Sensors and Actuators A 205 (2014) 133–142

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# A microfabricated shear sensor array on a chip with pressure gradient calibration

Zhengxin Zhao[a], Minchul Shin[a], Judith M. Gallman[b], Robert D. White[a,*]

[a] Mechanical Engineering, Tufts University, 200 College Avenue, Medford, MA 02155, USA
[b] Spirit Aerosystems, 3801 S. Oliver Street, Wichita, KS 67210, USA

ARTICLE INFO

*Article history:*
Received 16 April 2013
Received in revised form 15 October 2013
Accepted 2 November 2013
Available online 20 November 2013

*Keywords:*
Micromachined
Shear
Sensor
Floating element
Array
Pressure gradient

ABSTRACT

A micromachined floating element array sensor was designed, fabricated, and characterized. The sensor chip is 1 $\mathrm{cm}^2$ and includes 16 separate sensor groups in a 4 by 4 array with a pitch of approximately 2 mm. The device was fabricated using four layers of surface micromachining including copper and nickel electroplating. A capacitance to digital converter IC was used to measure the differential capacitance change resulting from flow forces. The achieved resolution is limited by white noise with a level of 0.24 $\mathrm{Pa}/\sqrt{\mathrm{Hz}}$, and linearity is demonstrated to >13 Pa. Experimental characterization in three different duct height laminar flow cells allowed independent determination of the sensitivity to shear stress and pressure gradient. The sensor chip with half the elements acting in parallel has a sensitivity of 77.0 aF/Pa to shear and −15.8 aF/(Pa/mm) to pressure gradient. Pressure gradient sensitivity is found to be an important contributor to overall output, and must be accounted for when calibrating floating element shear stress sensors if accurate measurements are to be achieved. This work is the first demonstration of a shear sensor array on a chip with independent pressure gradient sensitivity calibration.

## 1. Introduction

The measurement of wall shear stress is important in many flow testing and device applications. Examples include drag measurements on air, space, land, and oceangoing vehicles both in test environments such as wind tunnels and in operation, as well as applications in active flow control. The measurement of surface shear stress is also important in industrial flow applications for fluid handling and manufacturing operations such as extrusion, and for biomedical devices in such applications as tissue engineering, where tissue development may depend on local shear stress. Flow regimes of interest may be as diverse as subsonic and supersonic turbulent boundary layers, turbulent pipe flows, and laminar flow in microchannels. Both steady and unsteady shear forces are of interest, and for some applications, particularly in turbulent boundary layer flows for aeroacoustic and structural acoustic applications, it may be important to capture the fluctuating shear stresses as well as the mean. Ideally, in order to capture the fine structure of turbulence, this would be done with a high spatial resolution on the order of 100 μm or smaller, and with high temporal resolution on the order of 1 ms or less [1–3].

A number of techniques exist for measuring surface shear stress. These include oil film interferometry [4], heated patch or heated wire measurements [5–7], hair-like sensors [8–10], surface fence measurements [11,12], and floating element techniques (see below). These techniques have been reviewed in a number of excellent papers and have various advantages and disadvantages [1,2,13–15].

Microelectromechanical system (MEMS) floating element sensors are one approach to the measurement of wall shear stress. In this measurement technology, a micromachined plate or shuttle is suspended using micromachined beam tethers. Under the influence of hydrodynamic forces, this "floating element" experiences a lateral deflection. The motion may be detected using capacitance change, piezoresistance, or optical methods. MEMS floating elements have the advantages of ease of use, high spatial and temporal resolution, and are a "direct" measurement technology insofar as they respond to momentum transfer at the wall. However, MEMS floating element sensors suffer from some drawbacks, including sensitivity to pressure gradients, potential for misalignment, and a possible lack of robustness to water or particle impingement [1–3].

A number of authors have described these devices in the past. The earliest work on MEMS floating elements is that of Schmidt et al. in 1988 [16]. Between 1995 and 1997, major contributions were made by Padmanabhan et al. with the introduction of optical detection methods [17–19]. Using optical detection, a resolution of 1 mPa was reported, although most testing occurred at levels

---

[*] Corresponding author. Tel.: +1 617 627 2210.
*E-mail address:* r.white@tufts.edu (R.D. White).

0924-4247/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2013.11.002

below 1 Pa. A single point was recorded by the research group demonstrating linearity to 10 Pa.

Pan et al., Hyman et al., and Patel et al. used capacitive sensing for three different related designs that included on-chip electronics and force rebalancing [20–22]. Linear response was demonstrated out to 4 Pa for the first two designs. The third design is the largest maximum demonstrated linear response in the literature, maintaining linear response out to approximately 25–30 Pa of effective shear stress.

In more recent work, Zhe et al. used differential capacitive measurements in a cantilever structure, and focused on high resolution at low stress levels [23], achieving 0.04 Pa resolution at stresses up to 0.2 Pa. Chandreskaran et al. also used differential capacitive measurement focusing on unsteady shear stress measurement [24,25], and were able to demonstrate $15\,\mu\text{Pa/Hz}^{1/2}$ resolution at 1 kHz with linear response up to 2 Pa. Notable work by Barlian et al. [26] and Shajii et al. [27] describe piezoresistive floating elements for measurement in liquids.

