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Multiphysics model investigating performance of a micromachined floating element shear stress sensor

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ABSTRACT

A MEMS floating element shear stress sensor has been developed for flow testing applications, targeted primarily at ground and flight testing of aerospace vehicles and components. A comprehensive numerical model of this sensor is described in this paper, quantifying the behavior of the mechanical components, fluid interaction, and electrostatics in three, non-coupled, 3-D numerical simulations: 1) A finite element model of the static element. 2) A steady state, incompressible, viscous, laminar, Newtonian computational fluid dynamics (CFD) model, for both flat and textured versions of the floating shuttle. 3) A finite element model of the capacitive sensing combs. The distribution of aerodynamic forces over the floating element was studied to determine which features contributed most to the total applied force and sensitivity. Shear stress forces account for 74% of the sensitivity of the flat sensor, with the remainder coming primarily from pressure gradient effects. For a textured sensing element, while the total sensor sensitivity increases between 17% and 27%, only 34% of the output is due to shear forces, and the response is more nonlinear. Thus, a flat sensor with as little surface topology as possible is preferable to reduce pressure gradient sensitivity and nonlinearity, even though it may exhibit lower overall sensitivity to flow forces. In addition, the sensor is shown to not only deflect in the direction of flow due to shear forces, but also to lift away from the substrate and pitch its downstream edge away from the surface. Pitch rotation contributes as much as 37% of the output of the sensor for a textured element, but less than 1% for the flat element. For a perfectly symmetric device, differential measurement completely eliminates the contribution from lift. Overall, the model gives a more complete picture of the sensing mechanisms present in a floating element shear stress sensor, and demonstrates the aerodynamic complexities which motivate careful design and calibration of these types of sensors.

1. Introduction

Wall shear stress and skin friction measurements are important in a variety of experimental fluid mechanics scenarios. These include such diverse applications as laboratory and field testing of space (during atmospheric flight), air, ground, and ocean-going vehicles, flow control and industrial flow applications in high shear stress environments such as injection molding or pipe flow, and in the flow of biofluids for circulatory system modeling or tissue engineering. The operating environments for wall shear stress sensing are many, and the levels of shear span multiple orders of magnitude. Steady and unsteady forces are of interest, as are feedback applications for active flow control. In turbulent flow environments such as boundary layers on aircraft, the scales over which the shear stress changes may be small (sub millimeter scale) and fast (millisecond scale or faster) [1–5].

A number of established techniques for the measurement of wall shear stress exist, including oil film interferometry [6], boundary layer profile surveys, and thermal methods [1,7–9]. Other authors have described optical force measurement methods using whispering gallery mode resonators [10,11]. A recent paper introduces a method of using flow in an ionic fluid in communication with surface forces to measure stress [12]. These methods have various strengths and weaknesses. Sometimes, the measurements can be difficult to apply, or are indirect, relying on heat transfer analogies, or may not provide real time data [4,5,13–15]. MEMS floating element sensors are another option for sensing shear at the wall. These include capacitive [16–25] and piezoelectric [26] devices. MEMS floating element sensors can provide real-time, high bandwidth measurements, and have the potential for low topology,

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array sensing in multiple directions, and ease of use due to their direct electrical readout.

However, as with many of the other techniques, there are challenges associated with accurate calibration and application of MEMS floating elements. A primary concern is whether the floating element is truly measuring shear stress at the wall, or whether it might also be measuring stream-wise pressure gradients, acoustic pressures, or other features of the flow [25]. In order to understand these effects, MEMS floating element sensors have been typically modeled as a linear spring attached to a flat plate. The plate is assumed to experience uniform wall shear stress over its top surface, and the output Y is presumed to be proportional to the static lateral deflection of the element δ as follows

$$Y = \Phi\delta = \Phi\frac{A}{k}\tau_w \tag{1}$$

where Φ is the sensitivity coefficient, which depends on the transduction scheme (e.g. capacitive, piezoresistive, optical), k is the mechanical stiffness, τ_w is the wall shear stress (usually this is assumed to be the wall shear stress present in the system before the element was introduced), and A is the physical surface area of the top of the sensor.

In this work, it is found that while linear spring mechanical models and linear transduction models are generally sufficient to describe the physics, restricting the model to one dimension is not sufficient. It appears that the interaction of the flow with the floating element is much more complex than is suggested by Eq.(1) because the element also experiences vertical motion and a pitching rotation. Therefore, we developed a more complete numerical model of a floating element shear stress sensor. The model includes three dimensional mechanical and electrostatic models, but focuses primarily on the complexities of the fluid flow around the three dimensional sensor topology. The major contributing aerodynamic forces are examined in an attempt to identify the source of the pressure gradient sensitivity observed in earlier experimental characterization [25]. To this end, two different sensor geometries are examined: one with a flat upper surface and a second with a textured surface composed of raised posts. It is shown that the addition of topology to the surface substantially increases pressure gradient sensitivity.

