Power modulation based optical fiber loop-sensor for structural health monitoring in composite materials

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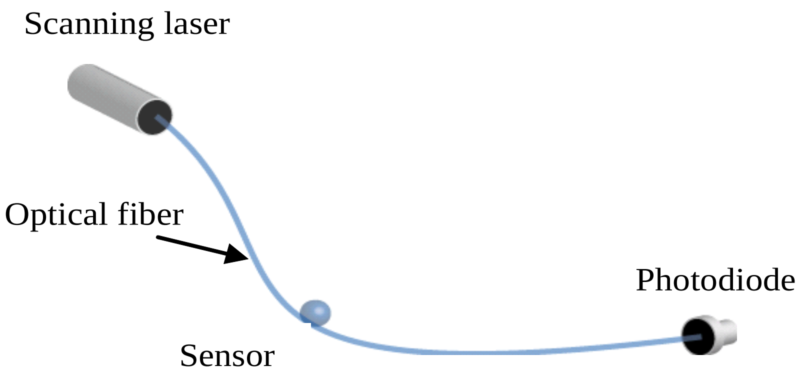
List of Publications and Patents

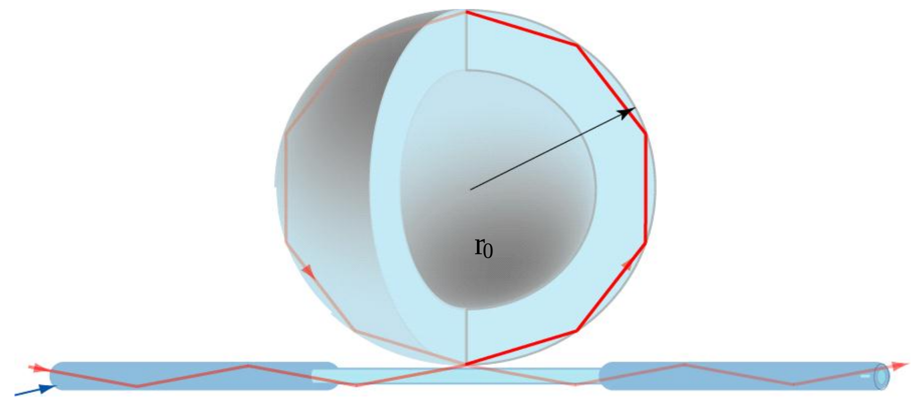
- The technologies covered in this work are presented in the following
  - **Patents**:
    - Fiber-optic extensometer, US Patent #8,428,400, April 23, 2013, Nikhil Gupta, Nguyen Q. Nguyen.
    - Method for measuring the deformation of a specimen using a fiber optic extensometer, US Patent #8,649,638, February 11, 2014, Nikhil Gupta, Nguyen Q. Nguyen.
  - **Papers**:
    - Nishino, Z., Chen, K., and Gupta, N. Power Modulation Based Optical Sensor for High Sensitivity Vibration Measurements. IEEE Sensors, 2014, (7): p. 2153 - 2158.
    - Nguyen, N. Q. and Gupta, N. Whispering gallery mode sensor for phase transformation and solidification studies. Philosophical Magazine Letters, 2010. 90(1): p. 61-67.
    - Nguyen, N. Q. and Gupta, N., Analysis of an encapsulated whispering gallery mode micro-optical sensor. Applied Physics B: Lasers and Optics, 2009. 96(4): p. 793-801.
    - Nguyen, N. Q. and Gupta, N., Power modulation based fiber-optic loop-sensor having a dual measurement range. Journal of Applied Physics, 2009. 106(3), #033502.

Introduction

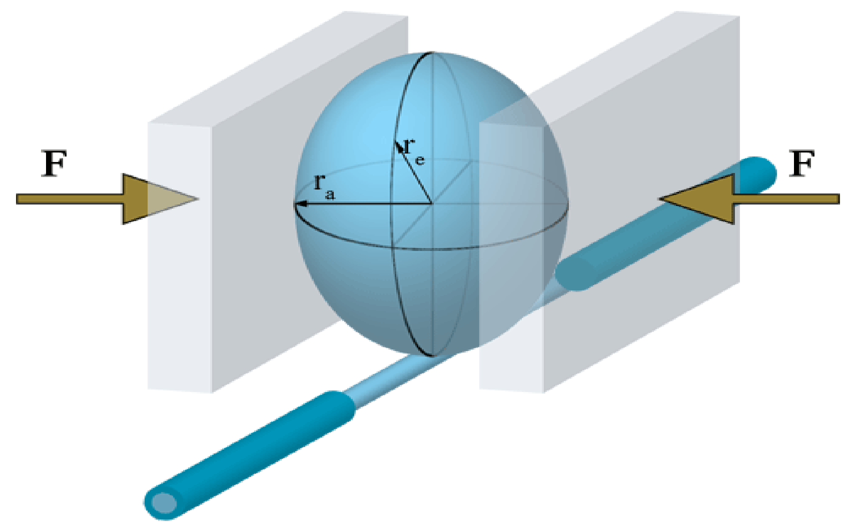
- Structural Health Monitoring (SHM)
  A process of identifying one or more of
  - Load applied or displacement obtained on the structure
  - Extent of damage
  - Growth rate of damage
  - Performance of the structure as damage accumulates
- SHM can help in moving from *predictive maintenance* to *need-based maintenance*
  - Increase in safety
  - Cost saving

Whispering Gallery Mode Sensors



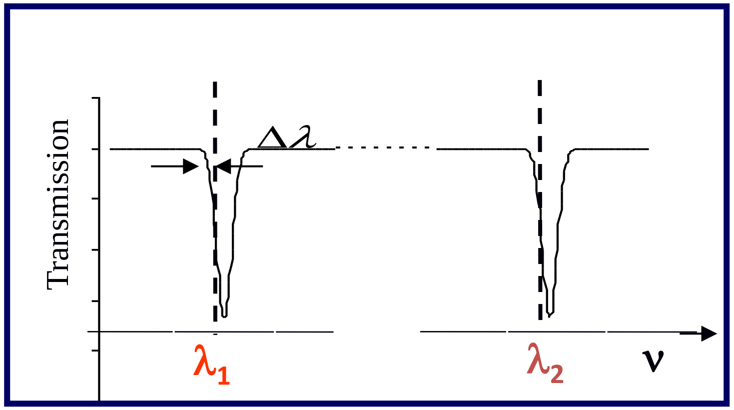


- Tunable laser is used
- Evanescent field of the stripped off section of fiber interacts with that of the resonator (particle)
- Coupling back of the evanescent field in the fiber gives resonance peaks, which can be tracked



Whispering Gallery Mode Sensors

- Very high sensitivity
  - Detection of single chemical molecules
  - Detection of a single HIV virus
  - Measurement of sub-nanometer displacement



