provides a measurable output at the lowest level of shear (taken to be 10 Pa), sufficient electrostatic force feedback to maintain the shuttle in position at the highest level of shear (10,000 Pa), all within the fabrication constraints imposed by the microfabrication technology, available circuitry, and physical constraints. The SiC surface micromachining process used, (MUSiC), sets the thickness of each layer forming the device, but there is complete flexibility for the inplane geometry, with minimum feature size of 2 microns (1/10,000th inch). The device requirements are summarized below in Table 2.

Table 2 MEMS Shear-Stress Sensor Requirements and Characteristics

Sensor Characteristic	Value/Comment
Shear Stress Range (Pa)	10-10,000
Response Time (μsec)	10
Exposure	Must withstand "harsh" environment. Use SiC; use mechanical stops. Must be flush-mounted into wall.
Resolution (Pa)	10
Direct or Indirect Measmt	Direct
Method of Measurement	Differential capacitance sensing; closed loop.

In defining the geometry, the springs are implemented as cantilever beams and the capacitance change is determined by the parallel plate capacitance between the stationary and movable electrodes. Since commercially available differential capacitance circuitry allows measurements on the order of 1fF, the lowest shear level must provide sufficient deflection and change of capacitance. This suggests thin clearances between electrodes, flexible springs, and a large number of electrodes (capacitance area). At high shear levels, a maximum voltage of 100 V is allowed between the stationary and movable electrodes in order to counteract the shear force, and maintain the shuttle centered. The design objective was to minimize the number of electrodes, hence minimizing the device size, while satisfying achieving the desired shear stress range of 10-10,000 Pa. Combining the governing equations, one finds that the number of electrodes, N_f, is given by:

$$N_f = \left[\left(\frac{\delta C_{\min} \tau_{\max} E}{2 \varepsilon_0^2 \tau_{\min} V_{\max}^2 h} \right) \frac{b^3 a^4}{L_f^2 L^3} \right]^{1/2}$$

where, the parameters are defined in Figure 6. This suggests small inter-electrode gaps and beam widths, as well as long beams and electrodes. The sensing pad size is then given by:

$$A_\tau = \frac{N_f L_f h V_{\max}^2 \varepsilon_0}{2 \tau_{\max} a^2}$$

Given the requirements and constraints, various designs are possible. Table 3 summarizes the nominal design as well as six other alternative designs which relax some of the specifications and constraints. This study suggests that the range of 10-10,000 Pa appears viable with force feedback. The natural frequency of these sensor designs also suggests time responses on the order of 0.1-0.01 msec.

Future Plans and Prospects

The designs presented above are currently being fabricated through the multi-user silicon carbide surface micromachining service, called MUSiC, offered by FLXMicro under the sponsorship of the Glennan Microsystems Initiative.[18]

Initial device inspection and electrical characterization will be done in the Microsystems Laboratory at Columbia University in order to validate the dimensions and basic functionality of the sensor. The mechanics of the device will be characterized through electrostatic actuation and dynamic response testing. Breadboard electronics with off-the-shelf integrated circuitry for differential capacitance measurement and feedback control will be used initially, but can eventually be miniaturized at the chip scale. Flow testing will then be conducted in the low speed wind tunnel and Mach 2 blowdown supersonic nozzle at Columbia University in order to develop necessary instrumentation and to calibrate device operation. Upon satisfactory performance, select sensors will be packaged for testing in the high speed tunnels at GASL (Figure 1-Figure 3) and their performance evaluated.

Packaging Issues: Most of the critical components of the device are protected from the environment by the top SiC layer, which covers the entire device surrounding the sensing element. Holes and clearances are less than 5 microns, which prevents typical dust particles from entering the device. Three approaches are envisioned to address the problem of contamination, if it should occur: 1) filling the device with oil, held in place due to surface tension forces; 2) covering the device top surface and holes with a thin, compliant polymer film, such as Parylene, which would preclude high temperature operation; and 3) providing a positive pressure under the device to maintain an outward flow, which could interact with the main flow.

