A MICROMACHINED GEOMETRIC MOIRÉ INTERFEROMETRIC FLOATING-ELEMENT SHEAR STRESS SENSOR

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- Fabrication
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  - Setup
  - Results
- Dynamic Calibration
  - Background
  - Setup
  - Results
- Conclusion
- Future Work

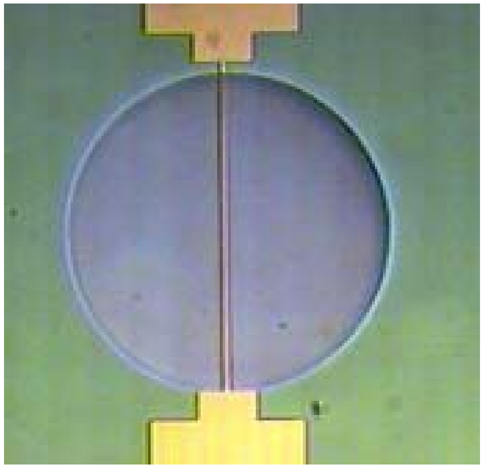
Motivation

- Long - Term Goal
  - To directly measure turbulent shear-stress fluctuations
    - w/ immunity from EMI
    - w/o disturbing the flow
- Existing Sensors
  - Thermal shear stress sensors
  - Floating-element shear stress sensors

Indirect Sensors

- Thermal shear stress sensors
  - Robust and simpler to fabricate
  - Indirect measurement technique based on heat transfer
  - Absolute calibration for quantitative measurement is difficult

Indirect (e.g., UCLA/CalTech, MIT, RIT, UF)



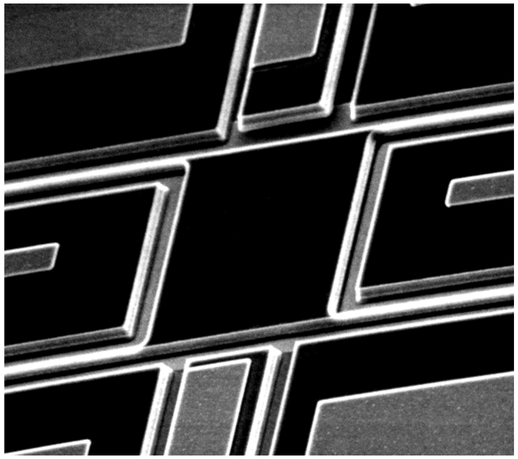
Ref:

Cain, A., *et al*., "Development of a Wafer-Bonded, Silicon-Nitride Membrane Thermal Shear-Stress Sensor with Platinum Sensing Element," Technical Digest, *Solid-State Sensor and Actuator Workshop*, HH, June'00

Direct Sensors

- Floating-element shear stress sensors
  - Various transduction techniques have been developed
    - Capacitive, Piezoresistive, and Intensity-based optical shutter
  - Direct measurement of shear stress
  - Susceptible to EMI and/or optical intensity fluctuations

Direct (e.g., MIT, CWRU)

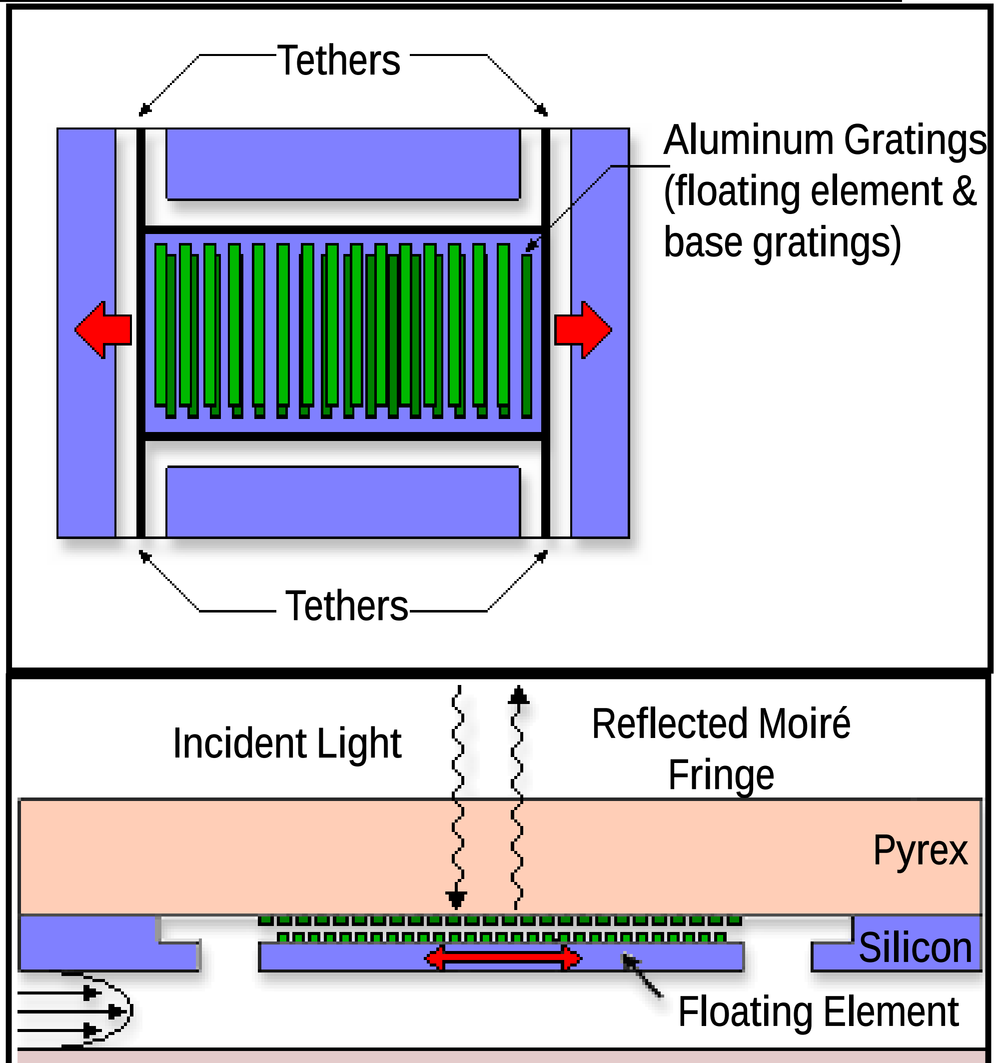


Ref:

Padmanabhan, A., *et al.*, "Wafer-bonded floating-element shear stress microsensor with optical position sensing by photodiodes," *JMEMS*, 1996.

