A MEMS OPTICAL MOIRÉ SHEAR STRESS SENSOR FOR HARSH ENVIRONMENT APPLICATIONS

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ABSTRACT

This paper describes the development of a shear stress sensor for use in harsh environments as well as experimental characterization of the sensor system. The microelectromechanical systems (MEMS) sensor utilizes optical moiré transduction of a floating element structure created using a silicon-on-Pyrex fabrication process. Interrogation of the amplified moiré displacement is achieved via a four-channel fiber optic array. The sensor and array are packaged in a robust housing to enable installation in multiple test facilities. Mean flow characterization of the system demonstrates a sensitivity of 13.4 mrad/Pa, minimum detectable shear stress of 54 mPa at 1 kHz with a 1 Hz bin, and experimentally verified dynamic range of 39.2 dB.

INTRODUCTION

The MEMS community has developed floating element shear stress sensors using several different transduction mechanisms, including capacitive [1,2], piezoresistive [3], and optical techniques [4]. The majority of sensors described in the literature, however, pose significant limitations on the ability to achieve real-time, continuous measurements in harsh environments, such as water tunnels and high-temperature wind tunnels. For these harsh-environment applications, optical sensors provide several advantages over traditional electrical sensing methods including being passive, immune to electromagnetic interference, and nonconductive.

Previous work presented by Horowitz et al. [5] and Chen et al. [6] has attempted to address this technology gap via the development of optical shear stress sensors that utilize a geometric moiré fringe to amplify the mechanical sensor displacement. The sensor presented herein is an extension of these efforts to improve upon sensor performance, packaging simplicity, and robustness. The design, fabrication, and packaging of the sensor are detailed, followed by mean flow characterization and noise floor measurement.

SENSOR DESIGN

Geometric Moiré Fringe Formation

A geometric moiré fringe pattern is an optical phenomenon that occurs when two bar and space gratings are superimposed. Moiré fringe formation for the shear stress sensor is accomplished by aligning two sets of parallel binary gratings with one another. In this method of fringe formation, a translation in the transverse direction of one of the gratings of pitch g_1 relative to a fixed reference grating of pitch g_2 creates an amplified relative motion of the moiré fringe period G in the same direction. From Yokozeki et al. [7], it can be shown that the moiré fringe period for such a pair of gratings under pure translation can be determined using the expression

$$\frac{1}{G} = \frac{1}{g_1} - \frac{\cos \alpha}{g_2}, \quad (1)$$

where α represents angular misalignment. Furthermore, for a small displacement δ of the movable grating, the amplified relative displacement Δ of the moiré fringe can be expressed as [8]

$$\Delta = \delta \frac{G}{g_1}, \quad (2)$$

which is illustrated in Figure 1. For the sensor presented in this work, $g_1 = 9.9 \mu\text{m}$ and $g_2 = 10.0 \mu\text{m}$, resulting in a moiré fringe period $G = 990 \mu\text{m}$. Thus, the fringe displacement Δ will be amplified by a factor of 100 times the grating displacement.

Figure 1: Illustration of the amplified displacement of a moiré fringe and optical fiber locations for quadrature phase shift estimation.

Quadrature Phase Estimation

The optical configuration used for interrogation of the moiré fringe is shown in Figure 2. A single LED source is coupled to four individual 1x2 fiber-optic couplers via a fiber bundle in order to minimize uncertainty due to fluctuations in the source. The four send/receive fibers packaged with the sensor are connected by a multiple-fiber push-on (MPO) connector to the fiber couplers to transmit the reflected light to an array of fiber-pigtailed photodiodes which then convert the incident light to voltage outputs via the use of transimpedance amplifier circuits.

Figure 2: Fiber-optic configuration for interrogation of the moiré shear stress sensor.

Determination of the moiré fringe displacement requires the use of a phase shift estimation technique. Previous efforts have used various methods to determine the amplified displacement Δ of the moiré fringe [5,6]; however, these techniques necessitated the use of bulky and/or custom optical components. The new sensor utilizes a simple quadrature technique that requires only four optical fibers spaced such that they are separated by a distance $G/4$ as shown in Figure 1 [9]. The phase ϕ can thus be calculated using the expression

$$\phi = \frac{2\pi\Delta}{G} = \tan^{-1} \left(\frac{V_{03} - V_{01}}{V_{04} - V_{02}} \right), \quad (3)$$

where V_{on} represents the output voltage of the n^{th} channel.

The result is a simple expression in which the dc offset in the signal is removed, reducing sensitivity to pressure fluctuations that can alter the reflected intensity. The fewer number of fibers enables smaller floating element sizes to increase sensor bandwidth. In addition, larger fiber spacing reduces cross-talk between channels and makes possible the use of v-groove arrays to locate the optical fibers more accurately than the 16-channel array used by Chen et al. [6].