These results point to a need to design MEMS floating element sensors with few gaps and little surface topology in order to enhance the shear sensitivity while reducing pressure gradient sensitivity. In addition, it is shown that other aerodynamic forces, beyond simply surface shear on the top face and pressure gradient, produce measurable output. There is a net lift force and pitching moment, non-uniform shear over the top surface, pressures acting on lateral surfaces, and recirculating flow below the element. The results provide guidance to researchers both in the design of MEMS floating element sensors and also in the method of calibration.

2. Sensor design

The particular shear sensor that is modeled in this work has been described previously [25,27–29]. The main feature of the structure is a floating element, shown in Fig. 1, suspended above a small air gap by flexure beams. When traction is applied to the floating element, the element translates or rotates with, potentially, six degrees of freedom (presuming no internal deformation occurs). As the element moves it bends the flexures and changes the gap distance between the fingers in the electrostatic combs. Two sets of combs are provided so that a differential capacitance measurement can be performed. Ideally, the differential capacitance change would be linearly related to surface shear, and insensitive to other forces. To bring the element back to center when there is no applied load, the eight flexures provide a restoring force and moment. Raised posts 12 μm in height were added to the surface of the floating element to increase the drag on the upper surface. These features increase the total aerodynamic force on the element and thereby increase the sensor translation and output. An SEM image of the sensor, and the as-built geometric parameters measured from the SEM images, are given in Fig. 2 and Table 1.

Table 1
Structure geometry as manufactured, measured from SEM images.

Geometric Parameter and Symbol	Value
Finger gap, d	2.88 μm
Finger width	5.13 μm
Finger overlap, X	20 μm
Number of comb fingers, N	64
Thickness of structure, t	8.8 μm
Width of folded beam, w	5.13 μm
Length of folded beam, L	99.2 μm
Height of bump	11.7 μm
Diameter of bump	24.7 μm
Height of air gap below shuttle	5.2 μm
Shuttle top area, A_m	0.085 mm^2

The model developed here is broken into three parts: (1) Determination of forces applied by the flowing fluid, (2) the deflection of the sensing element as a result of those fluid forces, and (3) the result of that deflection on the comb capacitance. Due to the very small motions of the element compared to the size of the gaps, the three models can be treated as uncoupled. This will be verified when model results are examined below. The overall model structure is diagrammed in Fig. 3.

A steady, laminar, incompressible, 3D computational fluid dynamics (CFD) simulation was used to describe the fluid flow around the sensor geometry and determine the aerodynamic forces. 3D linear elastic finite element analysis (FEA) was used to determine structural stiffness. Finally, a 3D electrostatic finite element model was used to extract the change in capacitance due to structural motion. The combination of the results of these three models can be expressed as a linear (small deflection) model analytically as

$$\Delta C = \Phi_y \underbrace{\frac{1}{k_y}\underbrace{\left(A\tau_w + V\frac{\partial P}{\partial y}\right)}_{F_D}}_{\delta_y} + \Phi_z \underbrace{\frac{F_L}{k_z}}_{\delta_z} + \Phi_\theta \underbrace{\frac{M_\theta}{k_\theta}}_{\delta_\theta} \tag{2}$$

where the differential capacitance change ΔC is produced by flow-direction motion δ_y, out-of-plane motion δ_z, and pitch angle $\delta\theta$ with respective sensitivities Φ_y, Φ_z, and $\Phi\theta$. The element motion is driven in the flow-direction by the total drag force F_D, which is decomposed into a wall shear component $A\tau_w$ and a pressure gradient component $V\frac{\partial P}{\partial y}$. A is the effective top surface area of the element, which in previous work was shown experimentally to be similar to the physical top surface area [25]. V is the effective volume of the element. If the flow field were maximally simplified, so that pressure varies along the sensor only in the y-direction, the integration of pressure force over the surfaces of a rectangular prism of dimensions $L_x \times L_y \times L_z$ results in a pressure difference $\frac{\partial P}{\partial y}L_y$ multiplied by the end area $L_x \times L_z$ for a net force of $\frac{\partial P}{\partial y}L_xL_yL_z$, that is, $V\frac{\partial P}{\partial y}$. However, as demonstrated experimentally in [25] and explored computationally in this work, the effective volume may be considerably greater than the physical volume, due to the more complex flow fields present in the actual geometry.

The motion is also affected by the net lift force F_L, and the net pitching moment $M\theta$. k_y, k_z and $k\theta$ are the mechanical element stiffnesses to flow-direction motion, lift motion and pitch rotation,