Device Concept

- Floating-Element Sensor
  - Transduction
    - Optical Moiré fringe shifting
  - Benefits
    - Direct measurement of shear stress
    - Immunity to EMI and optical intensity fluctuations
  - Construction
    - Silicon floating element
    - Four silicon tethers
    - Pyrex base
    - Two sets of aluminum gratings with slightly differing pitch



Mechanical Design

$$\delta = \tau_w \frac{L_e W_e}{4Et}\left(\frac{L_t}{W_t}\right)^3 \left\{1+2\frac{L_t W_t}{L_e W_e}\right\}$$

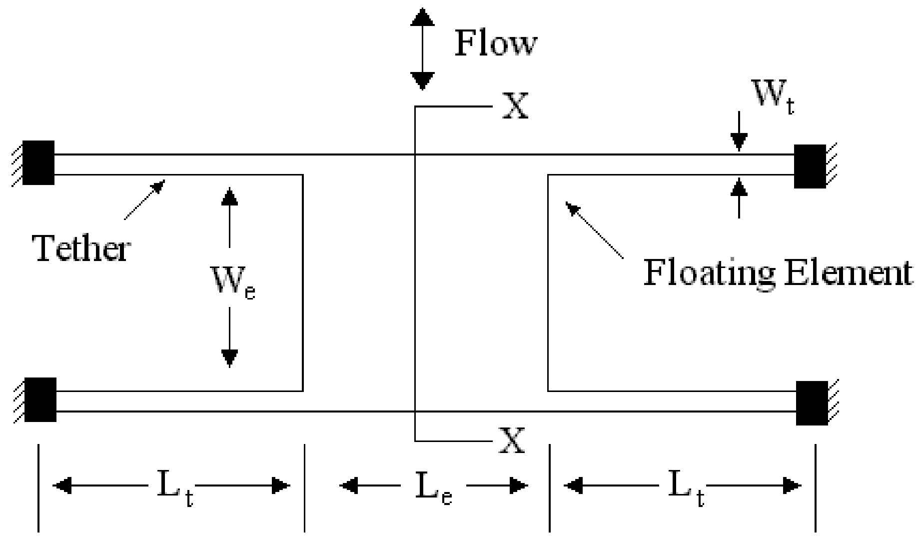
$L_t \rightarrow$ Length of tether

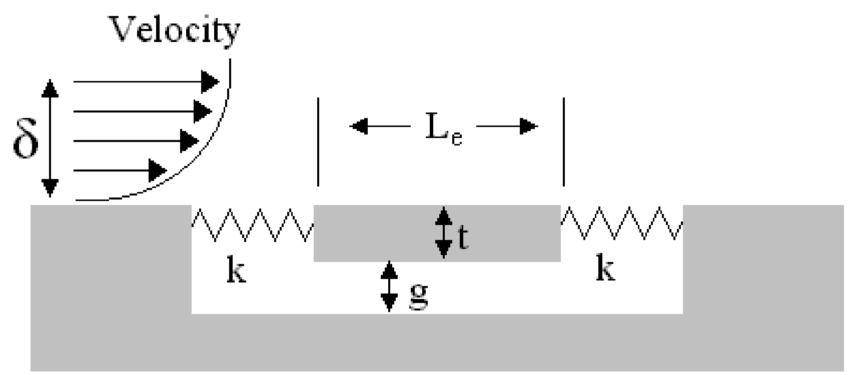
$W_t \rightarrow$ Width of tether

$t \rightarrow$ Thickness of tether

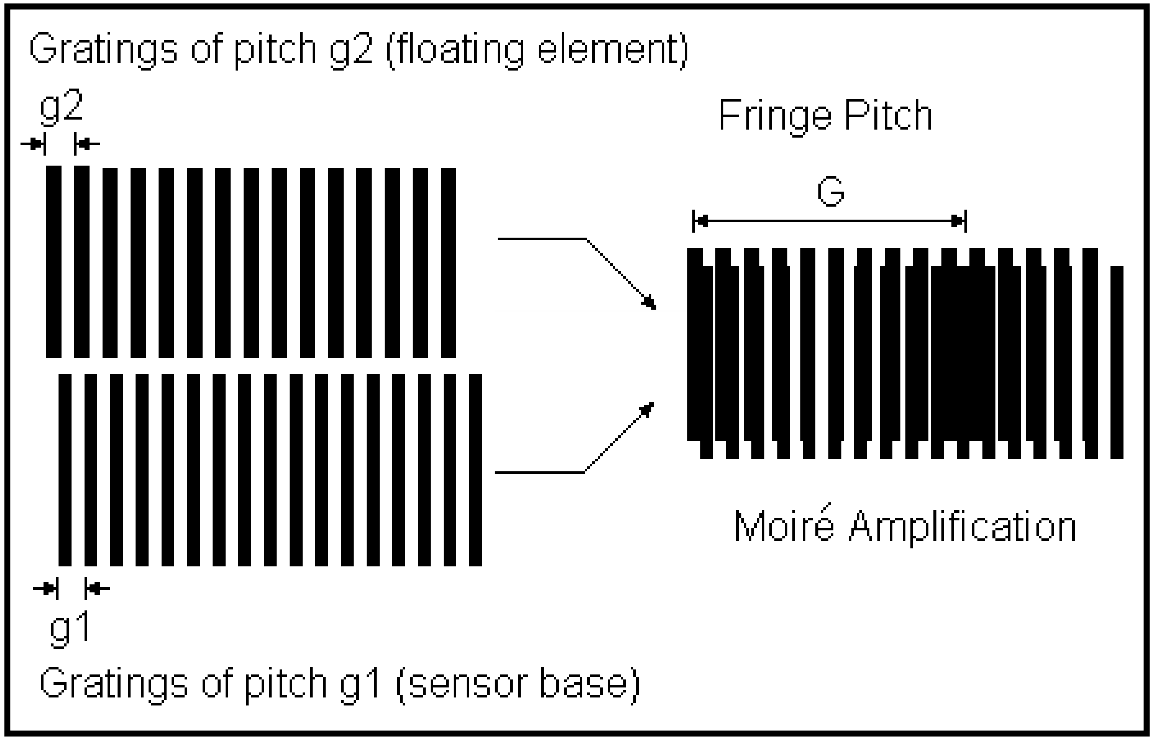
$L_e \rightarrow$ Length of floating element

$W_e \rightarrow$ Width of floating element





Moiré Amplification



- Two overlapping gratings of almost identical period
- Resulting Moiré fringe pitch related by

$$\frac{1}{g_1} - \frac{1}{g_2} = \frac{1}{G}$$

- Motion of one grating w.r.t. another leads to amplified motion of Moiré pattern

$$\Delta = \delta\left(\frac{G}{g_2}\right)$$

$\Delta \rightarrow$ displacement of Moire′ pattern

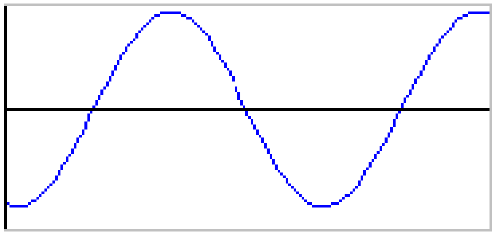
$\delta \rightarrow$ displacement of physical grating