For $r >> \lambda,$ resonance condition:

$$2\pi\, r\, n \approx \ell\lambda \qquad (\ell = integer)$$

$$\frac{\Delta n}{n} + \frac{\Delta r}{r} \approx \frac{\Delta\lambda}{\lambda}$$

n = refractive index of the micro-sphere
λ = wavelength
r = micro-sphere radius

WGM Sensors: Effect of Refractive Index

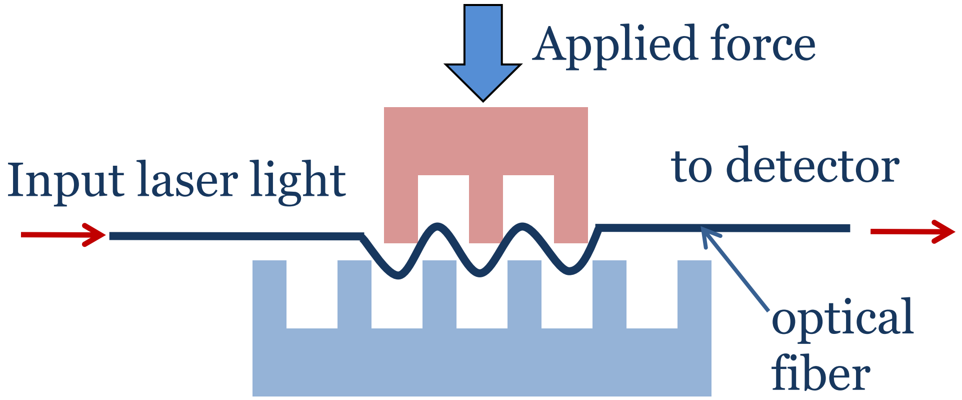
$$n_1 = n_0 + C_1\sigma_1 + C_2\left(\sigma_2 + \sigma_3\right)$$
$$n_2 = n_0 + C_1\sigma_2 + C_2\left(\sigma_1 + \sigma_3\right)$$
$$n_3 = n_0 + C_1\sigma_3 + C_2\left(\sigma_1 + \sigma_2\right)$$

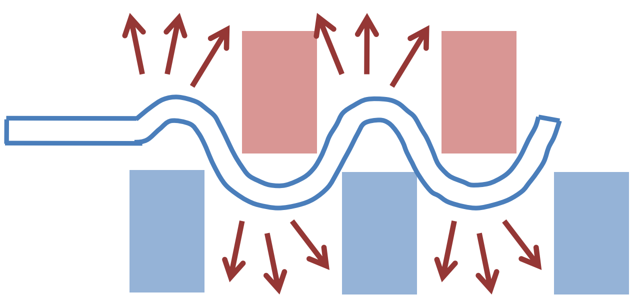
Where
n_0 undeformed index of refraction
σ_1, σ_2 and σ_3 are principal stresses
C_1 and C_2 are elasto-optic coefficients of the material of the sphere.

- Sensitivity comes at a price!
  - Signal to noise ratio can be low
  - Keeping the particle in resonance can be difficult

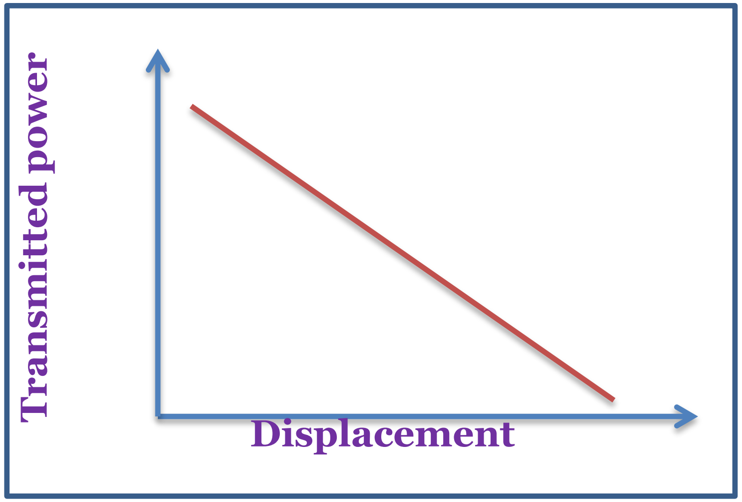
	Silica ***(Yves Belouard et al. 2006)***	**PMMA** ***(Feridun et al. 2004)***
C_1 (m²/N)	-4.22×10^{-12}	-12×10^{-12}
C_2 (m²/N)	-0.65×10^{-12}	-12×10^{-12}
n_0	1.467	1.4876

Introduction





- Microbend sensors
  - Use multi-mode fiber
  - Require high power light source
  - Normally used under compression
  - Large size



Results and Discussion

- Power attenuation
- Critical radius (Jeunhomme, 1983)

$$R_c = 20\frac{\lambda}{(\Delta n)^{3/2}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3}$$

where

λ is the operating wavelength

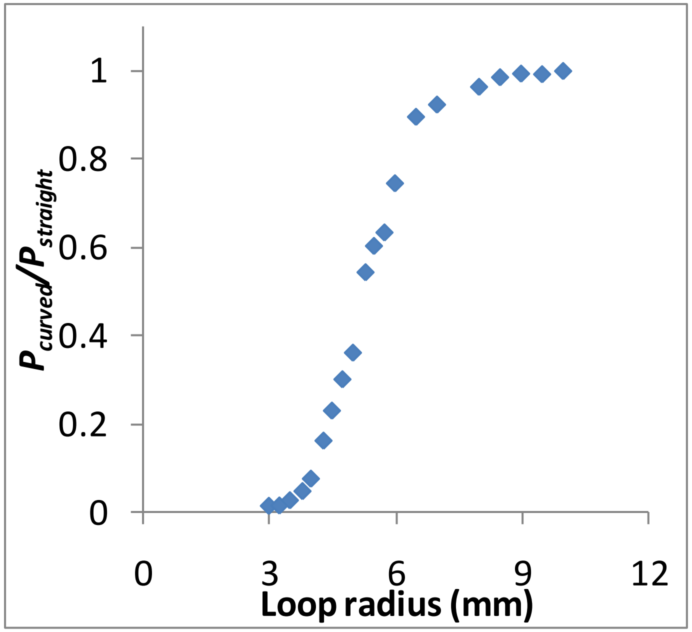
λ_c is cut-off wavelength

Δn: core-cladding index of refraction difference

- For present single-mode optical fiber

λ=1.31 μm, λ_c=1.26 μm, Δn=0.0058

R_c=11.8 mm



Fiber-loop sensors

- Power transmission due to curvature

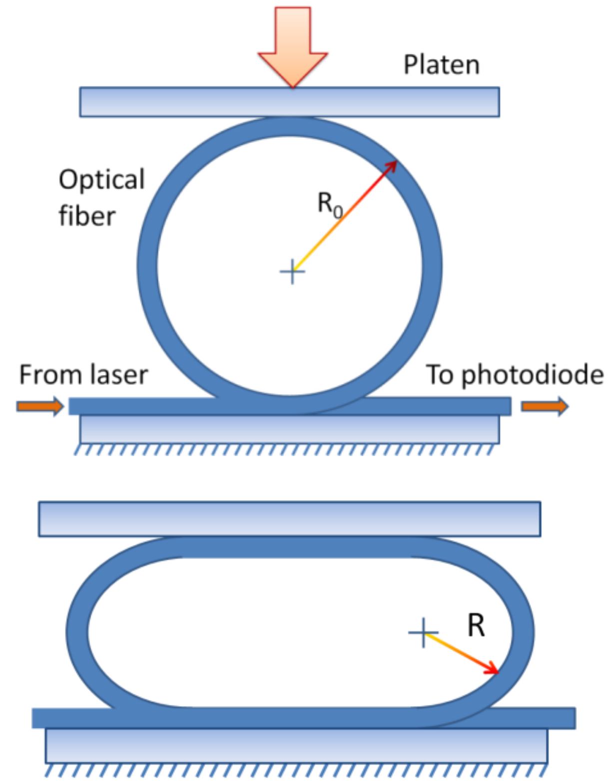
$$\overline{P}_R = \frac{P_{out}}{P_{in}}$$