Sensor Structure

The mechanical structure of the shear stress sensor is shown in Figure 3. The silicon (Si) floating element is suspended over a cavity by four tethers that are anchored to a fixed Pyrex substrate. Fluid flow across the surface of the floating element exerts an integrated shear force which causes a lateral displacement, and the tethers act as restoring springs to return the floating element to its central position under zero load. Similar to the design of previous optical moiré shear stress sensors [5,6], optical gratings patterned on both the floating element and the fixed substrate create a moiré fringe which amplifies the floating element displacement as previously discussed; however, the use of only four fibers facilitates leaving out sections of the gratings, creating four discrete moiré fringe segments to minimize cross-talk between channels, thereby improving device sensitivity.

Figure 3: Top and cross-sectional views of the shear stress sensor structure.

Because of the relatively high reflectance ($\geq 30\%$) of silicon over the visible and near-infrared range [10], an anti-reflective (AR) coating is used to improve the fringe contrast and increase the sensitivity of the sensor. The minimum reflectance is achieved when using a quarter-wavelength film thickness and the material's index of refraction n_1 is the geometric mean of the refractive indices of the surrounding medium n_0 and the substrate n_s , i.e., $n_1 = \sqrt{n_0 n_s}$. Using an 850 nm LED as the light source and silicon nitride (Si_3N_4) as the AR coating, the minimum reflectance is $R = 1.65 \times 10^{-3}$, resulting in a nearly 200x improvement in the contrast between the aluminum gratings and the bare Si surface.

The model used to determine the static and dynamic response of the mechanical structure is available in [5]. The physical dimensions, mechanical sensitivity, resonant frequency, and maximum shear stress for the chosen design are listed in Table 1.

Table 1: Sensor geometry and mechanical performance specifications.

W_e (μm)	L_e (μm)	W_t (μm)	L_t (μm)	T (μm)	f_{res} (kHz)	δ/τ (nm/Pa)	τ_{max} (Pa)
1100	1000	22.5	1430	45.0	5.0	9.8	480

FABRICATION

The sensor is fabricated using a six-mask silicon-on-insulator (SOI) micromachining process to create the floating element structure supported by an anodic-bonded Corning 7740 Pyrex base as shown in Figure 4. The process is similar to that used by Horowitz et al. [5], with the addition of the AR coating and a vent etch to prevent rupture of the sensors during the final floating element release step.

Figure 4: Illustration of the silicon-on-Pyrex process used for device fabrication.

The process begins by etching a $5 \mu\text{m}$ recess into a 100 mm diameter SOI wafer with a $50 \mu\text{m}$ device layer using a deep reactive-ion etch (DRIE) process to create a gap between the floating-element structure and the fixed gratings. The Si_3N_4 AR coating is then deposited using plasma-enhanced chemical vapor deposition and patterned using buffered oxide etch (BOE). Liftoff photolithography is used to pattern evaporated aluminum on the SOI wafer and a $300 \mu\text{m}$ thick Pyrex wafer to create the floating and fixed gratings, respectively. Vent holes are then etched partially through the SOI device layer prior to anodic bonding of the wafers.

Figure 5: Back-side microscope image of the completed shear stress sensor highlighting the moiré fringe segments.

After the wafers are bonded, removal of the bulk silicon and buried oxide layers is performed using DRIE and BOE, respectively. The remaining device layer is patterned and etched using a DRIE process to define the floating-element structure. Finally, the devices are diced into 5 mm x 5 mm die using heat release tape to protect the released floating elements during dicing. After removal of the heat release tape the sensor die are ready for packaging. Figure 5 shows a microscope image of the back side of the completed sensor after dicing.

PACKAGING

Sensor Packaging

The desire to make meaningful fluid dynamics measurements in harsh environments necessitates that the sensor package be hydraulically smooth [11], robust, and small. The lack of interface electronics near the sensor enables a simple package comprised of three components: the sensor itself, a four channel fiber-optic v-groove array, and an aluminum housing as shown in Figure 6. The compact form factor of the package allows the sensor to be mounted in a variety of different characterization facilities.

Figure 6: The assembled package showing the aluminum housing, flush-mounted sensor die, and 1x4 optical fiber array with MPO connector.

The 0.375 in diameter housing features a recess to flush mount the sensor as well as a through hole to accommodate the fiber-optic array. The array used for optical interrogation of the four moiré fringe segments was fabricated by Senko Advanced Components and features 250 μm spacing of 62.5 μm core diameter graded-index fibers. The array is aligned with the moiré fringe segments and bonded using a special fixture mounted to a Semiconductor Equipment Corp. Model 850 Flip Chip Placement System.

