The Need for a Shear Stress Calibration Standard

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By surveying current research of various micro-electro mechanical systems (MEMS) shear stress sensor development efforts we illustrate the wide variety of methods used to test and characterize these sensors. The different methods of testing these sensors make comparison of results difficult in some cases, and also this comparison is further complicated by the different formats used in reporting the results of these tests. The fact that making these comparisons can be so difficult at times clearly illustrates a need for standardized testing and reporting methodologies. This need indicates that the development of a national or international standard for the calibration of MEMS shear stress sensors should be undertaken. As a first step towards the development of this standard, two types of devices are compared and contrasted. The first type device is a laminar flow channel with two different versions considered: the first built with standard manufacturing techniques and the second with advanced precision manufacturing techniques. The second type of device is a new concept for creating a known shear stress consisting of a rotating wheel with the sensor mounted tangentially to the rim and positioned in close proximity to the rim. The shear stress generated by the flow at the sensor position is simply $\tau = \mu r\omega/h$, where μ is the viscosity of the ambient gas, r the wheel radius, ω the angular velocity of the wheel, and h the width of the gap between the wheel rim and the sensor. Additionally, issues related to the development of a standard for shear stress calibration are identified and discussed.

Nomenclature

a	=	half height of a plane wave tube with square cross section
b	=	flow channel height
c	=	speed of sound
dp/dx	=	pressure gradient across a sensor
f	=	acoustical excitation frequency for circular plane wave tube
f_{co}	=	3 dB cut-off frequency
g	=	gap between a floating element and the immobile substrate
h	=	height of water flow channel
k	=	wave number
M	=	Mach number
p'	=	pressure fluctuating magnitude
Q	=	flow rate
R	=	radius of circular plane wave tube
t	=	thickness of floating element
w	=	width of water flow channel
γ	=	ratio of specific heats for a gas
ρ	=	density
τ	=	effective shear stress
τ	=	wall shear stress
μ	=	dynamic viscosity
ν	=	kinematic viscosity
ω	=	angular acoustic excitation frequency for square plane wave tube

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I. Introduction

THE measurement of shear stress for aerodynamic applications has been a subject of extensive research for many years. When a body is exposed to flow the force developed on the surface due to the viscosity of the fluid is the shear stress τ_w. This force is related to the velocity profile over the body by

$$\tau_w = \left(\mu \cdot \frac{\partial u}{\partial y} \right)_{y=0} \tag{1}$$

where μ is fluid viscosity at the temperature of the surface and u is the tangential velocity component as a function of y perpendicular to the surface. Typical wind tunnel measurements in the past have relied on indirect methods with extensive limiting assumptions. These methods include techniques such as Preston tubes, Stanton tubes, hot wires, and hot films.

Generating a known shear stress is different from what is needed for generating many other physical phenomena. Some phenomena such as voltage and pressure are easily transferable from one location to another. Pressure can be generated at a location and then transferred to another location via tubing to the sensor being calibrated. Precision pressure calibrations with a dead weight tester rely upon this transference ability. In the case of a dead weight tester, the only additional correction needed is based on the difference in height of the reference point of the dead weight tester and the reference point of the device under calibration. Other quantities are easily determined by the simple process of measuring, controlling, or knowing a limited number of variables. An example of this is mass flow: measure time and total mass transferred while controlling temperature and the mass flow can be determined. This is a simplification of the process used for precision mass flow calibrations but does capture the basic requirements. Shear stress is not transferable like voltage and pressure, the force generated over an area by the shear stress is transferable but not the shear stress itself. Also, shear stress is not a direct result of two or more easily measured variables, but is by definition dependent on the gradient of a flow at a particular location. This *in situ* requirement greatly complicates any calibration of a shear stress sensor.

Because of the difficulty in generating a known shear stress and the lack of guidance, in the form of an accepted standard, the calibration of shear stress sensors receives significant attention in the literature. This includes multiple methods for calibration by generating either a known steady state or known dynamic shear stress. However, calibration may not be the correct terminology for most work done with these sensors; rather characterization may be the more appropriate terminology. What makes calibration of shear stress sensors a questionable description is the previously mentioned lack of a standard for calibration methods from the National Institute of Standards and Technology (NIST) or any other standards organization.