Summary

During this initial development work, a MEMS-based direct shear sensor was designed for a range of shear of 10 to 10,000 Pa, characteristic of aeropropulsion applications in GASL Division's high speed wind tunnels. The proposed MEMS device consists of a silicon carbide, surface micromachined, freely-suspended sensing element, whose motion is sensed capacitively and negated with force feedback control to achieve the large shear stress range. Devices are currently under fabrication and testing plans were presented. Such shear measurements would: (1) allow for the calibration of computer code shear stress calculations; (2) help identify when and where flow separation and boundary layer transition occurs in the engine flow path; and (3) allow for direct measurement of vehicle component drag.

Acknowledgements

The authors wish to acknowledge: Dr. Clay Rogers of NASA-Langley and Dr. Robert Foelsche of Allied Aerospace for providing typical flow conditions in the HYPULSE Facility, the Glennan Microsystems Initiative for sponsoring the microfabrication costs and FLXMicro for providing the micromachining services and technical support.

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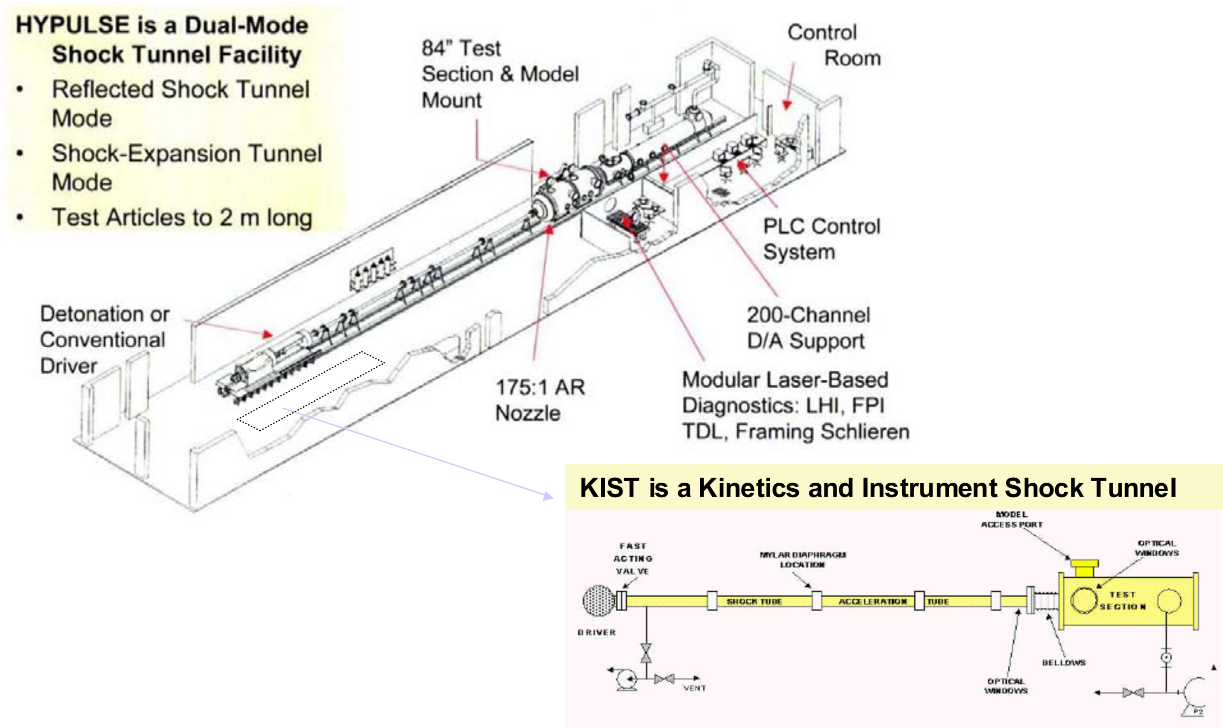


Figure 1 The HYPUSLE and KIST Facilities operate in the Shock Tunnel Laboratory, located at the GASL Division, Allied Aerospace.