Device Concept

- Floating-Element Sensor

Applied Shear Stress

- Moiré Intensity Pattern



Device Design

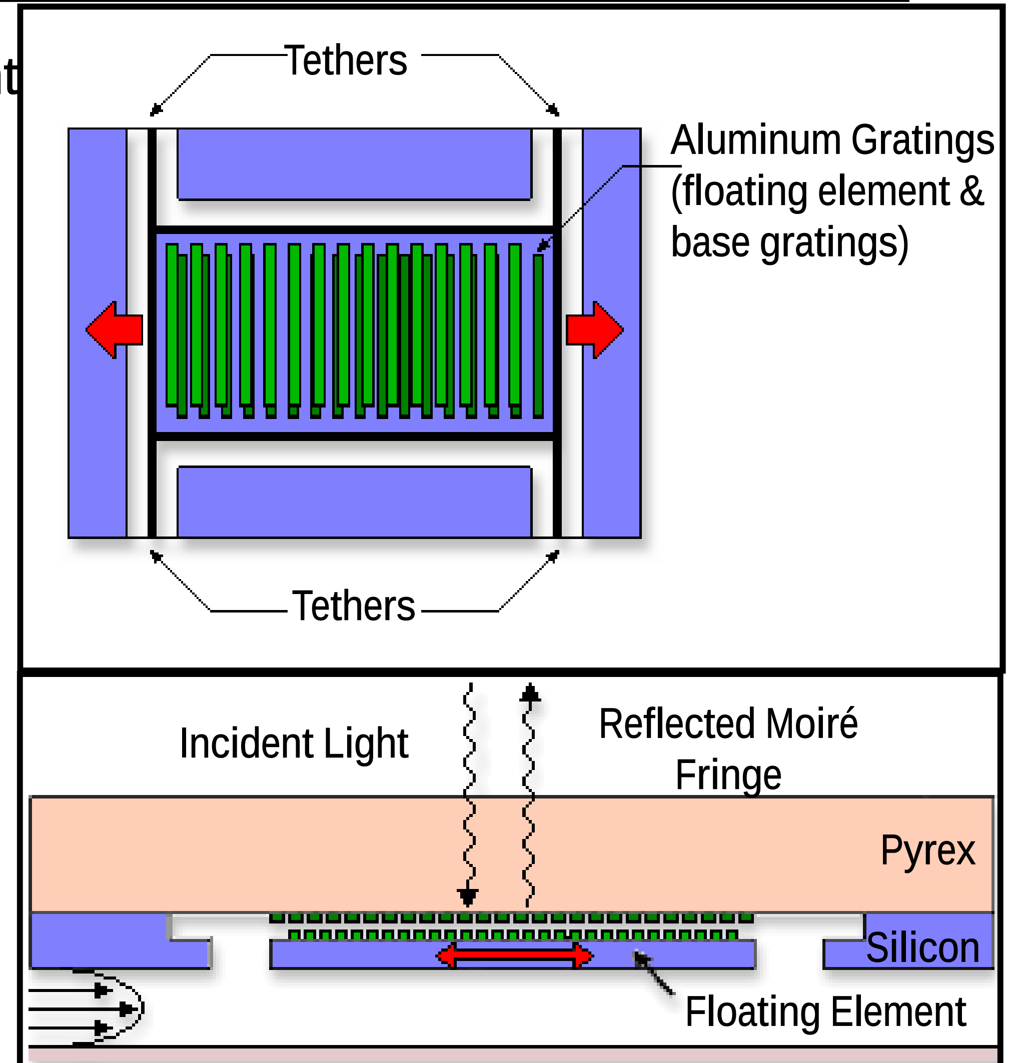
- 1280 ***μm*** x 400 ***μm*** floating element
- Two sets of aluminum gratings
  - Pyrex base

$$g_1 = 9.9\mu m$$

  - Floating element

$$g_2 = 10\mu m$$

- Moiré pitch → $G = 990\mu m$
- Moiré Amplification → $\frac{G}{g_2} = 100$



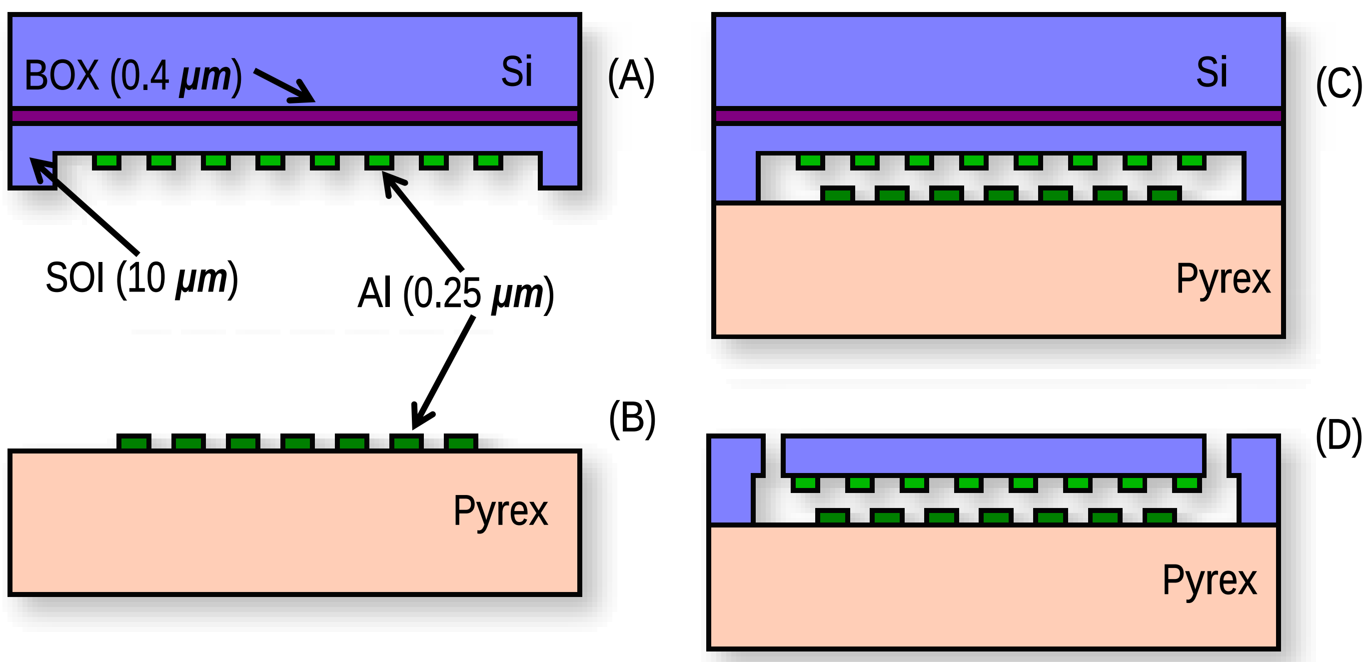
Fabrication Process

(A) Etch 2 μm recess on SOI wafers deposit and pattern device gratings

(B) Deposit 0.25 μm of Aluminum on the Pyrex wafer and pattern handle gratings.