  - P_{out} is transmitted power through the loop
  - P_{out} is power incoming to the loop

- Compressing loop creates more losses, relative transmitted power

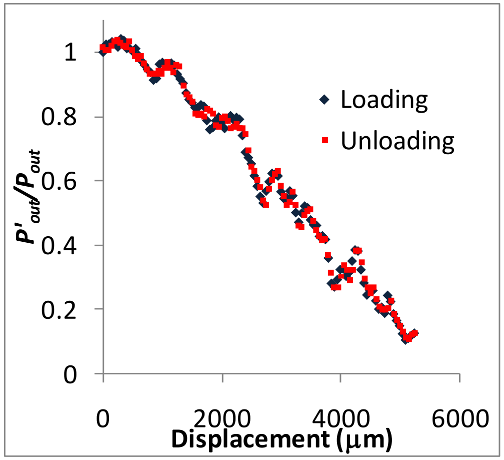
$$\overline{P} = \frac{P'_{out}}{P_{out}}$$

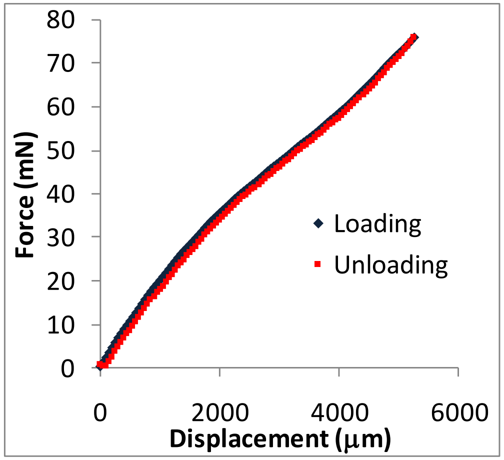
  - P'_{out} is transmitted power with the applied force
  - P_{out} is power with no load applied

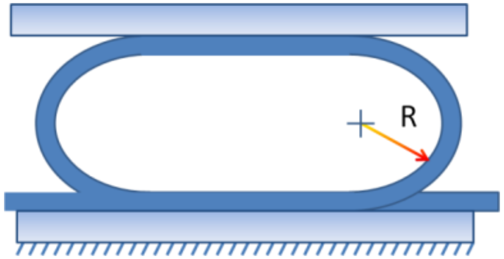


Fiber-loop sensors

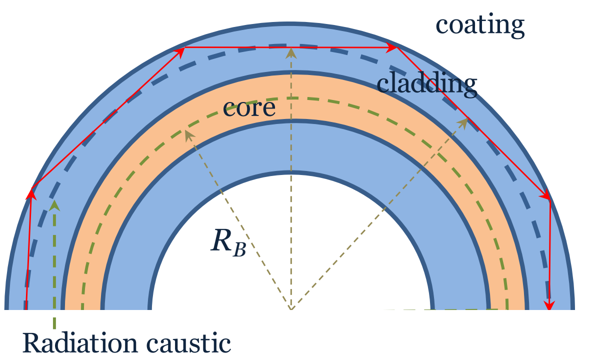
- Compression of loop R_B=7 mm







- Resonances occur between leaky mode reflected from cladding/coating interface and fundamental mode



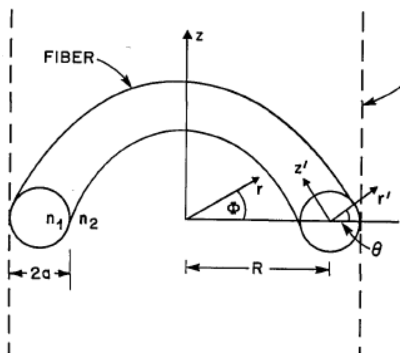
Fiber-loop sensors

- Pure bend loss-Marcuse model

Assumption: infinite cladding, large bend radius, weakly guided index fiber

$$\overline{P}_R = \exp\left(-2\alpha_B l_B^e\right)$$

where



$$k = 2\pi/\lambda$$

$$V = ak\left(n_{co}^2 - n_{cl}^2\right)^{1/2}$$

$$\kappa = \left(k^2 n_{co}^2 - \beta_0^2\right)^{1/2}$$

$$\gamma = \left(\beta_0 - k^2 n_{cl}^2\right)^{1/2}$$

$$2\alpha_B = \frac{1}{2}\left(\frac{\pi}{\gamma^3 R_B^e}\right)^{1/2} \frac{\kappa^2}{V^2 K_1^2(\gamma a)} \exp\left(-\frac{2\gamma^3 R_B^e}{3\beta_0^2}\right)$$

$$l_B^e = 2\pi R_B^e$$

n_{co} and n_{cl} are indices of refraction of the core and cladding

β_o is the propagation constant in straight fiber, solved by the eigenvalue equation

$$\kappa \frac{J_1(\kappa a)}{J_0(\kappa a)} = i\gamma \frac{H_1^1(i\gamma a)}{H_0^1(i\gamma a)}$$

R^e_B is effective bend radius, differing from R_B by a stress correction factor, taken 1.28 for SMF28e fiber

SMF28e from Corning, NY

Fiber layer	Radius (μm)	Index of refraction
Core	4.1	1.4517
Cladding	62.5	1.447
Coating	125	1.4786

Fiber-loop sensors

- Renner model- finite, coating and cladding thickness

$$\overline{P}_R = \exp\left(-2\alpha_{BC} l_B^e\right)$$

where

$$2\alpha_{BC} = 2\alpha_B \frac{2\left(Z_{ct} Z_{cl}\right)^{1/2}}{\left(Z_{ct} + Z_{cl}\right) - \left(Z_{ct} - Z_{cl}\right)\cos\left(2\Theta_0\right)}$$

$$Z_{cl} = k^2 n_{cl}^2 \left(1 + 2b / R_B^e\right) - \beta_0^2$$

$$Z_{ct} = k^2 n_{ct}^2 \left(1 + 2b / R_B^e\right) - \beta_0^2$$

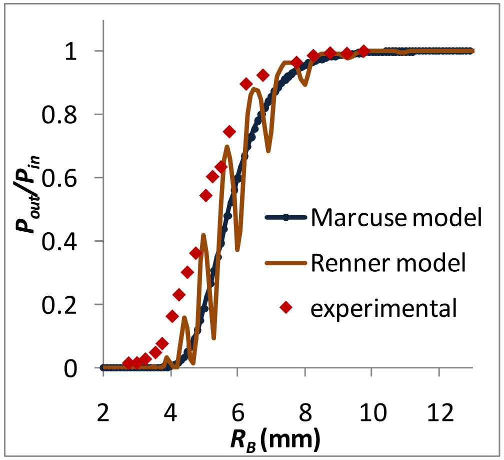
$$\Theta_0 = \frac{\gamma^3 R_B^e}{3k^2 n_{cl}^2}\left(\frac{R_c}{R_B^e} - 1\right)^{3/2} \qquad R_c = \frac{2k^2 n_{cl}^2 b}{\gamma^2}$$