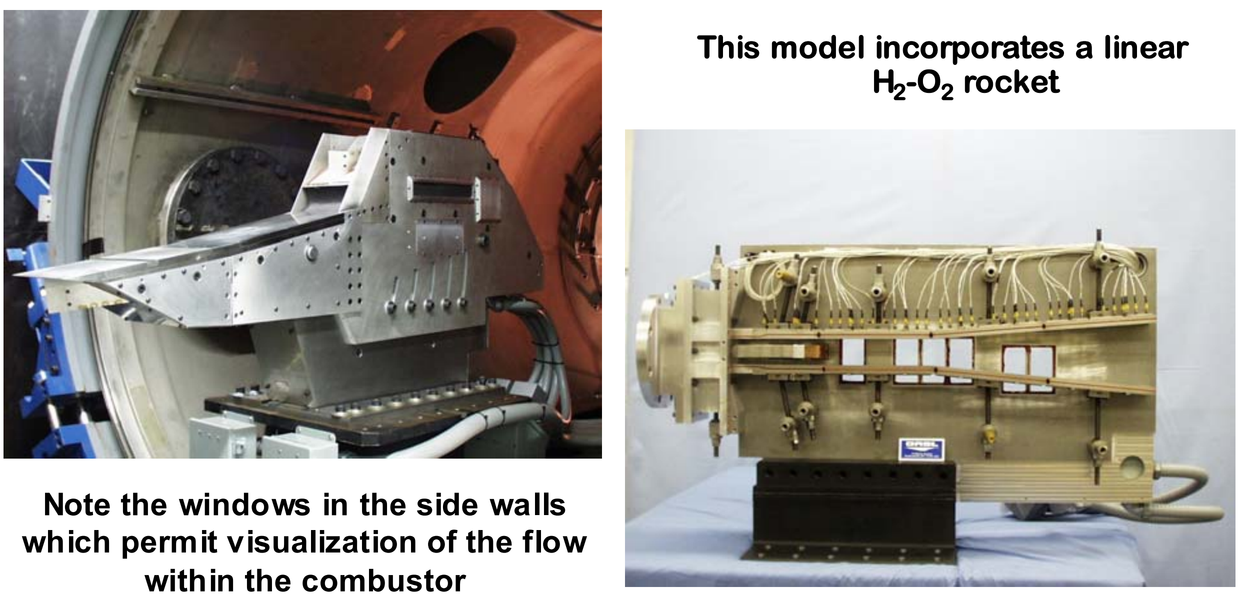
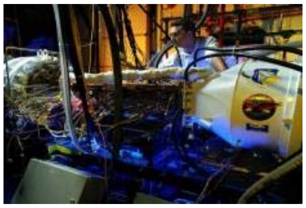
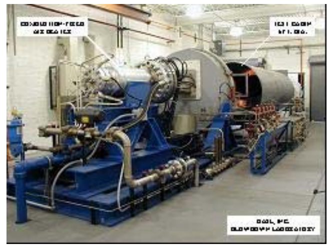


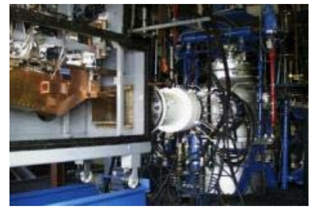
Figure 2: Photographs of a scramjet model and a RBCC (Rocket Based Combined Cycle) model built and tested by GASL in the HYPULSE facility, located at the GASL Division, Allied Aerospace.