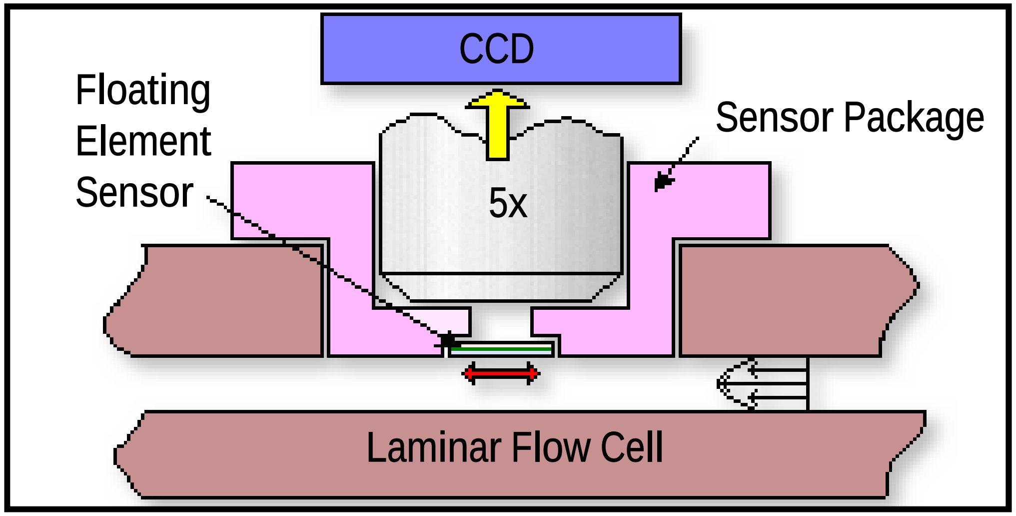
(C) Anodically bond Pyrex and SOI wafers.

(D) Aligned DRIE up to the recess to release the floating element.



Static Calibration Setup

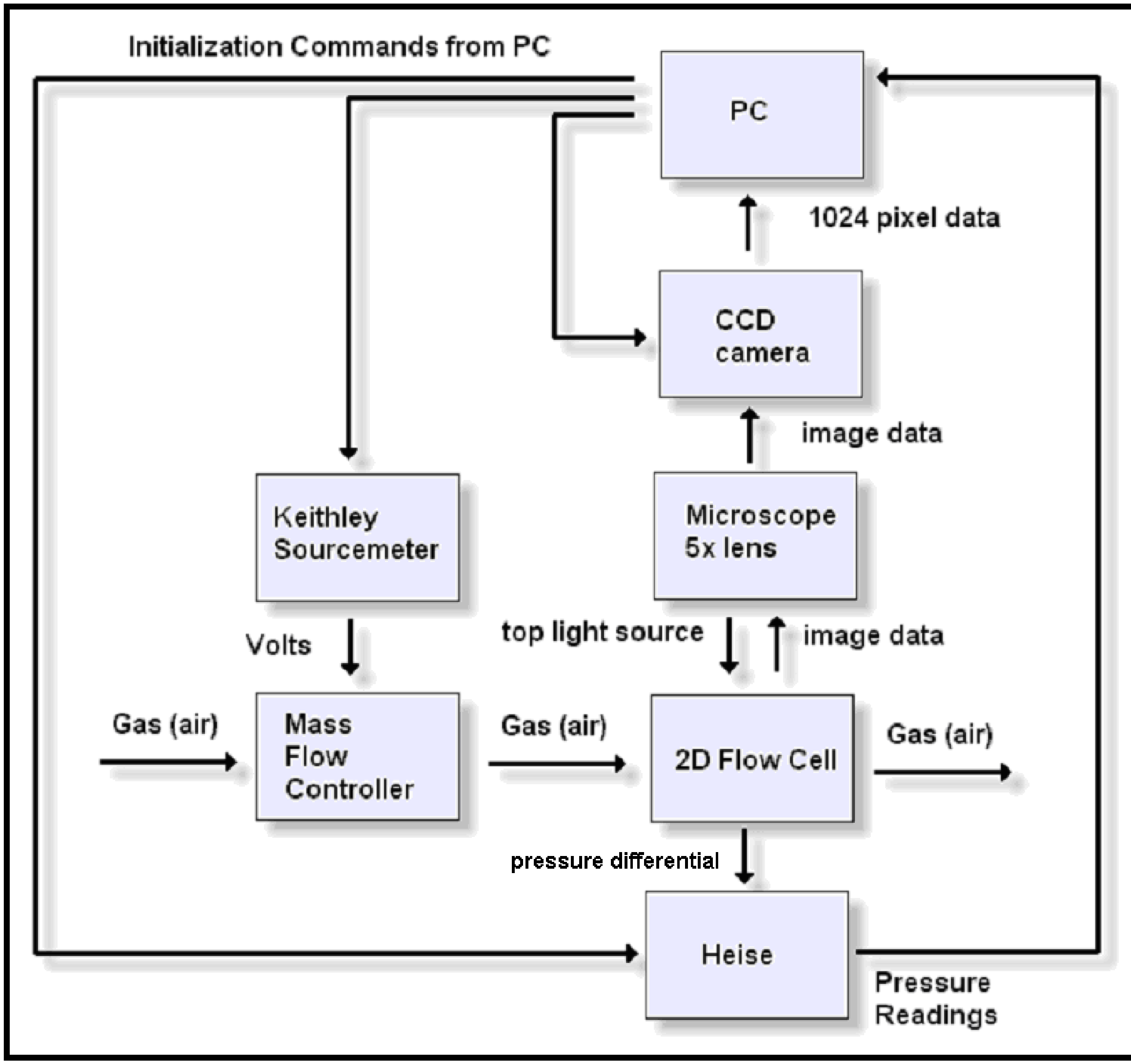
- Lucite Package
  - Fluidic access to floating element
  - Optical access to gratings from backside
- 2-D laminar flow cell
  - Allows for controlled application of variable mean shear-stress
  - Pressure differential measurement provides calibrated shear-stress value
- Imaging system
  - Optical microscope for image magnification (5x lens)
  - Linescan CCD camera (1024 x 1 pixels, 10 μm pixel size)