The purpose of this paper is not necessarily to challenge the in-depth analysis of the various characterization techniques as they are presented in the literature but to gather information about the dominant techniques. The intention is also to identify issues both the existing techniques and newly developed techniques should address. To do this, example sensors will be presented from the literature with particular attention to the characterization methods used. Next, a novel approach for the implementation of a flow channel will be discussed along with its advantages over conventional implementations. Then a new concept will be introduced for a rotary flow channel and its advantages and disadvantages will be reviewed. Finally, a general overview of the issues and questions to be answered as part of the process of developing a standard for shear stress calibration will be presented.

II. Example Sensors and Methods Used for Characterization

A. Floating Element Sensors

Floating element type sensors are one of the most attempted methods for the measurement of shear stress. According to Ref. 1 there are several disadvantages to floating element type sensors, including but not limited to their susceptibility to stream-wise pressure gradients and the potential for contamination of the gaps leading to errors our even sensor failure. For many flows with MEMS scale sensors these disadvantages are not sufficient to preclude the use of a floating element sensor design.

In Ref. 2 an equation is developed for the shear stress generated along the walls in a flow channel: based only on the continuity equation with the following assumptions: (1) constant cross sectional area, (2) ideal gas, (3) isothermal gas, (4) stabilized flow conditions have been reached, (5) mean value for local Mach number (and velocity) can be used to represent their distribution, and (6) temperature is held constant. This analysis resulted in the following equation for shear stress in a flow channel without limiting flow state to the laminar condition:

$$\tau_w = -\frac{b}{2}\left[\frac{dp}{dx}\left(1-\gamma M^2\right)\right] \tag{2}$$

where b is the height of the channel, dp/dx the pressure gradient across the sensor, γ is the ratio of specific heats of the gas, and M is the mach number at the sensor location. Further analysis based on the specific sensor geometry with gaps and a possible flow path under the floating element resulted in an equation for the total effective shear stress acting on this sensor:

$$\tau_{eff} = -\frac{dp}{dx}\left|\frac{b}{2}\left(1-\gamma M^2\right)+\frac{g}{2}+t\right| \tag{3}$$

where the new term g is the gap between the floating element and the immobile substrate and t is the thickness of the floating element. Using the dimensions of this sensor (g=2.5μm and t= 2μm) and the maximum shear stress condition of τ_{eff} = 80.55Pa, we can solve for the pressure drop and determine that τ_w=80.54 Pa. This correction is less than 0.013%. Since the physical dimensions are very small for this device the correction is very small as expected. The actual calibration was developed in terms of the total force acting upon the sensing element yielding $\tau_{eff} = f(V)$ and to convert the output voltage into the real wall shear stress required the local pressure gradient and the physical geometry of the sensor as follows:

$$\tau_w = f(V)+\frac{dP}{dx}\left(\frac{g}{2}+t\right) \tag{4}$$

where $f(V)$ is the function relating the sensor output voltage to τ_{eff} from the flow channel characterization, dP/dx is the local pressure gradient at the sensor location, g is the gap around the floating element, and t is the thickness of the floating element. The pressure gradient identified in Eq. (4) must be measured independently and in as close proximity to the sensor as possible. It is even recommended that MEMS pressure sensors be co-located on the same die for an accurate determination of this factor.

To improve the total accuracy of the characterization based upon this analysis, a microstrip was designed for installation into the same location where the sensor would be installed. The purpose of this microstrip was to decrease the inaccuracy of channel height measurement from the 5% claimed when using optical microscopes to 1.5%. The details on the microstrip design and implementation are not critical for this discussion but the time and effort spent to improve this quantity does illustrate the importance of improvements in the height measurement as part of the effort to decrease the total uncertainty. An important additional claim is that the uncertainty in the measurement of the channel height is comparable to the fluctuation in channel height itself. The uncertainty in the cross sectional area is dominated by the channel height uncertainty.