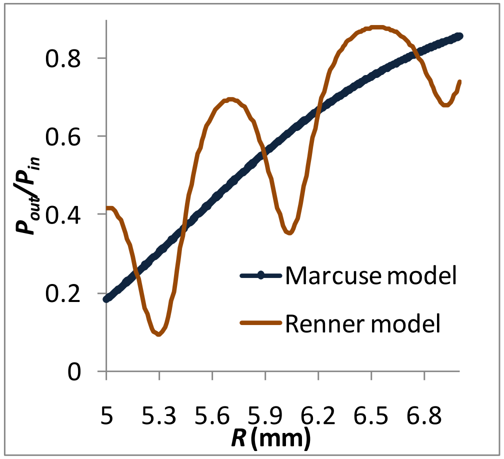
$$\frac{4b\gamma R_B^e}{3\pi R_c}\left(\frac{R_c}{R_B^e} - 1\right)^{3/2} = \begin{cases} 2m - 1/2 \text{ for maximum} \\ 2m - 3/2 \text{ for minimum} \end{cases}$$, m is an integer

$l^e_B = 2\pi R^e_B$ is the effective length of the loop

R_c is the critical radius

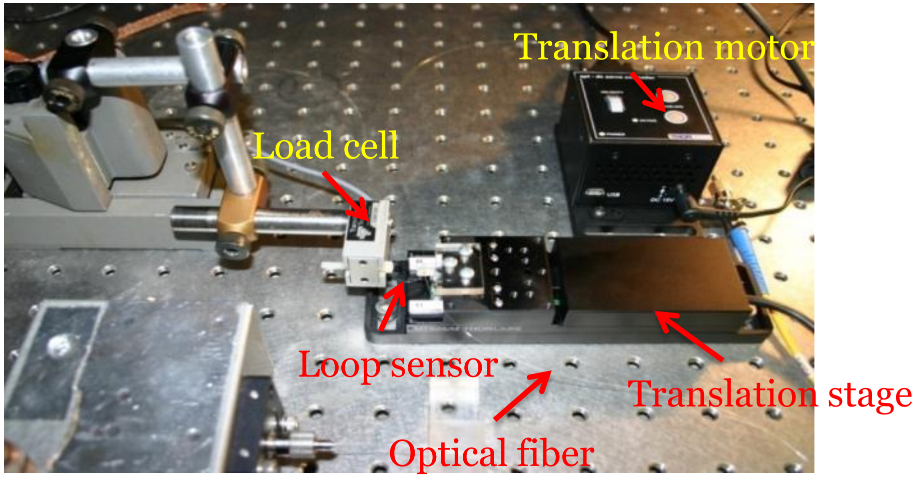
- Experimental data are obtained by changing the radius of fiber-loop

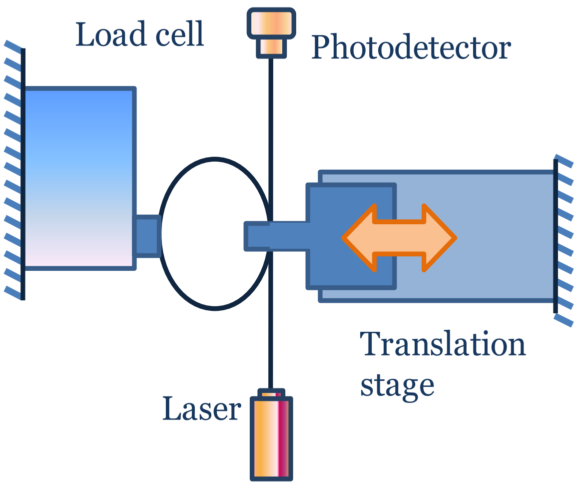




Loop sensor calibration setup

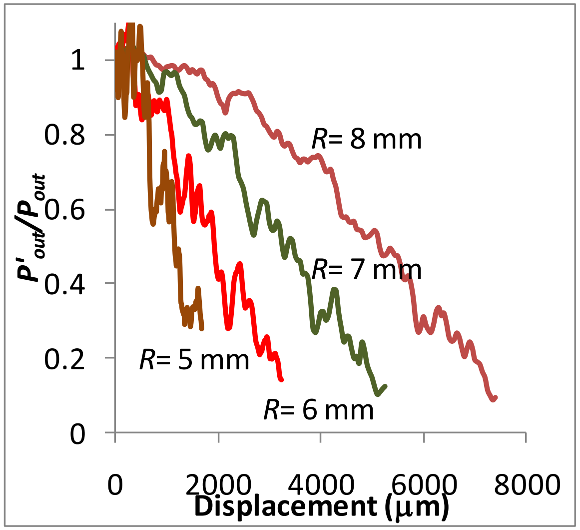
- Square wave signal is sent to the loop
- Photodetector tracks the transmitted power
- Relative transmitted power and force are monitored with respect to increment in displacement

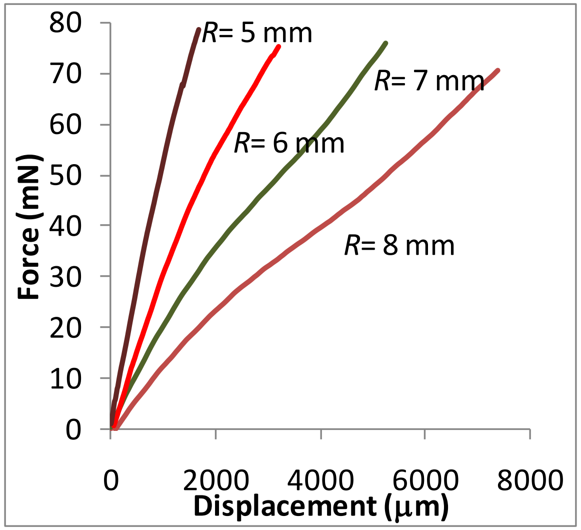




Loop sensor calibration

- Calibration of different loop radii

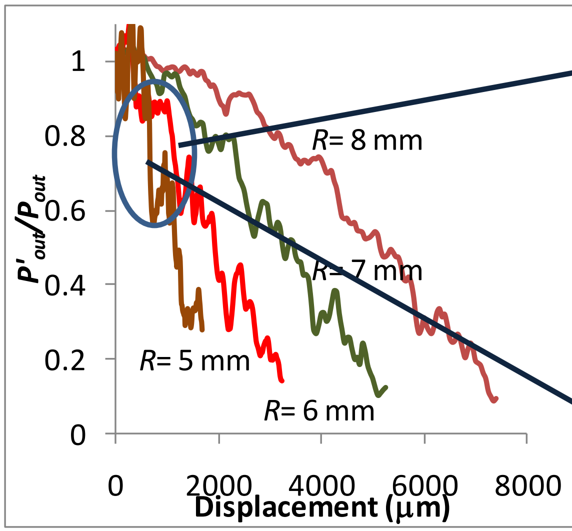


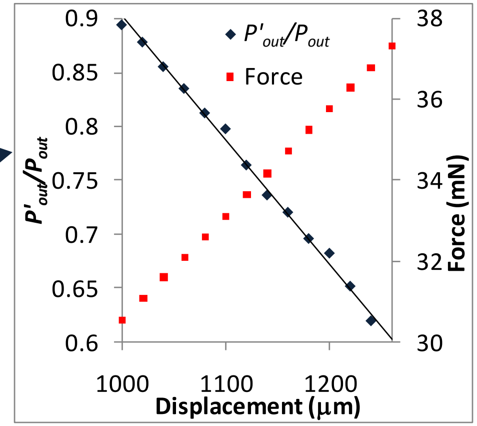


- Smaller loops have higher sensitivity but lower measurement range
- Loop-sensors allow large deformation without losing its elasticity and repeatability