Static Calibration Setup

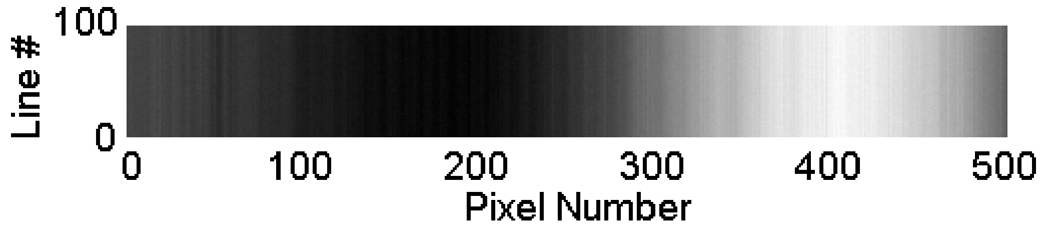
- Pressure differential, dp, measured via Heise Pressure Meter
- Shear stress, τ, calculated from dp

$$\tau = -\frac{h}{2}\frac{dp}{dx}$$

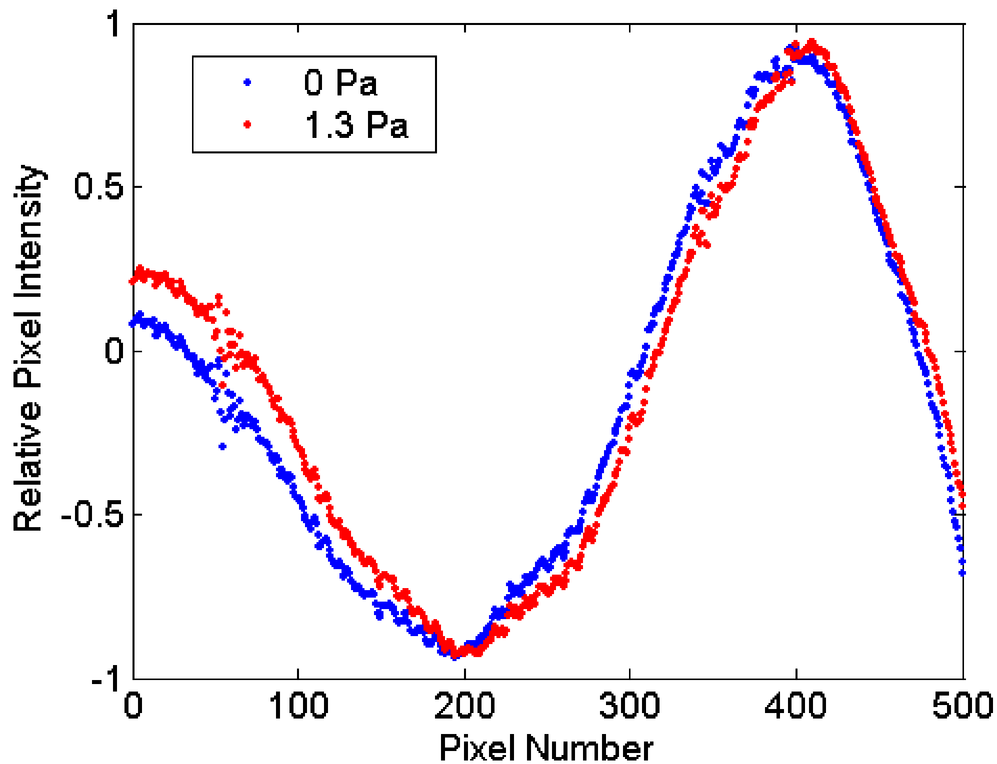


Static Calibration Results

- Moiré fringe pattern
  - Image from 1024 pixel linescan camera
  - for 0 ***Pa*** shear stress



- Relative pixel intensity
  - Data for 0 ***Pa*** and 1.3 ***Pa*** shear stress



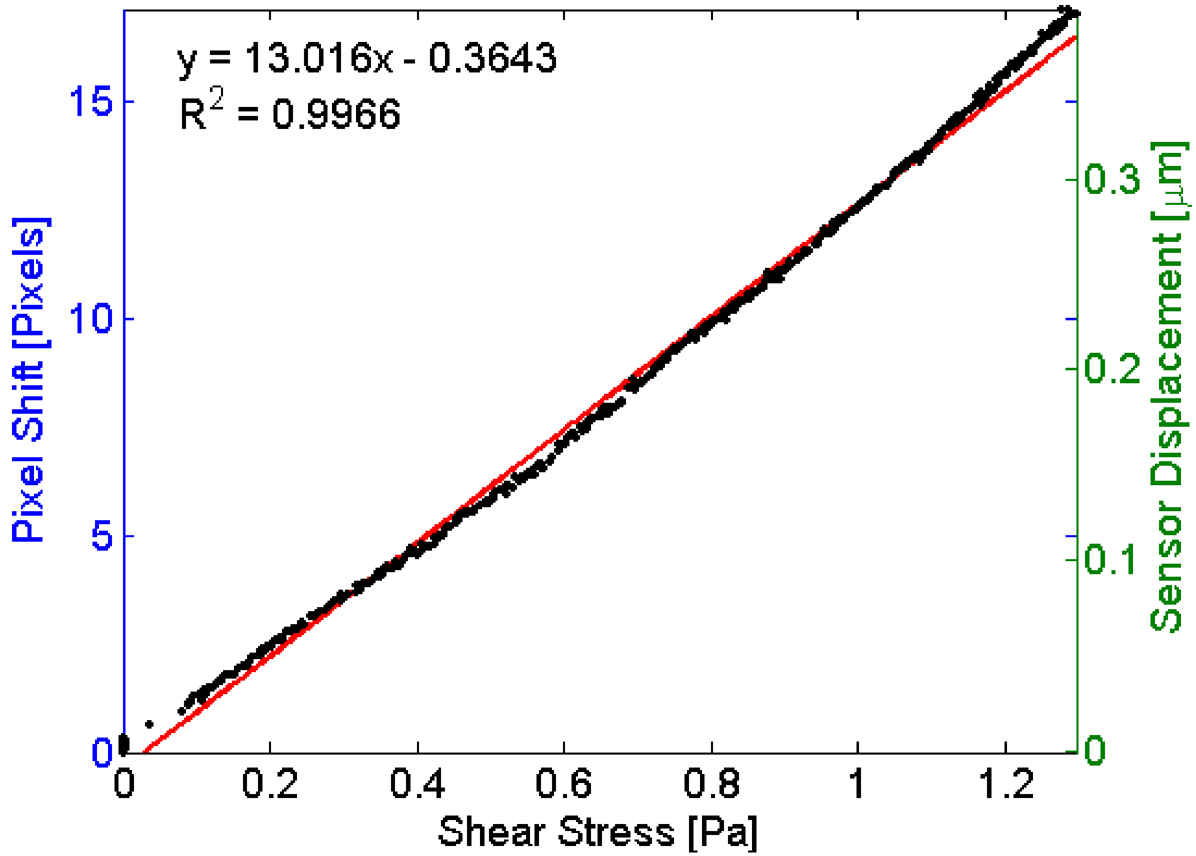
Static Calibration Results

- Pixel shift / sensor displacement
  - extracted from phase of Moiré pattern
- Sensitivity
  - Pixel

$$13 \ \frac{Pixels}{Pa}$$

  - Mechanical

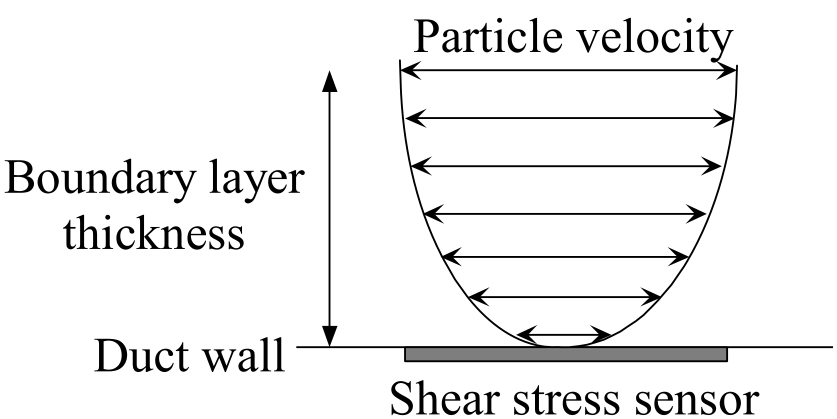
$$0.26 \ \frac{\mu m}{Pa}$$



Dynamic Calibration - Theoretical Basis

System modeled as linear and time invariant over a narrow range of shear stress values

