Diffractive optic fluid shear stress sensor

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Abstract: Light scattering off particles flowing through a two-slit interference pattern can be used to measure the shear stress of the fluid. We have designed and fabricated a miniature diffractive optic sensor based on this principle.
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1. Measurement concept

The goal of this sensor is to determine the shear stress of a fluid within the first few hundred microns from a wall. Within this region, the velocity gradient is linear, \( u = \sigma y \), where \( u \) is the velocity, \( \sigma \) is the shear stress, and \( y \) is the vertical coordinate. Our diffractive optical micro-sensor generates a linearly diverging fringe pattern as illustrated in Fig. 1. The fringe spacing can be expressed as \( \Delta = Ky \), where \( K \) is the slope of the first non-vertical fringe.

As particles in the fluid flow through the linearly diverging fringes, they scatter light to a detector with a frequency \( f \) that is proportional to the velocity and inversely proportional to the fringe separation, \( f = u/\Delta \). Using the relations for \( u \) and \( \Delta \) above, the measured frequency is directly proportional to the wall shear,

\[
f = \frac{\sigma y}{K y} = \frac{1}{K} \sigma
\]

This technique was first presented by Naqwi and Reynolds using conventional optics [1]. A non-linearity of the velocity profile or the fringe pattern will translate into widening and skewness of the frequency distribution.

2. Design and modeling

A conceptual drawing of the micro shear stress sensor is shown in Figure 2. The diverging light from a diode laser is focused by a diffractive optical element (DOE) to two parallel line foci. These foci are coincident with two slits
in a metal mask on the opposite side of a quartz substrate. The light diffracts from the slits and interferes to form linearly diverging fringes to a good approximation. The light scattered by particles traveling through the fringe pattern is collected through a window in the metal mask. Another DOE on the backside focuses the light to an optical fiber connected to a detector.

![Figure 2. Schematic of the shear stress sensor assembly.](image)

A series of simulations were performed to aid in the design of the sensor. A finite-difference simulation of the fringe pattern for 2 \( \mu m \) wide slits separated by 10 \( \mu m \) is shown in Figure 3. The fringe pattern displays a suitable number of fringes for adequate measurements. The number of high-contrast fringes is determined by the slit width and the divergence of the fringe pattern is determined by the slit separation.

![Figure 3. Fringe pattern resulting from 2 \( \mu m \) slits separated by 10 \( \mu m \) (propagation of a finite-difference solution of slit diffraction when illumined by the dual-line-focus laser lens).](image)
3. Fabrication and testing

The main sensor element was fabricated by two-sided lithography on a 500 μm thick quartz substrate. The slits and collecting window on the front were fabricated by direct-write electron-beam lithography followed by wet etching of evaporated chrome. The polymethyl methacrylate (PMMA) diffractive optical elements on the back were fabricated by analog direct-write electron-beam lithography followed by acetone development [2]. A photograph and atomic force microscope scan of the dual-line focus-laser lens are shown in Fig. 4.

![Figure 4. Photograph (left) and AFM scan (right) of the center of the dual-line-focus laser lens.](image)

The shear stress sensor’s elements were assembled into a package (Fig. 5) with a diode laser (660 nm) and a port for the collection fiber. The overall size of this prototype is 15 mm in diameter and 20 mm in length. The fringes were imaged with a CCD camera using a microscope objective and are shown in Fig. 5. The fringe divergence was measured to be linear with a slope in close agreement with theory. The contrast is very satisfactory and preliminary tests using a moving surface through the fringe pattern yield a clear signal. Testing of the receiver side of the sensor element is underway.

![Figure 5. Shear stress sensor assembly (left) and photographs of the fringes at different heights above the surface (right).](image)

4. References


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Wall Shear Principle

• Wall shear, \( \sigma = \frac{\partial u}{\partial y} \)

• Velocity is linear near the wall \((u \propto y)\)
  \[ \sigma = \frac{u}{y} \]

• Measured frequency proportional to \( U \) and the inverse of the local fringe separation, \( \delta \)
  \[ f = \frac{u}{\delta} \]

• Use linearly diverging fringes \( \delta = k_1 \times y \)

• Measured frequency, \( f \), is directly proportional to wall shear
  \[ f = \frac{\sigma \cdot y}{k \cdot y} = \frac{1}{k} \sigma \]
Wall Shear Principle

\[ \frac{\partial U}{\partial z} = f_{\text{Doppler}} \cdot \frac{\partial \eta}{\partial z} \]

\[ f_{\text{Doppler}} = \frac{1}{\tau} \]
Shear Stress Sensor Design

- Diffractive optical element (DOE) focuses light from laser diode onto slits (dual-line focus)
- Scattered light from particles is collected with another DOE and focused into optical fiber
Shear Stress Sensor Modeling

Cross-section through dual-line-focus laser lens
Laser Lens Focusing Simulation

Magnitude of Electric Field

x (microns)

z (microns)

0 100 200 300 400 500 600 700

-80 -60 -40 -20 0 20 40 60 80

0 1 2 3 4 5 6

Propagation Through Slits Simulation
(Finite-Difference)

Instantaneous Electric Field

Air
Chrome
Quartz
Input field from lens focusing simulation

Magnitude of Electric Field
Measurement Volume Intensity for 2 μm Slits
(Propagation of Finite-Difference Solution)
Shear Sensor Fabrication

- Open slits, windows, and alignment marks in chrome using electron-beam lithography

- Define Ti/Pt alignment marks using optical lithography

- Fabricate diffractive lenses using analog direct-write electron-beam lithography
Front-Side Lithography on Chrome

1 µm slits
10 µm separation

2 µm slits
10 µm separation
E-Beam Fabrication of Analog Diffractive Optics

Fabrication Method

- Thin film of polymethyl-methacrylate (PMMA - thin film Plexiglas) spun on substrate
- Direct-write analog-dose electron-beam lithography using JEOL JBX-5DII (50 kV)
- Electron beam breaks bonds in the PMMA - increases solubility in acetone
- Acetone etches exposed PMMA to produce surface relief pattern

Advantages

- Well controlled analog depth (< 5% error)
- Arbitrary patterns
- No pattern misalignment
- Prototype elements are easily fabricated
Dual-Line-Focus Laser Lens

Photograph of Center Region

AFM Profile of Surface

Section Analysis

Horiz distance(L) 1.17 μm
Vert distance 1.443 μm
Packaging

Fiber Optic hole

Enclosure

Sensing Element

Overall prototype Size: Ø15x20mm

Laser Diode
Fringe Pattern Images

- 2 micron slits separated by 10 microns
- Interference fringes at 50 and 150 microns

Slits 50\(\mu m\) from surface 150\(\mu m\) from surface
Measured Fringe Separation

Fringe separation, $\Delta$ (microns)

Distance from sensor, $z$ (microns)

Actual: $\Delta = 0.064z$

Model: $\Delta = 0.066z$
Shear Stress Sensor Test Setup

Optical fiber

External Receiver

Shear Stress Sensor

Optical fiber

Fringes

Receiver lens

Rotating disk
Signal with External Receiver
Conclusion

- Designed a non-invasive fluid shear stress sensor
- Utilized a two-sided fabrication technique to realize the diffractive optic sensor head.
- Tested the emitter side of the sensor and obtained good agreement with the model
- Future work will include improvement of emitter/receiver isolation and integration of the receiver fiber.