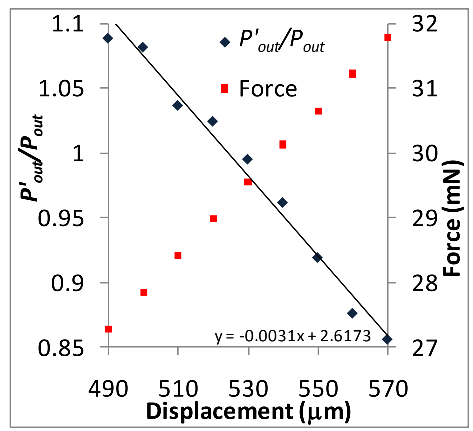
Loop sensor calibration

- In high sensitivity domain





R_B =6 mm

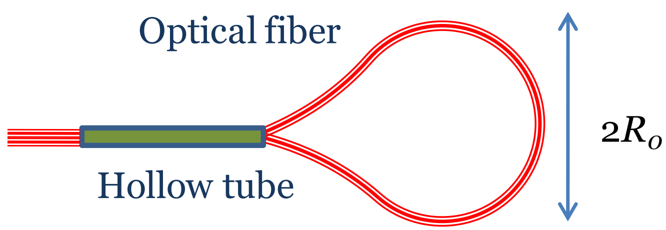


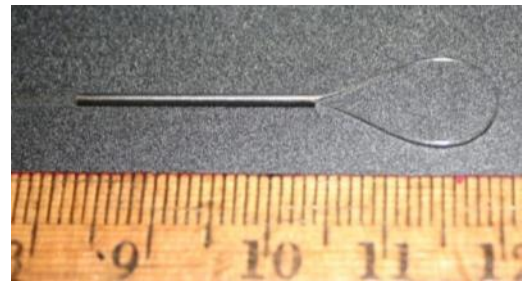
R_B =5 mm

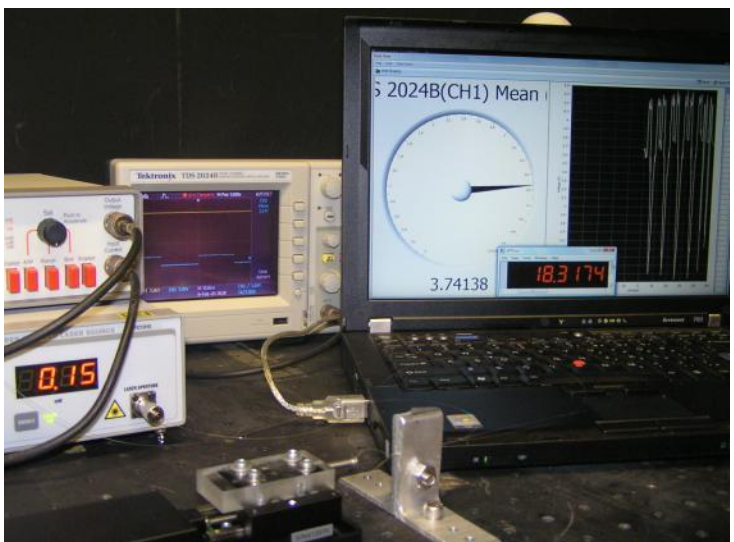
- Resolution
  - Force: 10^{-4} N
  - Displacement: 10^{-5} m