Stokes Layer Excitation (1-D semi-infinite medium)



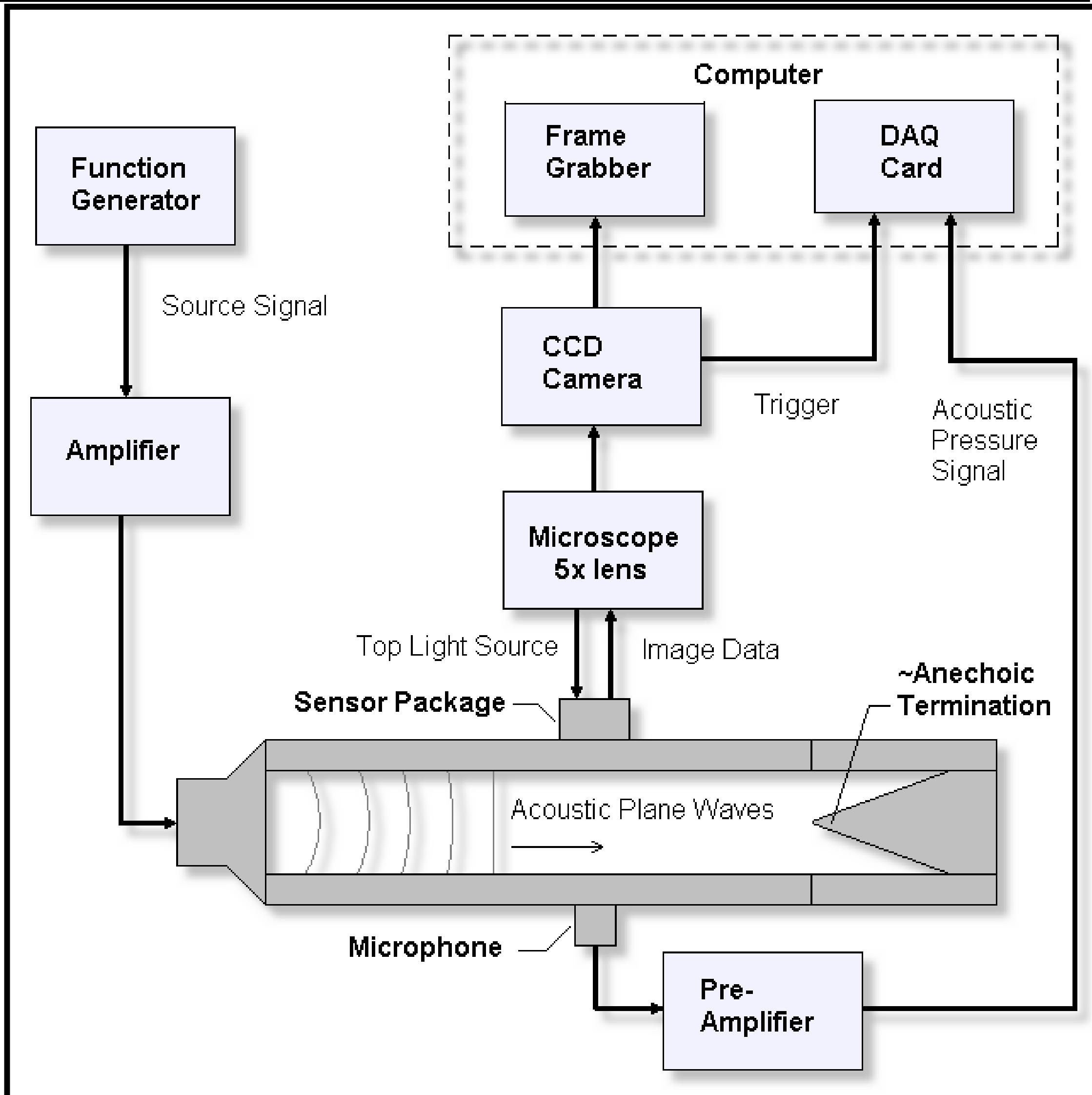
$$\delta(\omega) \sim \sqrt{\frac{\nu}{\omega}}, \quad p' = \rho c\, u'$$

$$\tau'(\omega) = \mu \left.\frac{\partial u'}{\partial y}\right|_{wall} \sim \mu \frac{u'}{\delta} \sim p'\sqrt{\omega}$$