As part of the uncertainty analysis an equation was developed for the uncertainty in the effective shear stress.

$$\left(\frac{\Delta\tau_{eff}}{\tau_{eff}}\right)^2 = \left(\frac{\Delta(\partial p/\partial x)}{\partial p/\partial x}\right)^2 + \left(\frac{\Delta b}{b}\right)^2 + \left(\frac{2\gamma M\Delta M}{(1-\gamma M^2 + g/b + 2t/b)}\right)^2 + \left(\frac{(1/b)\Delta g}{(1-\gamma M^2 + g/b + 2t/b)}\right)^2 + \left(\frac{2\Delta t/b}{(1-\gamma M^2 + g/b + 2t/b)}\right)^2 \qquad (5)$$

The value of $(\Delta(\partial p/\partial x)/(\partial p/\partial x))$ is 0.002 (0.2%). The uncertainty is ±3μm for a 200μm height channel resulting in an uncertainty of 0.015 (1.5%) which is $(\Delta b/b)$. The term with $2\gamma M\Delta M$ in the numerator has a value of 0 for M=0 and 0.014 (1.4%) for M=0.4. The other two terms, containing $((1/b)\Delta g)$ and $(2\Delta t/b)$ in the numerators, have a value of 0.001 (0.1%). This results in a worst case uncertainty at M=0.4 of 0.021 (2.1%) versus the listed 0.02 (2%). The resultant uncertainty is dominated by both the uncertainty in channel height and the uncertainty in the Mach number. Upon a detailed analysis the Mach number uncertainty contains components dependent on the uncertainties in the channel height, pressure gradient, and the measurement of a volumetric flow rate. This leads to the conclusion that a decrease in the uncertainty in channel height will improve the total uncertainty by a greater value than obtained just by changing the $(\Delta b/b)$ term in Eq. (5). Improvements in the Mach number uncertainty can possibly come from several sources: decreased uncertainty in the cross sectional area, use of higher accuracy pressure transducers, increased resolution in determining the pressure gradient by the use of more measurement locations, and by use of Venturi flowmeters.

B. Thermal Shear Stress Sensors

Thermal type sensors are the other most attempted method for implementation of a MEMS shear stress sensor. This type of sensor is an indirect indicator of shear stress. The output of the sensor is dependent on anything that can change the heat transfer between a heated body and its surroundings. Two of the advantages of most of these implementations are the lack of physical gaps and an inherent dynamic response capability. There is a great deal of discussion concerning the applicability of these sensors. High accuracy quantitative measurements are difficult if not impossible to make. These sensors are excellent for determining relative changes in shear stress as well as detecting the frequency content of disturbances in the flow. A thorough review of thermal shear stress sensors can be found in Ref 3. Many issues are identified for this type of device but one key point from this review that has direct ramifications on both the static and dynamic calibration and subsequent use of any thermal type shear stress sensor is for the calibration to be valid in both the calibration facility and the test article or for the sensor to be calibrated *in situ*. The calibration can be valid if the thermal boundary generated by the heated sensor is completely contained within the linear region of the velocity profile. This is a critical factor for thermal shear stress sensors but is an example of a type of particular concern that must be investigated and identified for any indirect shear stress sensor. The ability to generate the same shear stress with two or more distinctly different velocity profiles would greatly enhance the ability to study these types of calibration issues for all indirect shear stress sensors.

The ability to perform a dynamic calibration for shear stress sensors, particularly thermal shear stress sensors, is an important component of any standard for shear stress calibration. There are two implementations of a characterization device based upon Stokes Layer excitation.

The first implementation consists of a plane wave tube with a circular cross section and has zero mean flow. The analysis of this device has shown that the generated shear stress was proportional to the square root of the excitation frequency and the acoustic pressure magnitude,

$$\tau(z,t) = -\frac{p' e^{j(2\pi ft - kz)}\sqrt{j\rho 2\pi f u}}{c} \cdot \frac{I_1\left(R\sqrt{j2\pi f/v}\right)}{I_0\left(R\sqrt{j2\pi f/v}\right)} \qquad (6)$$

with ρ is the density, μ the viscosity of the fluid, R the radius of the tube, p' the magnitude of the pressure fluctuation, c the speed of sound, k is the axial wave number ($k = 2\pi f/c$), z is the downstream coordinate, f the frequency of the acoustic excitation, v is the kinematic viscosity, t is time, and I_0 is the zeroth-order modified Bessel function. Also of interest is the upper frequency limit for calibration using this type of device given by,

$$f_{co} = \frac{0.2931c}{R} \tag{7}$$

This analysis assumes plane-wave propagation which imposes an upper limit on the frequencies that can be used in the characterization. Other complications can arise from potential for the existence of higher-order wave modes reflecting from the duct walls. Testing of the tube resulted in shear stresses from 0.0014 Pa to 10 Pa for a frequency range of 700 Hz to 4 kHz. Since most, if not all, sensors are not designed to mount in a circular tube a correction needs to be developed for this flatness.[4]

