EXPERIMENTAL VERIFICATION OF A CAPACITIVE SHEAR STRESS SENSOR FOR LOW-SPEED WIND TUNNEL APPLICATIONS

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ABSTRACT

This paper describes the development of a shear stress sensor system for use in wind tunnels and the comparative performance of the system in two different tunnel facilities. The MEMS sensor uses differential capacitive transduction of a tethered floating-element plate. The sensor is microfabricated using a silicon-on-Pyrex fabrication process. An analog synchronous modulation-demodulation circuit is implemented in order to make time-resolved measurements of the mean and dynamic change of the sensor capacitance. The sensor system is packaged in a robust, small form factor enabling convenient installation into multiple test facilities. The final system has a sensitivity of 10.8 mV/Pa and a minimum detectable signal of 6.5 mPa at an 8 V_{ac}, 100 kHz sinusoidal excitation.

INTRODUCTION

The ability to make time-resolved, continuous, direct mean and fluctuating measurements of skin friction or wall shear stress is currently not available. Wall shear stress characterization has an impact on both the research and commercial communities. Skin friction drag accounts for approximately 50% of the total drag on an aircraft at cruising speeds [1]. Additionally, wall shear stress is important for the characterization of turbulent flow and is important for the development of turbulence models.

In response to this technology gap, many shear stress measurement techniques have been developed, as outlined in several reviews [2], [3]. Floating-element sensors are the most promising to achieve direct, time-resolved shear stress measurements. Concerns of fabrication complexity, spatial averaging, bandwidth, and cross-sensitivities indicate microelectromechanical systems (MEMS) as an enabling technology for the fabrication of floating-element shear stress sensors. Of the many MEMS floating-element shear stress sensors that have been presented, the most promising for continued development into a robust sensor system is a differential capacitive comb-drive sensor presented by Chandrasekharan et al. [4].

The sensor structure is a floating element suspended over a cavity by tethers. The floating element displaces when a shear stress is applied and the tethers act as restoring springs. On either side of the floating element are interdigitated comb fingers. A schematic of this structure and the equivalent electrical circuit of the structure are shown in Figure 1. The comb fingers form a differential capacitive half bridge and are nominally matched to each other. The modeling of the static and dynamic response of this structure is available in [4]. The dimensions of the device design chosen for this study are shown in Table 1.

W_e	L_e	W_t	L_t	g_{01}	g_{02}	L_o	W_f	T_t
1000	1000	15	1000	3.5	20	170	20	45

Table 1: The dimensions of the floating element structure shown in Figure 1. All in units of [μm]

For a given flow direction, as indicated in Figure 1, capacitance C_1 , which is formed between electrodes E_1 and E_2 , decreases as the floating element moves. The capacitance C_2 , formed between electrodes E_2 and E_3 , increases as the floating element moves. These capacitances as a function of shear stress are represented as

$$C_1(\tau) = C_0 - \Delta C(\tau) \quad (1)$$

and

$$C_2(\tau) = C_0 + \Delta C(\tau). \quad (2)$$

Figure 1: A schematic of the floating element structure with an enlargement of the interdigitated comb fingers, a cross section of the sensor along line XX', and an electrical representation of the sensor structure.

FABRICATION

The sensor is fabricated using a two-mask process, shown in Figure 2. The process begins with a 100 mm Corning 7740 Pyrex wafer. Chrome is deposited and patterned using the first photomask to create a hard mask for a hydrofluoric acid etch, which creates the cavity beneath the floating-element structure. The chrome is removed, and a silicon-on-insulator wafer is anodically bonded above the cavity. The bulk silicon is removed in a 20% KOH bath, followed by the removal of the buried oxide layer in buffered oxide etchant. The remaining device layer is patterned with the second photomask, and the floating element structure is defined using a deep reactive ion etch process. The resulting sensors are diced to a final size of 3.5 mm x 3.5 mm using a heat release tape from Nitto Denko America, Inc. to protect the floating elements during dicing. Exploiting the reciprocal nature of capacitive transduction, the sensor dice are electrically tested via electrostatic actuation to confirm mechanical release. Fully released die are then packaged.

Figure 2: A schematic view of the process flow to create the capacitive floating element sensor structure.

PACKAGING

In order to be useful as a tool for fluid dynamics measurement the final form factor of the sensor package must be hydraulically smooth [2], robust, and small. In order to achieve this, the package is made of two components: an end cap into which the sensor die is flush mounted and attached to electrical leads, and a cylindrical housing that provides mechanical support for mounting the sensor die into a wind tunnel and contains any interface electronics co-located with the sensor die. The assembly of these two components is shown in Figure 3.