Result - Generation of a frequency dependent boundary layer and shear stress

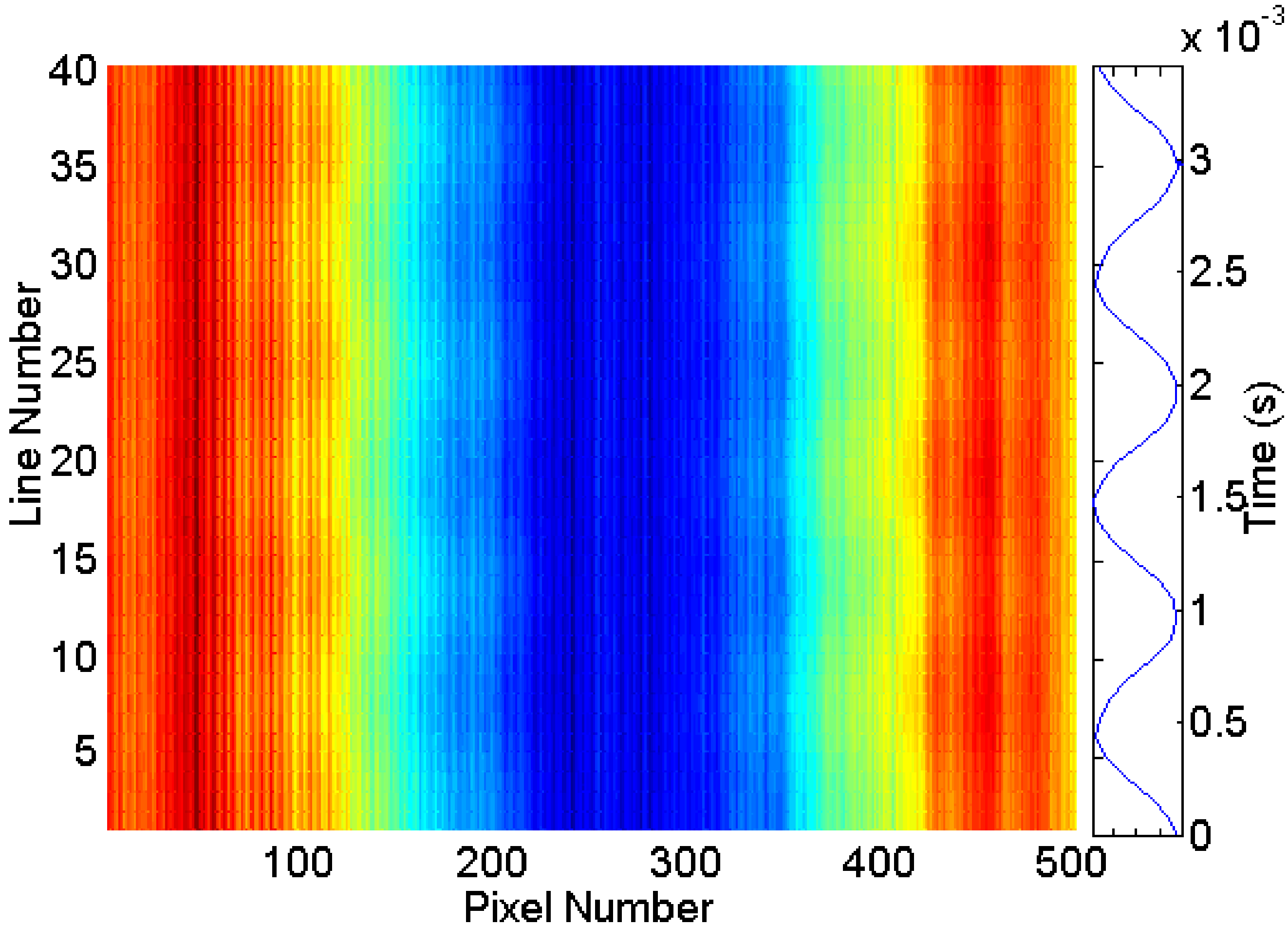
Dynamic Calibration Setup

- Imaging system captures Moiré pattern
  - 11.42 ***kHz*** line rate
- Pixel shift calculated for each line
  - Spatial FFT & phase extraction
- Brüel & Kjaer microphone measures acoustic pressure
  - Triggered by CCD camera for simultaneous sampling



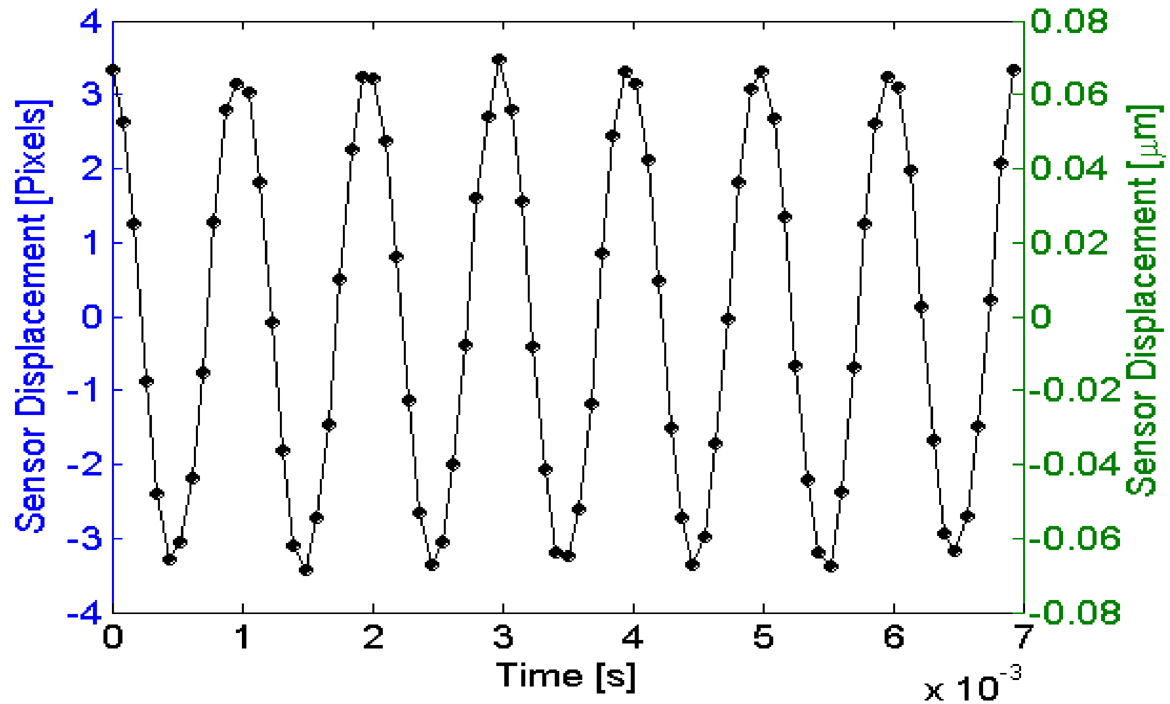
Dynamic Calibration Results

- Moiré fringe pattern
  - Image from 1024 pixel linescan camera
  - for 1 ***kHz*** sinusoidal shear stress input