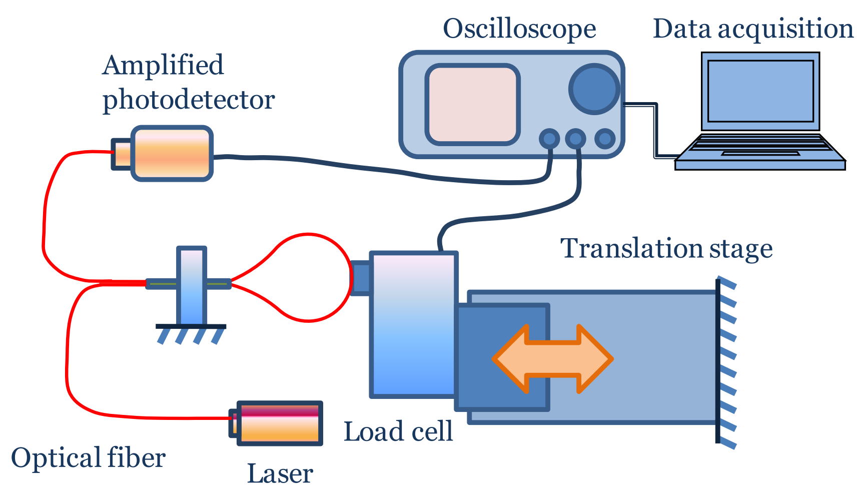
Cyclic loading tests

- Pear-shaped loop and experimental setup



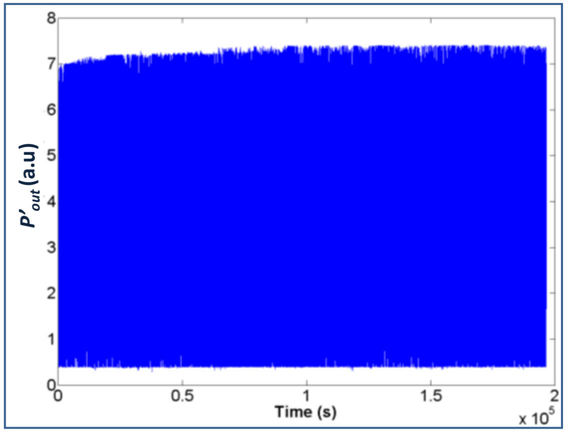


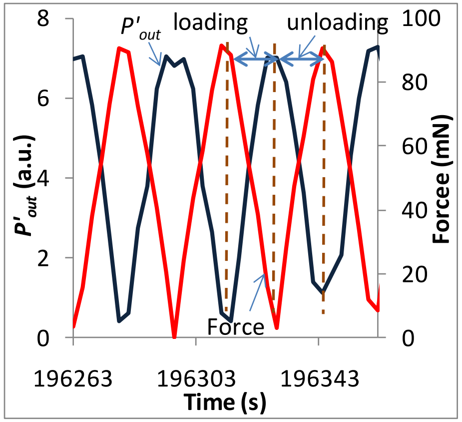




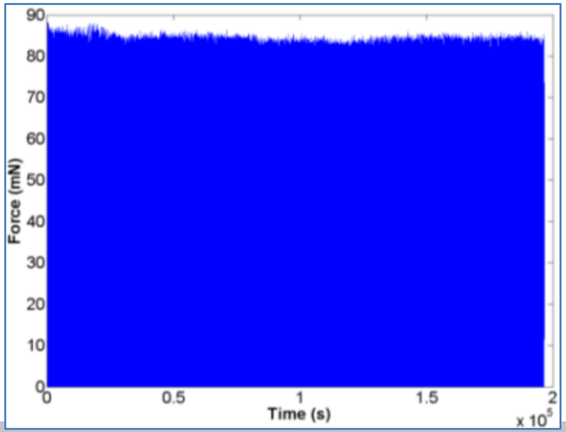
Cyclic loading tests

- Results in 10,000 cyclic loading





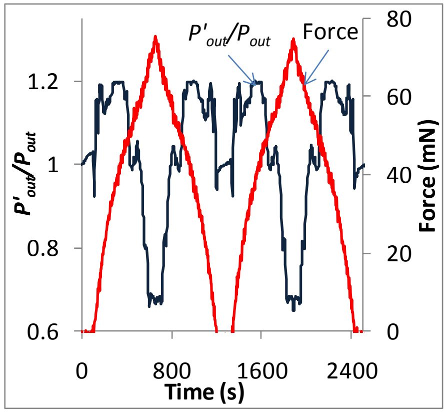
- Loop radius: 5 mm
- Displacement: 6 mm
- Displacement rate: 0.4 mm/s
- 30 s per loading/unloading cycle



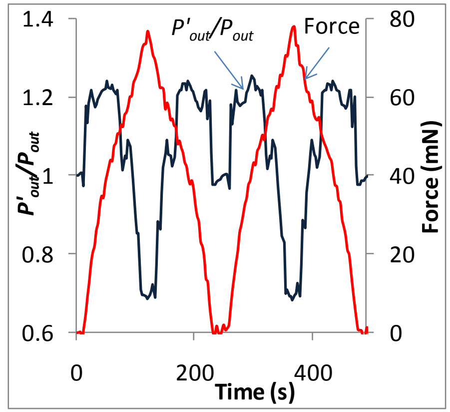
- Total testing time: 4 days
- The sensors survived after 10,000 cycles
- Results show repeatability and consistency for 10^4 loading/unloading cycles

Cyclic loading tests

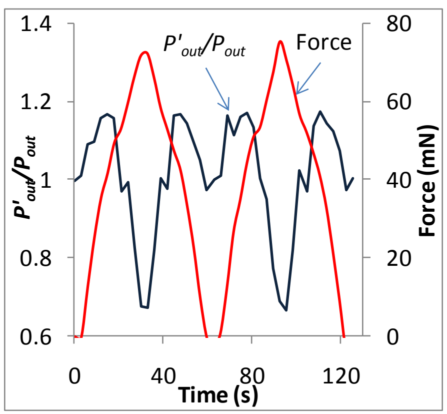
- Different displacement rate



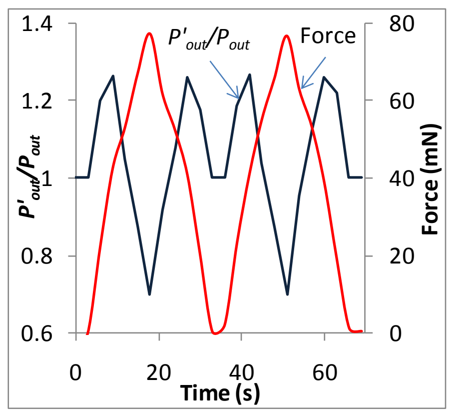
v=0.01 mm/s



v=0.05 mm/s



v=0.2 mm/s

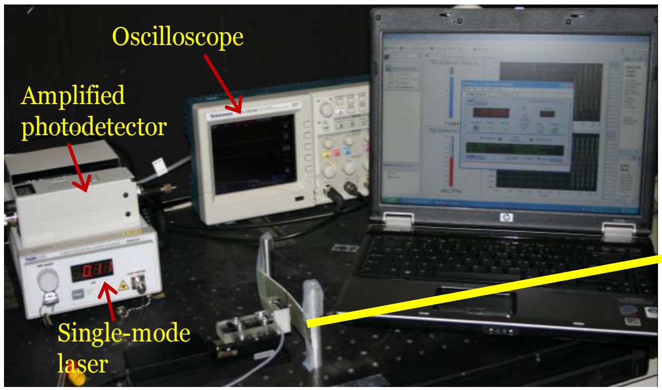


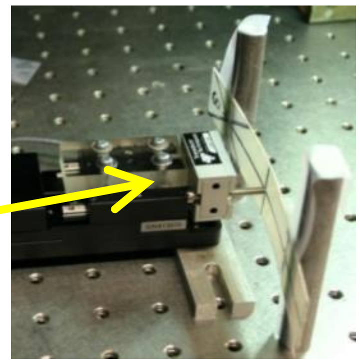
v=0.4 mm/s

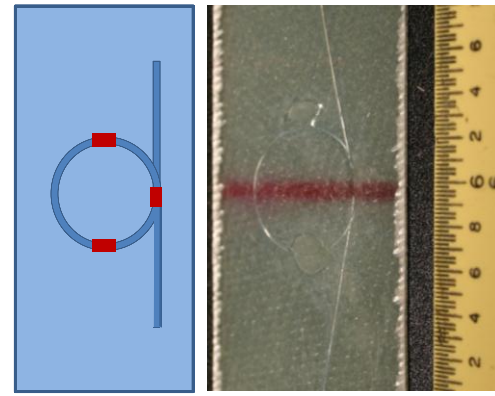
- Loop radius: 6 mm
- Displacement: 6 mm

SHM of laminated composites

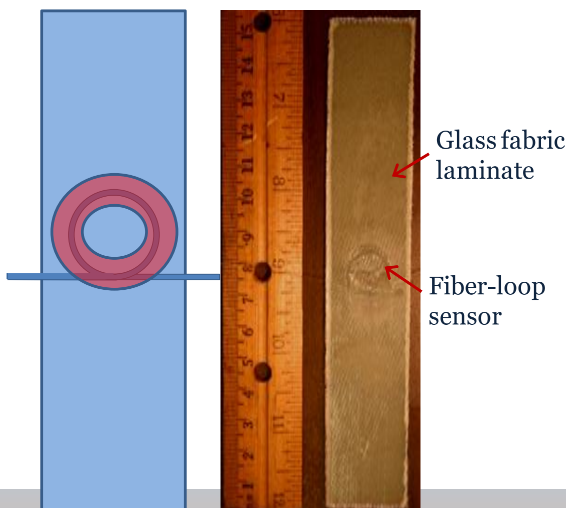
- Loop sensors bonded to laminated composites under flexural loading