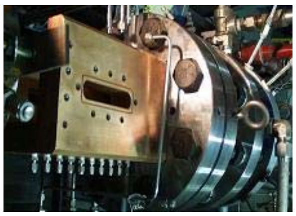
Leg I and Leg 2 – Offer Direct Connect Combustor and Materials Test Capabilities



Leg VI- GASL's Large Hypersonic Freejet Test Facility



Leg IV- Storage Heated Facility for Clean-Air Combustion and Aerodynamic Testing



Leg III – The Panel Oxidation and Evaluation Test Facility Offers Efficient High-Temperature Materials Testing

Leg V- The Flight Acceleration Simulation Test Facility is Unique to GASL

These facilities achieve total temperatures up to 5600 ^oF and total pressures up to 1800 psi.

Figure 3: Photographs of six high-temperature wind tunnels that operate in the Test and Evaluation Laboratory located at the GASL Division, Allied Aerospace.

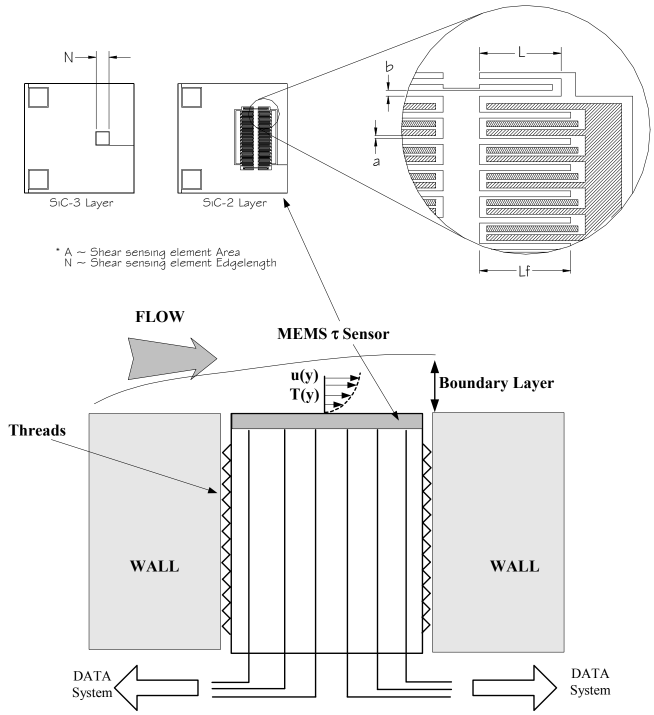


Figure 4: Schematic of the MEMS shear stress sensor embedded in a wall exposed to a flowfield.

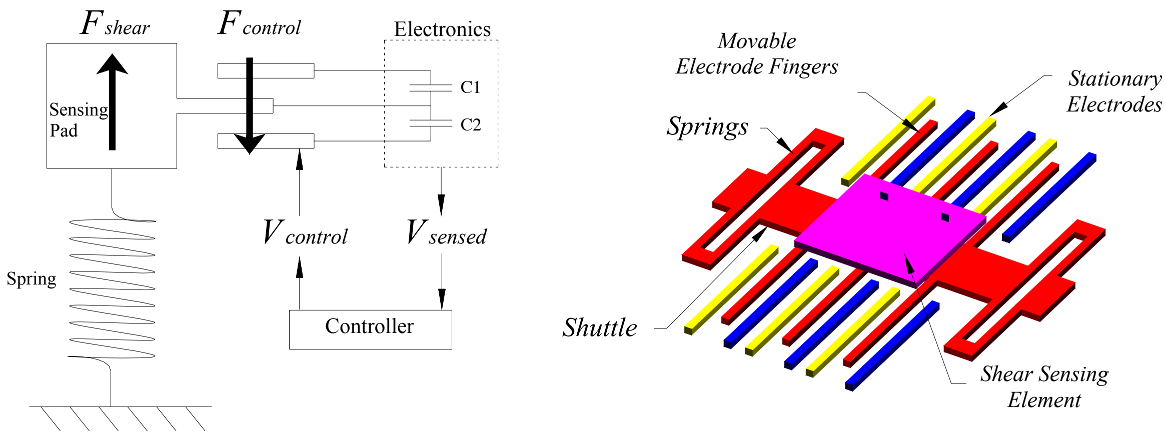


Figure 5: Shear sensor operating principle and configuration.