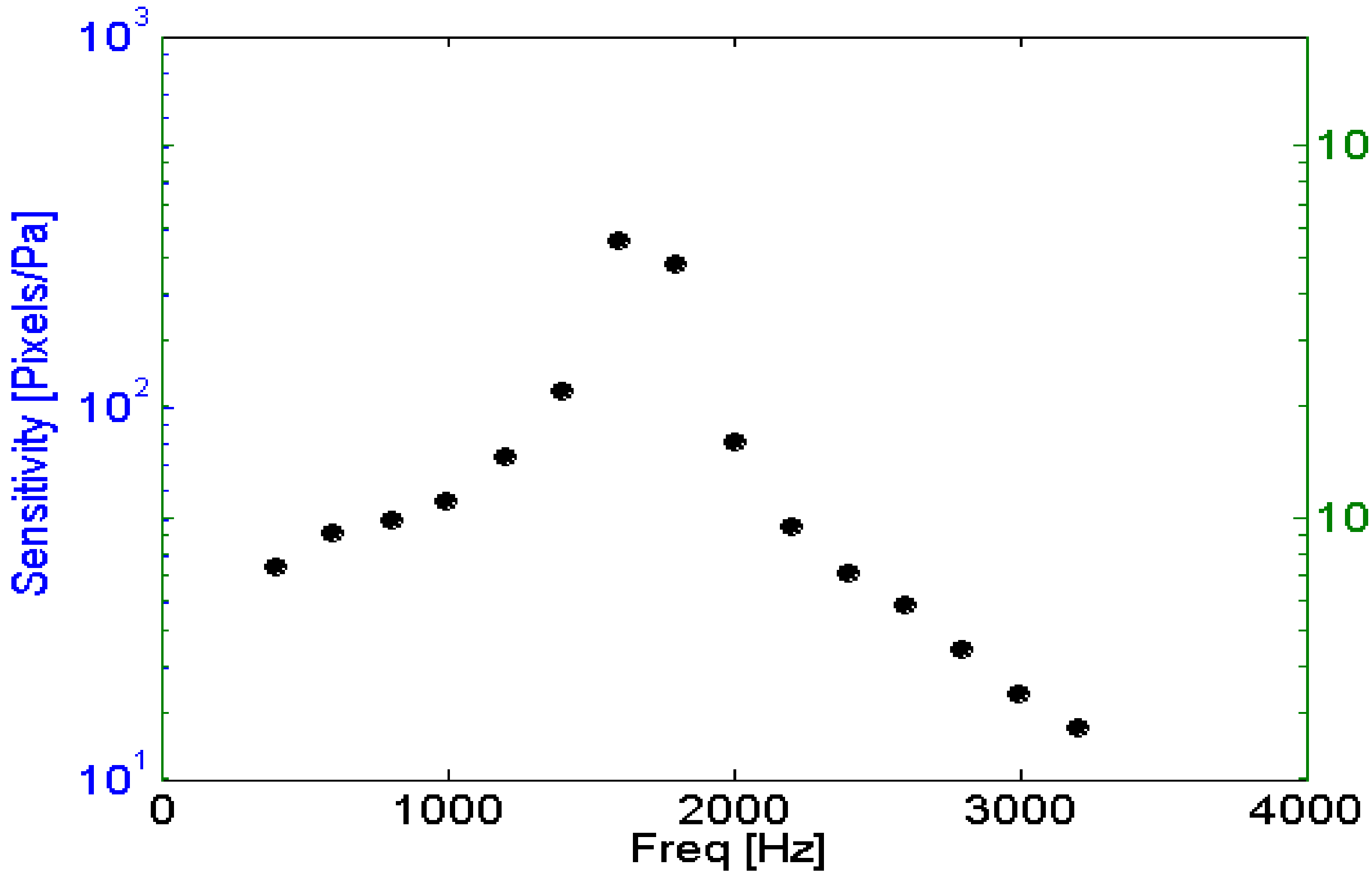


Sinusoidal Moiré Shift

- Phase of Moiré pattern calculated for each line
  - 1 line → 1 sample
  - for 1 ***kHz*** sinusoidal shear stress input

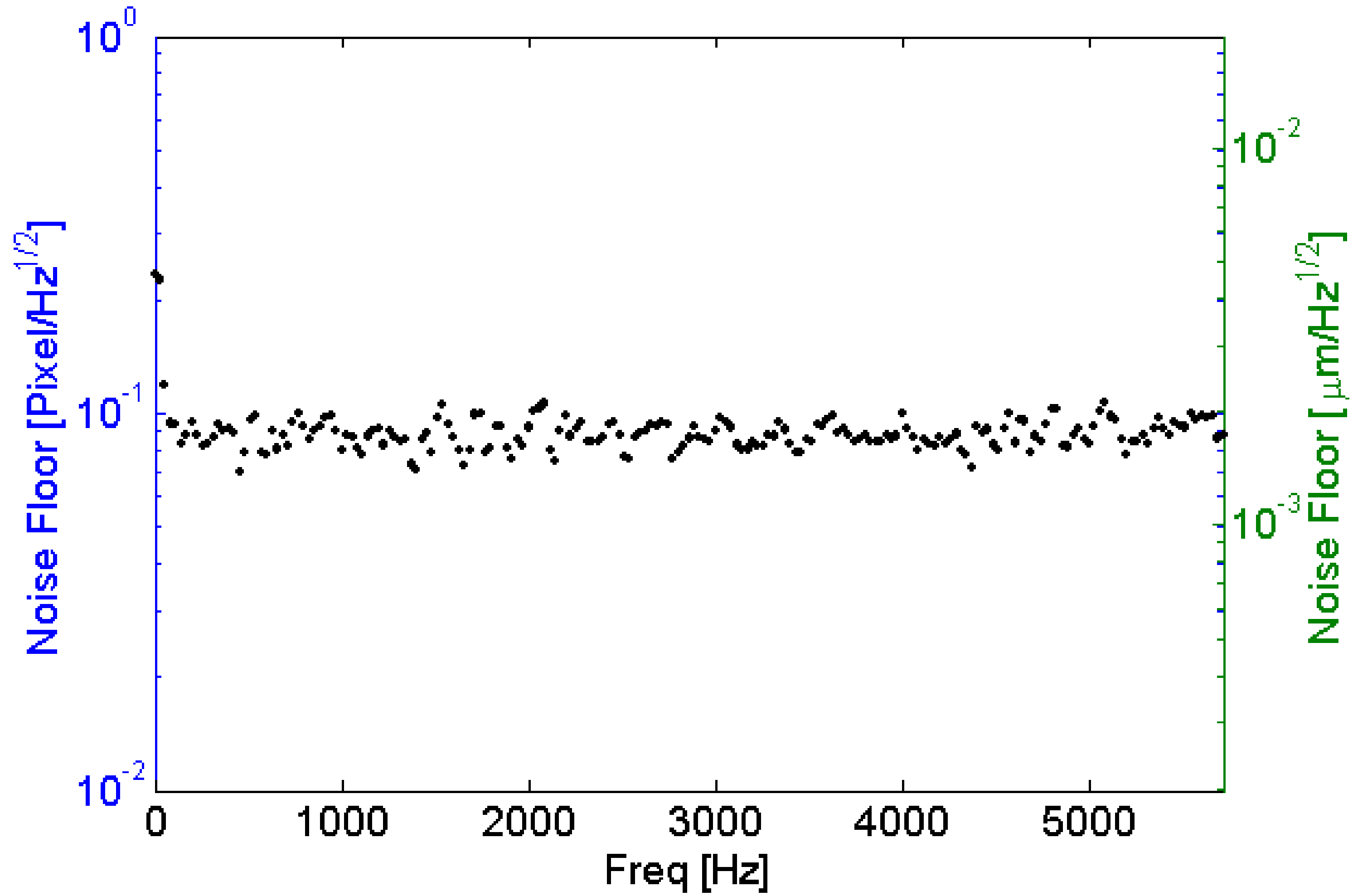


Frequency Response



Resonant Freq → 1.76 *kHz*

Noise Floor



10^0
10^-1
10^-2
Noise Floor [Pixel/Hz^1/2]
10^-2
10^-3
Noise Floor [μm/Hz^1/2]
0
1000
2000
3000
4000
5000
Freq [Hz]

Conclusion

- Summary
  - Developed & fabricated Moiré based MEMS sensor for direct measurement of shear-stress
  - Performed static calibration
    - Linearity
    - Sensitivity
  - Performed dynamic calibration
    - Frequency response
    - Noise floor

Conclusion

- Future Work
  - Perform calibrations of multiple sensors to determine variability
  - Optimize design for improved sensitivity and bandwidth
  - Incorporate optical fiberscope into imaging system for improved portability
- Acknowledgements

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