Transimpedance Circuit

A transimpedance circuit is used to convert the currents I_{sn} generated by the Thorlabs FDSP625 photodiodes to output voltages V_{on} to be sampled by the data acquisition (DAQ) system. A schematic for a single channel of the four-channel array is shown in Figure 7 with a simplified model of the photodiode. The transfer function of the transimpedance circuit is [12]

$$V_{on} = I_{sn} \frac{R_f}{1 + s \left(R_f C_f + \frac{1}{\omega_c} \right) + s^2 \frac{R_f (C_f + C_i)}{\omega_c}} \quad (4)$$

where R_f and C_f are the feedback resistance and capacitance, respectively, C_i is the parallel combination of the junction and parasitic capacitance of the photodiode and the common-mode and differential capacitances of the OPA129 Ultra-Low Bias Current amplifier, R_i is the parallel combination of the photodiode shunt resistance and the common-mode and differential resistances of the amplifier, and ω_c is the unity gain frequency of the amplifier. Equation (4) shows that the dc gain of the amplifier circuit is

determined by the 1.5 M Ω feedback resistance. The value of the feedback resistance is selected to provide sufficient gain while maintaining a large usable bandwidth. A 1.5-5.0 pF variable feedback capacitor is used to tune the circuit to improve stability at high frequencies and maximize the bandwidth.

Figure 7: Schematic of the transimpedance amplifier circuit with a simplified electrical model of a photodiode.

EXPERIMENTAL SETUP AND RESULTS

Mean Flow Characterization

To assess the performance of the packaged sensor, static characterization is performed within a known shear stress field to determine the sensitivity of the device. The sensor is mounted in a laminar flow cell constructed of two aluminum plates separated by a metal shim to form a thin flow channel 330 mm long by 100 mm wide. If steady, incompressible, 2D Poiseuille flow through the channel is assumed, the wall shear stress may be expressed as [13]

$$\tau_w = \frac{h}{2} \frac{dP}{dx}, \quad (5)$$

where h is the channel height and dP/dx is the pressure gradient at the sensor location. The pressure gradient is approximated by the differential pressure between two pressure taps P_1 and P_2 separated by a known distance Δx as shown in Figure 8. The mass flow rate is adjusted by an Aalborg GFC47 mass flow controller (MFC) connected to a Keithley 2401 source meter and the pressure drop is recorded through a serial connection to a Heise ST-2H pressure indicator with a 0-10" H₂O HQS-1 differential module. The four output voltages from the photodiode array are simultaneously sampled at each shear stress level by using two National Instruments (NI) PXI-5122 cards in an NI PXI-1045 chassis connected to a PC via an NI PXI-ExpressCard8360.

Figure 8: Schematic of the laminar flow cell used for static characterization of the shear stress sensor.

To determine the static sensitivity of the sensor, a shim height of 547 μm is used, and the input voltage to the MFC is increased from 1.0-5.0 V in 0.5 V steps, providing nine flow conditions with shear stress values ranging from 1.1 to 4.9 Pa. The four output voltages are sampled at 2 kHz for a block length of 10000 samples. Serial communication with the pressure indicator limits the data acquisition speed, and thus only 31 samples are recorded for the pressure drop at each flow rate. Figure 9 shows the resulting plot including 95% confidence intervals for the mean shear stress and phase. Linear regression analysis yields a static sensitivity of 13.4 mrad/Pa with a normalized residual (R^2) value of 0.998.

Figure 9: Plot of phase versus mean shear stress used to determine the static sensitivity of the sensor.

Noise Floor Measurement

The noise floor of the packaged sensor is determined by using a Stanford Research Systems SR785 spectrum analyzer with the packaged sensor and battery-powered optoelectronics placed inside a Faraday cage for shielding. A user-defined function is implemented to determine the phase noise power spectral density (PSD) shown in Figure 10. At 1 kHz for a 1 Hz bin the noise floor is 0.72 mrad. The minimum detectable shear stress (MDSS) is determined by dividing the voltage noise by the flat band sensitivity, which is equivalent to the static sensitivity assuming the sensor structure is a second-order mechanical system. Using the sensitivity determined during mean shear stress characterization, the MDSS of the sensor is 54 mPa.

Figure 10: Differential noise measurement of the packaged shear stress sensor.

CONCLUSIONS

The design, fabrication, packaging, and static characterization of a moiré optical shear stress sensor were described in this paper. Characterization of a packaged device yielded a static sensitivity of 13.4 mrad/Pa and a noise floor of 0.72 mrad at 1 kHz with a 1 Hz bin, resulting in an MDSS of 54 mPa. Combining the MDSS with the maximum tested shear stress of 4.9 Pa gives an experimentally verified dynamic range of 39.2 dB, with the potential to extend the range to 79.0 dB based on a theoretical maximum shear stress of 480 Pa. These performance characteristics are on par with other sensors in the literature, demonstrating the potential for the sensor developed in this work to provide a direct measurement tool for estimating mean shear stress values in multiple harsh-environment flow facilities.

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