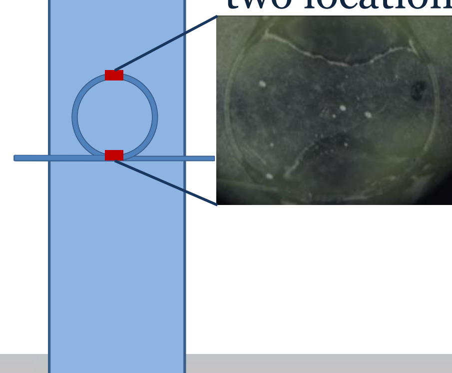


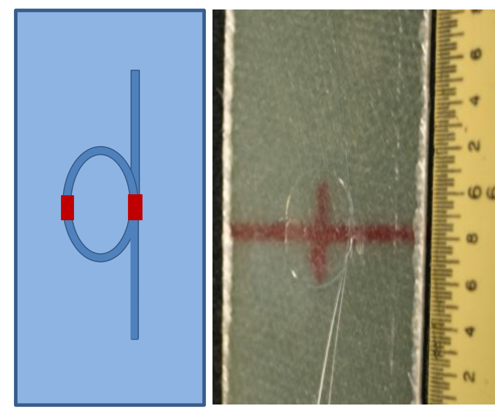


Full surface bonded



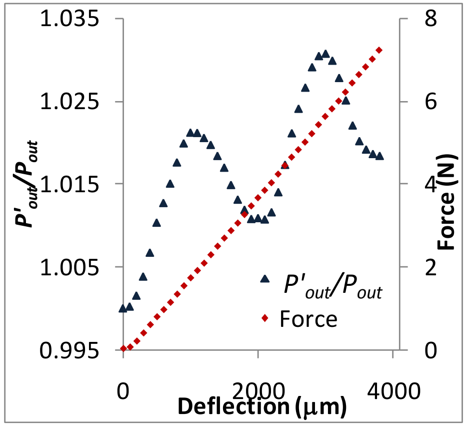
Bonded at two locations



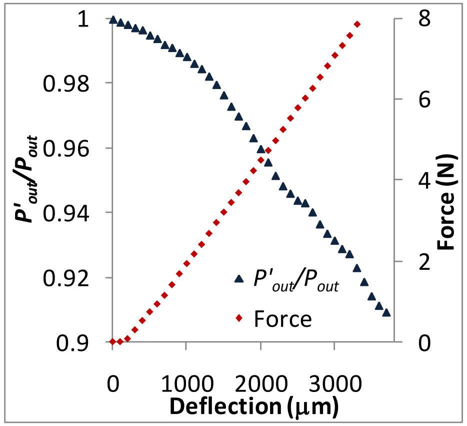


Pre-compressed loop

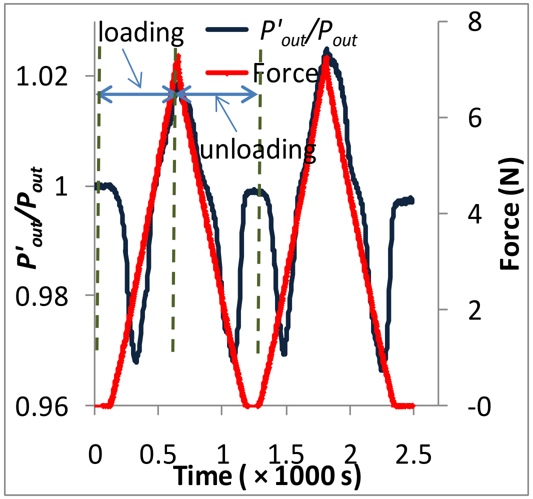
SHM of laminated composites



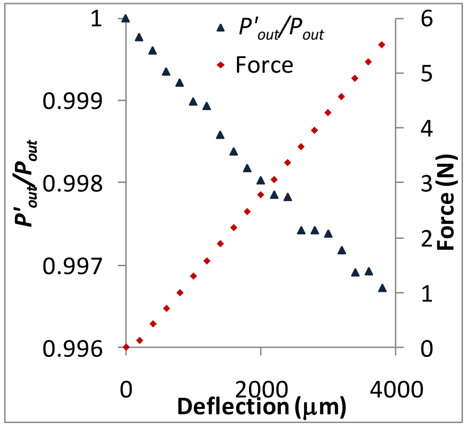
R_B =4.9 mm



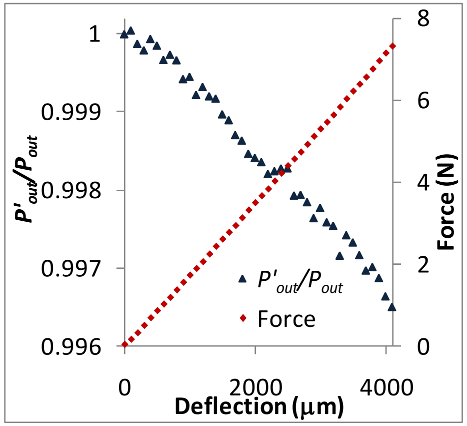