Figure 3: The assembled package showing the end cap, aluminum tube, and flush mounted sensor die (left), and a photo of the 1/2-inch outer diameter assembled device (right).

The end cap is an FR4 circuit board with a die-shaped recess to enable a hydraulically smooth surface. Adjacent to the sensor die are three immersion gold bond pads that fan out to vias, which permit electrical connections to the bias voltages and interface circuitry on the backside of the circuit board. Gold wire bonds are used to connect the sensor die to the circuit board bond pads.

The sensor housing is a 1/2-inch diameter, 3/4-inch long aluminum tube. The aluminum tube serves two purposes: it acts as a mechanical support onto which mounting fixtures can be attached without inducing stress onto the sensor structure directly and it acts as a Faraday cage to protect the interface electronics located within the tube from electromagnetic interference. The small diameter allows for several sensors to be integrated into a single test in an array. The short length allows for integration into small wind tunnel models.

INTERFACE CIRCUITRY

As shown in Figure 3, there is room in the mechanical support structure to house a small printed circuit board with interface electronics. The complexity of that interface is due to the high impedance of the capacitive transducer and the requirement to make a measurement of a mean capacitance change. The interface circuit is broken into two components; the immediate interface with the sensor die, in the form of a voltage buffer, and the signal conditioning circuitry, which is the frequency translating synchronous modulation/demodulation (synch MOD/DMOD) component.

Voltage Buffer

The immediate interface to the transducer should preserve the output signal of the transducer, contribute minimal noise to the system, and buffer from a high impedance to a low impedance to prevent contamination from electromagnetic interference. A voltage buffer, shown in Figure 4, is implemented. The overall transfer function of the buffer is

$$V_{out} = \frac{j\omega R_b}{j\omega R_b(2C_0 + C_p) + 1} 2V_b \Delta C(\tau), \quad (3)$$

where R_b is the bias resistance, shown in Figure 4, ΔC and C_0 are shown in Equation 1, and C_p is the parasitic capacitance of the packaging and the input capacitance of the operation amplifier chosen to implement the buffer. Equation 3 shows that an overall high pass filter function is implemented with the corner frequency set by the bias resistance and the dominant sensor capacitance. The voltage buffer is implemented with the AD8022 from Analog Devices and a single bias resistor, which was chosen due to a low voltage noise floor and low input capacitance. The output is also only defined when there is an excitation frequency; at dc there is no steady-state output voltage.

Figure 4: A schematic of the complete voltage buffer circuit, including bias resistor and sensor die.

In order to have a steady-state response to a mean change in capacitance, a sinusoidal bias is applied, making the output of the buffer an amplitude-modulated signal. As the signal is now driven by a low-impedance source, further interface circuitry may be located away from the sensor without raising additional concerns about electromagnetic interference. The voltage buffer, in a single integrated circuit implementation, is co-located with the sensor die in the aluminum housing of the sensor package. The additional interface circuitry can be located near the data acquisition system without consequence.

Synchronous Modulation/Demodulation

While it is possible to simply acquire the amplitude-modulated signal and demodulate it in post-processing to obtain flow information, an analog demodulation scheme is implemented to relax requirements on the data acquisition system and extend the use of the system into areas like flow control, which require baseband flow information for feedback. The system is an active envelope detector [5] and is made of five major components: a bias generation, a bandpass filter, an active rectifier, a lowpass filter, and digital control circuitry that control the active rectifier block.

Mathematically, active rectification can be described as the low-pass filtering of the multiplication of an amplitude-modulated signal with a square wave possessing unity amplitude and frequency ω_b . Using a Taylor series expansion of a square wave, the multiplication product, $v_{\text{rectified}}$, is

$$v_{\text{rectified}} = \frac{1}{2} \frac{2\Delta C(\tau)}{2C_o + C_p} V_b + \frac{2\Delta C(\tau)}{2C_o + C_p} V_b \sin(\omega_b t) + \frac{2\Delta C(\tau)}{2C_o + C_p} V_b \cos(2\omega_b t) + \dots \quad (4)$$

Applying a low-pass filter to Equation 4 recovers the demodulated flow information. Any phase errors in the synchronization would be represented by a phase contribution to the square-wave terms and result in more harmonic generation but would not change the final magnitude of the recovered baseband signal or the requirements on the final low-pass filter.