The second implementation has a square cross section duct with a non-zero mean flow. A mean flow is established and purely traveling acoustic plane waves are superimposed. It is assumed that the problem can be solved as a duct flow driven by an oscillatory pressure gradient. This analysis assumes the boundary layer thickens is considerably smaller than the width of the duct and the sensor being tested is located at the center of the wall resulting in a simplification of the flow field to that of a flow between two parallel plates. The resultant shear stress from the purely traveling acoustic wave becomes,

$$\tau = \frac{-p'}{c} e^{j(\omega t - kx)} \sqrt{\frac{j\omega\mu}{\rho}} \left[\tanh\left(a\sqrt{\frac{j\omega}{\nu}} \right) \right] \tag{8}$$

where k is the wave number, p' is the magnitude of the pressure fluctuation, c is the speed of sound, ρ is the density, μ is the dynamic viscosity, ω is the angular frequency, ν is the kinematic viscosity of the fluid, a is half the height of the duct, and x is the axial coordinate. Equation (8) only holds true for plane wave propagation and is therefore limited by the cut-off frequency which can be determined by,

$$f_{co} = \frac{c}{4a} \tag{9}$$

Additionally, the flow that the traveling acoustic wave is superimposed upon must be laminar. To satisfy the laminar flow requirement the Reynolds number must be less than 2300. For the 8.5mm square duct used in this test the maximum mean shear stress obtainable due to the laminar flow requirement was 0.09 Pa. At the centerline of the duct the shear stress due to the flow is,

$$\tau_w = -\frac{8a}{\pi^2}\left(\frac{\partial p}{\partial x}\right)(0.833133) \tag{10}$$

By simultaneously solving Eq. (8) and Eq. (10) the instantaneous shear stress value can be determined as long as all limiting assumption identified earlier are satisfied.[5]

Another device has been used to characterize a non-MEMS implementation of an oscillating-hot-wire sensor. The characterization was done using a Couette flow facility consisting of a rotating disc parallel to a stationary disc.[6] A direct numerical simulation is presented in Ref. 7 for the flow field of a device of this type and showed the flow profile to be linear. While linear, this flow field is very complicated and has components in r, θ, and z.

C. Flow Obstruction Sensors

Another indirect method has been developed based on the bending of an obstruction placed in the flow of interest. Two generations of a device of this type have been developed and tested. Two aspects of the testing done on these devices are of primary interest and the first should be applied to all shear stress sensors if possible. The first aspect of testing that is not commonly implemented is an angular sensitivity test for rotation from 180˚ to –180˚. A MEMS implementation of this type of sensor has been fabricated and tested. This sensor is shown to follow a cosine (θ) relationship where θ is the angle between a line perpendicular to the obstruction and the actual flow angle. This includes negative shear stresses obtained by reverse mounting the sensor. Unfortunately, details on the flow calibration are not provided other than to state the calibration was conducted in a known flow in a reference wind tunnel.[8-11]

An important consideration in the use and design of any device based on an obstruction to the flow is for it not to alter the flow field. These type devices have similar issues with the validity of a calibration extending to the actual use of the sensor. If the obstruction is small enough that it is completely contained within the laminar sublayer for *all* flows of interest in a particular test then it may be possible to calibrate in a flow field with a linear velocity profile. It may even be possible to develop a correction factor for a calibration done in a parabolic flow distribution and then used in a liner flow distribution but the height of the obstruction would have to be less than half the height of the flow channel as an upper limit. A more realistic upper limit on the height of the obstruction would require a detailed flow field solution including the effects of the blockage caused by the obstruction.