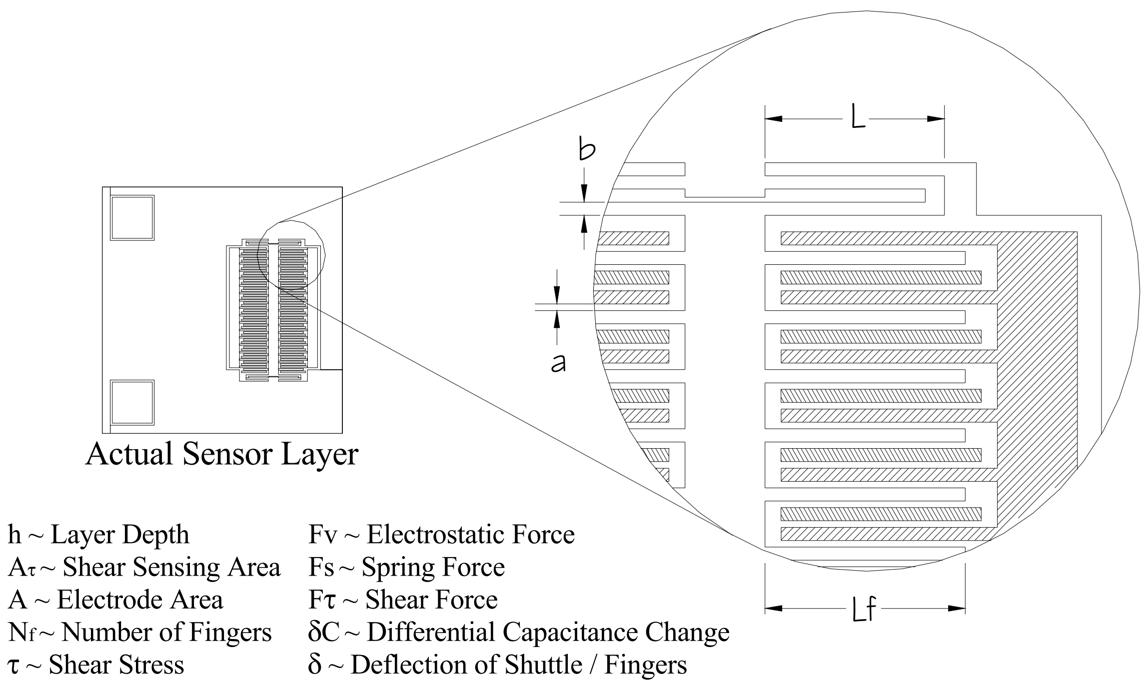


Figure 6: Main sensor shuttle, springs, and electrode geometry with nomenclature

	Sensors						
	Primary	Off-Design					
	A	**B**	**C**	**D**	**E**	**F**	**G**
Dimensions							
a (μm)	2.5	2.5	4.0	2.5	4.0	4.0	4.0
b (μm)	4.0	8.0	4.0	8.0	4.0	8.0	8.0
L (μm)	190.0	190.0	190.0	190.0	190.0	100.0	100.0
Lf (μm)	115.0	115.0	115.0	115.0	115.0	115.0	115.0
A_τ (μm x μm)	92 x 92	87 x 87	51 x 51	275 x 275	163 x 163	445 x 445	140 x 140
Nf	52.0	46.0	42.0	46.0	42.0	34.0	34.0
Ranges							
τ_{min} (Pa)	10	100	100	10	10	90	900
τ_{max} (Pa)	10000	10000	10000	1000	1000	110	1100
Natural Frequencies							
fn (kHz)	16.21	34.90	16.45	34.91	16.27	95.93	96.43

Table 3 Various proposed shear sensor designs