The system is implemented using discrete components. The bias generation block generates two out-of-phase sinusoids at 100 kHz and variable amplitude to serve as bias signals for the sensor. One of the bias signals is fed into the digital control circuit in order to provide phase information to synchronize the demodulation. The output of the sensor package is fed into a band-pass filter. This filter removes any spurious frequencies that have been introduced into the signal path, through electromagnetic interference, harmonic distortion, or any other source. The remaining amplitude-modulated signal is used to derive two signal paths, one inverted and one non-inverted, which are fed into the active rectifier. The control signal for this switch is derived from one of the bias signals and remains in-phase with that bias signal, meaning the rectification is in-phase with a bias signal. The output of the analog switch is the rectified signal given by Equation 5. This signal is fed into an LTC1653 low-pass filter with a corner frequency of 20 kHz. The output of this low-pass filter stage is the baseband flow information over the entire bandwidth of the sensor.

SENSOR CALIBRATION

With the assembled sensor system and package, characterization is performed in a known shear stress field to verify sensor performance. The sensor is calibrated in an acoustic plane wave tube using a Stokes' layer excitation to generate a known oscillating shear stress [6]. The experimental set up for this is shown in Figure 5.

Figure 5: Shear stress calibration experimental setup

Increasing the sound pressure level of the incident acoustic wave, the dynamic sensitivity is determined. The ac normalized sensitivity, shown in Figure 6, is 1.34 mV/V/Pa. At a bias of 8 Vac, the sensitivity of the system is 10.8 mV/Pa, and the minimum detectable signal is 6.5 mPa. A similar technique is used to measure the frequency response function of the sensor, and the sensor resonance is experimentally determined to be 4.6 kHz. With this characterization, the sensor is transitioned into two wind tunnel facilities for validation.

Figure 6: The normalized sensitivity of the shear stress measurement system.

EXPERIMENTAL SETUP

The sensor is installed into two different wind tunnel facilities; one small-scale wind tunnel at the University of Florida (UF) and the 20" x 28" shear flow control facility at NASA Langley Research Center (LaRC). At UF, the sensor is installed into an elliptical leading-edge flat plate airfoil. The flow over the airfoil is untripped and, for a wide range of Reynolds number, remains laminar. A velocity profile is acquired using particle image velocimetry (PIV) and fit to Blasius' solution [7] in order to deduce the mean shear stress acting on the sensor. At LaRC the sensor is again installed into a flat plate, and the flow is tripped, resulting in a zero-pressure-gradient turbulent boundary layer at the sensor location. A traversing hotwire is used to acquire a velocity profile, which is fit to Musker's equation [8] in order to estimate the mean shear stress acting on the surface. Additionally, a hotwire is placed near the wall in the viscous sublayer in order to estimate the dynamic shear stress content of the flow. The result is an estimation of the dynamic shear stress based on the velocity field within the viscous sublayer. This provides a comparison for magnitude and frequency content of the dynamic sensor data.

RESULTS AND CONCLUSIONS

In Figure 7, the results of the velocity-profile-based estimation of mean shear stress are compared to the results of the MEMS floating-element based estimation of shear stress, with a line indicating perfect correlation. The sensor shows good agreement to current velocity-profile-based mean shear stress estimation technologies. There are many possibilities that would explain deviations from this line: additional environmental sensitivities, effects of the wirebonds protruding into the flow, and the feed-through of pressure signals into the sensor output. With further bench top and tunnel characterization these effects can be isolated.

Figure 7: A comparison of the mean shear stress determined by velocity based methods compared to the mean sensor data with a line indicating perfect agreement.

The dynamic shear stress can be estimated by a near wall hotwire. If the hotwire is located within the viscous sublayer of the boundary layer the velocity at a known height can be related to the dynamic shear stress on the surface by

$$\tau_{ac}(t) = \frac{v_{hw}(t)\nu}{h} \quad (5)$$

where v_{hw} is the velocity determined by the hotwire, ν is the kinematic viscosity, and h is the height of the hotwire. Figure 8 shows the autospectra of the dynamic shear stress determined by the sensor and the near wall hotwire at a freestream velocity of 43 m/s and Re_θ of 13,500 at NASA LaRC. The apparent offset between the two datasets is most likely an error in the estimation of the hotwire placement, which resulted in the hotwire being just outside of the viscous sublayer ($< 52\mu\text{m}$ from the wall) at a height of $82\mu\text{m}$ above the wall.

The agreement in both mean and dynamic performance of the sensor compared to traditional boundary layer measurement techniques demonstrates that the capacitive shear stress sensor system developed in this work is capable of being transitioned into multiple facilities and serving as a direct measurement tool for laminar and turbulent boundary layers.

Figure 8: Qualitative comparison of the dynamic shear stress.

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