D. Optical MEMS Shear Stress Sensors

An optical MEMS (MOEMS) shear stress sensor has been developed based upon the principle of Laser Doppler Anemometry (LDA) and determines the shear stress by measuring the flow velocity gradient near the wall. This method requires a linear velocity profile at the region of interest so can not be applied to the flow in a flow channel. This sensor design measures the flow field in 30µm region centered 66µm above the surface. Since this entire region must be contained within the laminar sublayer for turbulent flow conditions, the Reynolds number must be less than 10^6. Most of the testing with this sensor has been in water tunnels but recently reported results for testing in a wind tunnel over a flat plate show that the technique can be applied to flows other than water. Also, based on previous results a new sensor was designed that measured the velocity profile in regions centered at 65µm and 110µm above the surface. Plots of shear stress versus Reynolds number indicate the data follows the theoretical trend but the error bars indicate a relatively high degree of uncertainty at Reynolds numbers over approximately $3\cdot10^6$.[12-14]

E. Non-floating Element Direct Shear Stress Sensor with Optical Measurement

A new device concept was recently reported in the literature that is gapless and uses an interferometer based detection method to sense a movement that will correspond to a shear stress. A reflective post is suspended from a membrane. The membrane measures 1.5 mm × 1.5 mm with a thickness of 20µm and is made of silicon rubber. The reflective post has a 200µm square cross section and is 400µm tall with one surface coated with by a thin metal reflection film. Displacement tests and temperature sensitivity tests were performed on the device. This device has been tested in a water based channel that was 10 mm wide, 0.5 mm deep, and 150 mm long. The shear stress on the wall of the channel was determined to be,

$$\tau_w = \frac{6\mu Q}{wh^2} \tag{11}$$

where µ is the viscosity of the fluid, w is the width of the channel, h is the height of the channel, and Q is the flow rate. The minimum detectable shear stress with this sensor is estimated as 0.065 Pa. The sensitivity is reported as 0.65 Pa/nm (shear stress/spectrum shift) with a total possible displacement of at least 10nm.[15]

III. Alternate Shear Stress Generation Methods

A. Precision Flow Channel

A major source of uncertainty in a standard flow channel is the height of the channel. As stated earlier the analysis of the flow channel assumes a constant cross sectional area. Variations in the height, especially near the sensor installation, can cause errors. For the small channel heights used for MEMS shear stress sensors it is very difficult to get high accuracy height measurements at any single location, let alone for the entire channel. Very seldom are height measurements made at multiple locations along the channel. As mentioned previously attempts have been made to improve the measurement accuracy of determining channel height and have resulted in an uncertainty of 1.5% in the channel height measurement. It may be possible, though expensive, to fabricate a precision flow channel where the height is constant within 0.2μm (worst case estimate prior to fabrication) for the entire channel which would reduce the uncertainty in the height measurement and minimize possible variations in the height as well. Discussions with personnel at the Lawrence Livermore National Laboratory indicate a channel with this specification could be built with a total flow channel size up to one meter in length with constant channel height, this channel would not use a shim to set the height as is often done. Initial discussions were focused on a channel height of 200μm. While this level of precision is not needed for every flow channel in use, the fabrication of at least one of these high precision flow channels may be advisable if a flow channel is to be included as part of a shear stress calibration standard. Due to the well defined height and cross sectional area that this implementation provides the uncertainty for the total measurement can be reduced. Applying the procedure from Ref. 16 to Eq. (2) to determine the total uncertainty in the shear stress generated in a flow channel without a sensor installed yields,

$$\left(\frac{\Delta\tau_w}{\tau_w}\right)^2 = \left[\frac{\Delta(\partial p/\partial x)}{(\partial p/\partial x)}\right]^2 + \left(\frac{\Delta b}{b}\right)^2 + \left[\frac{2\gamma M\Delta M}{(1-\gamma M^2)}\right]^2 \tag{12}$$

Solving for this uncertainty using the new value for $(\Delta b/b) = (0.2/200) = .001$ (0.1%) and the rest of the values from the previous cited example $((\Delta(\partial p/\partial x)/(\partial p/\partial x))=0.002$ (0.2%), $\gamma=1.4$, $M=0.4$, and $\Delta M=0.01$) we determine the worst case uncertainty for generated shear stress to be 0.015 (1.5%). With this implementation the dominate term in the uncertainty becomes the uncertainty due to the determination of the Mach number at the sensor location. By applying the improvements discussed earlier to all aspects of the Mach number determination it is expected the uncertainty can be reduced thereby improving the total uncertainty. The maximum shear stress obtainable for a flow channel will still be limited by the choked flow condition at the exit. This choked flow condition occurs at $M=(1/(\gamma)^{½})$ which results in $M=0.845$ in air and $M=0.774$ in neon.[17]