Significantly, the majority of MEMS sensors so far described in the literature for measurement in air have either not been calibrated, or not shown linear response, at shear stress levels above 4 Pa, yet average shear stresses on the order of 50 Pa or higher may be routinely encountered in typical air vehicle flow applications. For instance, at a free stream velocity of approximately 250 m/s (Mach 0.8), typical of commercial air liners, in air with sound speed 300 m/s, at a density of 0.4 kg/m$^3$ and a viscosity of $1.5 \times 10^{-5}$ Pa s (approximate properties at a cruise altitude of 10 km), the Reynolds number is $7 \times 10^6$ based on a 1 m length scale (for example, 1 m down a flat plate). At these conditions, the 1/7th power law skin friction coefficient correlation [28] may be used to approximate the skin friction,

$$C_f = \frac{0.027}{Re_x^{1/7}} = \frac{\tau_w}{0.5\rho U^2} \tag{1}$$

where $C_f$ is the skin friction coefficient, $Re_x$ is the Reynold's number based on distance down a flat plate, $\tau_w$ is the wall shear stress, $\rho$ is the density of air and $U$ is the free stream velocity. This results in a $C_f$ of 0.003 at 1 m from the leading edge, equivalent to a wall shear stress of 40 Pa for the above conditions. A location 1 m from the leading edge is selected as an example location; shear will vary over the body. It is emphasized that this is an estimate only; Eq. (1) is an incompressible friction factor for a turbulent boundary layer on a flat plate with zero pressure gradient. Compressibility effects at high subsonic Mach numbers will reduce the friction factor by approximately 10% [28], assuming there is not a great deal of heat transfer from the wall to the flow. These results are consistent with recent oil film measurements on a 2.7% scale model of a commercial airliner, the common research model, conducted in the NASA Ames 11 foot transonic tunnel under similar Mach and Reynold's number conditions to those experience in commercial flight. Measured values of $C_f$ on the majority of the wing, tail, and body varied from approximately 0.002 to 0.004 [29].

In this paper we describe a floating element sensor array on a chip that has been calibrated to high shear levels, and also characterized in an effort to directly determine the sensitivity to streamwise pressure gradients. The sensor uses a differential capacitive sensing modality, and is configured mechanically in a folded beam floating element structure. The structure differs from previous devices in a number of ways. First, micromachined bumps are included on the sensor surface in an effort to increase sensitivity. Secondly, the chip includes 16 separately addressable sensors, which increases system robustness and opens the possibility of measurement of the spatial variation of shear with approximately 2 mm spatial resolution. Third, the sensor is fabricated in a low cost and easily implemented nickel on glass fabrication process that does not require deep etching or bonding steps. Finally, a direct capacitance to digital readout chip, the AD7747 [Analog Devices, Wilmington, MA], is used for high resolution differential measurement of capacitance that can be transmitted digitally over long distances with no concerns regarding shielding.

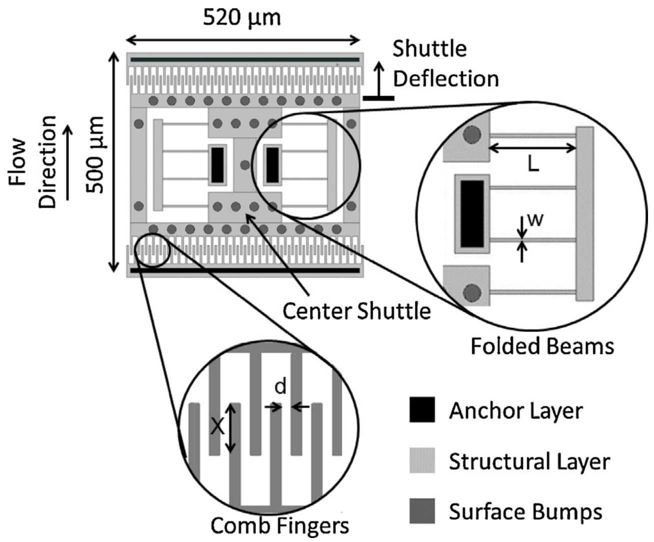

**Fig. 1.** Diagram of the mechanical structure of the floating element sensor.

In an effort to extend the operational range toward high shear stresses, the sensor has been calibrated and shows linear response up to 13 Pa in laminar flow. Patel et al. and Padmanabhan et al. are the only works of which we are aware that shows linear results above 4 Pa. Patel demonstrates linear calibration results up to 25 Pa, but these calibrations are done in transitional and turbulent flows, and make assumptions about the effects of pressure gradient based on a simple mechanical model without experimental verification [22]. Padmanabhan performs the majority of his calibrations below 1 Pa, including a single point at 10 Pa, but with no description of the calibration method used for the high stress result [18].

In order to address important concern regarding the sensitivity of floating element sensors to pressure gradients, the sensor described in this paper has been tested in three laminar duct flow configurations, allowing separate experimental determination of the sensitivity to pressure gradient and shear stress. The pressure gradient sensitivity in these flow fields was found to be substantial, contributing approximately as much force on the structure as the surface shear. This appears to be a very important effect that should be considered whenever calibration of a MEMS floating element sensor is attempted. As far as we are aware, this paper gives the first result experimentally distinguishing these two sensitivities for a MEMS floating element sensor.

## 2. Design

### 2.1. Electromechanical modeling

The design of an individual floating element sensor in the array, shown in Fig. 1, has many similarities to the sensor described in [21]. Each element has a movable center shuttle which experiences forces from interaction with the flow, two sets of comb fingers for differential capacitive sensing of the motion of the shuttle, and a series of folded beams to act as an elastic support. The four inner beams and the outer fingers are fixed on the substrate through the anchors. A folded beam structure is employed to reduce the effects of residual stresses introduced during manufacturing. The dimensions of the element are given in Table 1.