B. Rotary Flow Channel

The rotary flow channel consists of a rotating wheel with a sensor mounted tangential to the rim in a trough. The trough is an arc segment at a constant distance from the rim of the wheel with sidewalls to contain the flow and simplify the analysis. The shear stress generated by this device can be determined with only measurements of the gap, the rotation of the wheel, and the temperature (for accurate viscosity values):

$$\tau_w = \frac{\mu r\omega}{h} \tag{13}$$

where μ is the absolute viscosity of the gas, r is the radius of the wheel, ω is the angular velocity of the wheel, and h is the height of the gap between the wheel rim and the trough. A stability analysis and corrections for the sensor installation, the width of the wheel, and the curvature of the wheel can be found in Ref. 18. Two of the advantages of this device are the ability to generate high values of shear stress and the possibility of generating dynamic shear stress about a wide range of mean values.

IV. Creating a National Standard

There are many issues relating to any standard for shear stress calibration. One part of the shear stress calibration standard could define a methodology for testing of a sensor for susceptibility to each of the identified issues. The identification of the issues and methods to test for the impact of various assumptions is critical. If there can be no consensus on which issues to consider, then how can a consensus be reached that a particular sensor or calibration is "good"? The ability to discuss particular response characteristics of a shear stress sensor would be greatly facilitated if the need to continuously derive calibration equations from some basic principle and repeat every aspect of a detailed uncertainty analysis could be eliminated.

The issues that must be considered for potential impact on a shear stress sensor calibration include the impact of laminar, transitional, and turbulent flow; presence or absence of pressure gradients, both favorable and unfavorable; and sensitivity to the shape of the velocity profile resulting in a particular shear stress. For designs with gaps or other potentially flow altering characteristics an analysis or testing method must be identified for any calibrator. Any standard should also require identification of all the parameters pertinent to the calibration (e.g., excitation voltages or wavelengths), minimum detectable shear stress, the maximum detectable shear stress, temperature sensitivity (if any), and the shear stress resolution obtained.

A detailed uncertainty analysis must be performed for any device intended for a shear stress calibration standard and the standard must clearly identify the methodologies used in this analysis. The ability to quickly and concisely identify the uncertainty for a particular set of measurements would greatly facilitate the comparison of different shear stress sensor designs and implementation. This is a key factor with MEMS devices, two groups can start with the same basic concept and end up with drastically different sensitivities, noise floors, and uncertainties even if the devices are tested in the same facility using the same equipment and the test conditions are repeated as closely as possible. This is because MEMS devices are not designed, developed, or fabricated in a standard process. The differences in a design from the thickness of a particular layer, doping levels used, the exact chemical composition of an etching solution, or even the particular piece of equipment or its settings used to generate a particular layer or perform a specific etch in a process can all change the functional characteristics of a device. This complexity makes documentation of processes used and careful preservation of actual masks used during the process or at least the files used to generate the masks critical for any shear stress sensor that a designer hopes to make a truly useful device.

V. Conclusions

This paper presents many of the methods currently used to characterize shear stress sensors. Until a national standard is available a great deal of effort will continue to be spent on characterization with a corresponding need for a thorough uncertainty analysis. The issues relating to indirect shear stress sensors such as those relating to thermal type sensors need to be systematically identified, discussed, and a consensus must be reached on how to address the questions on the basic operation. The technical issues for indirect shear stress sensors are extensive and challenging if the goal with a particular sensor is high accuracy quantitative measurements. Identification of a set of characterization devices for different levels of uncertainty and how they can examine different aspects of the operation of a shear stress sensor would be a useful first step.

One thing that must not be overlooked is if a particular application only requires qualitative comparisons or frequency content of a particular flow field then the concerns raised in this paper are not of such overwhelming importance. A great many difficulties lie ahead during the development of a shear stress standard and they are not all technical. The unique combination of applying the difficult field of MEMS design to the equally complex shear stress measurement challenge can be both a rewarding and frustrating endeavor and will most likely not be solved tomorrow.

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