R_B =5.9 mm



Quasi-static loading on loop of radius 6 mm

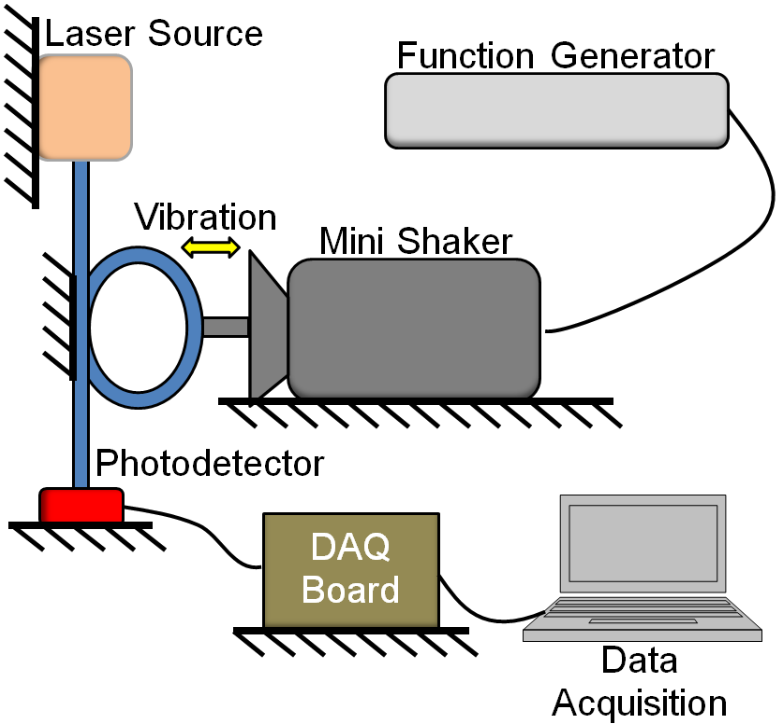


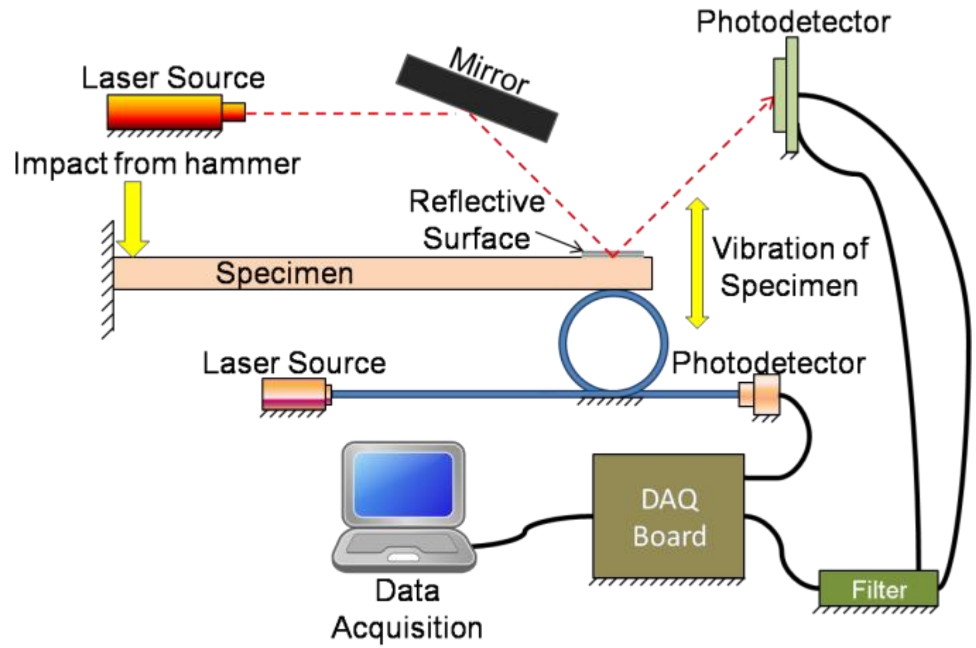
R_B =6.2 mm



R_B =6.5 mm

Vibration Measurement

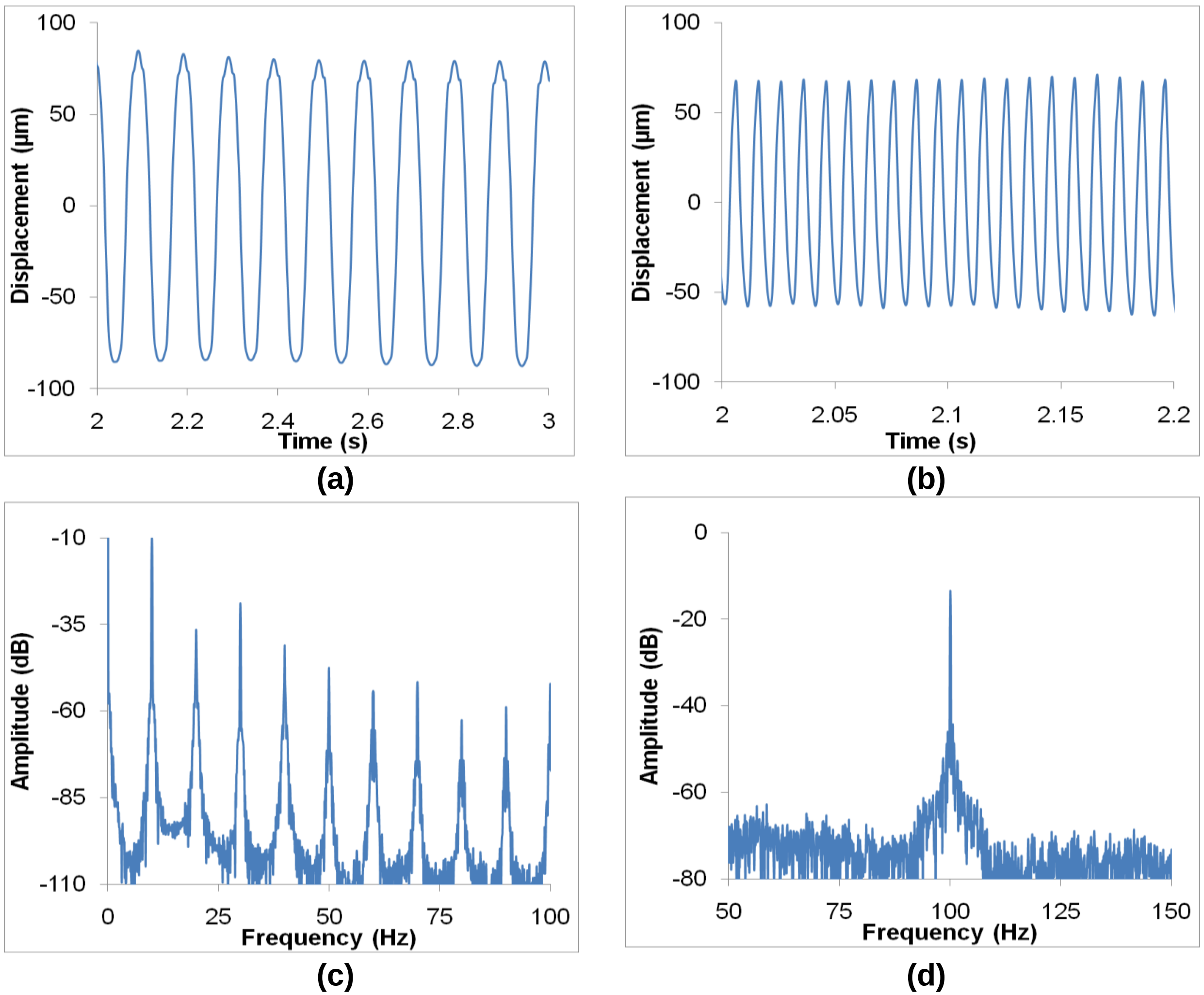




Optical fiber loop sensor setup for calibration of vibration measurement

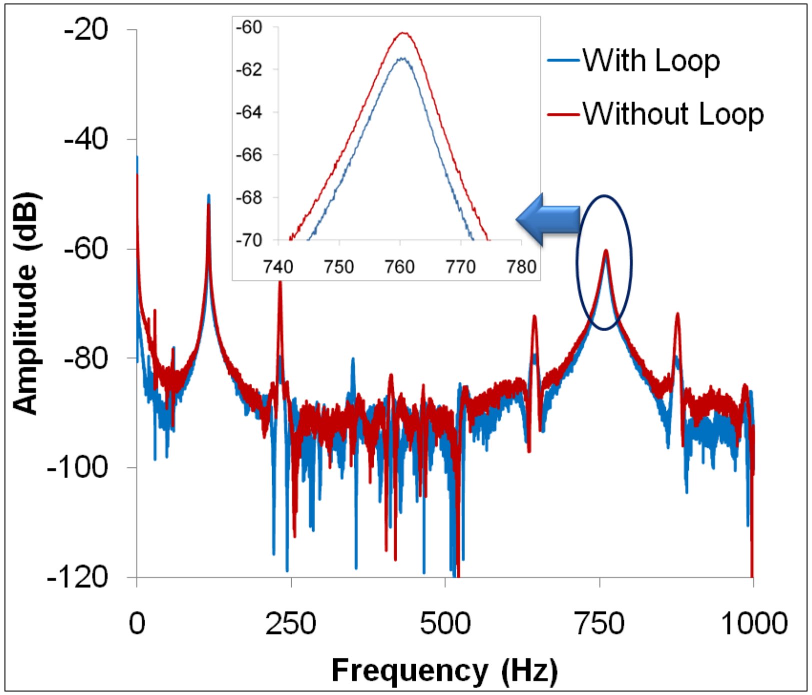
The setup used for measuring the free vibration characteristics of a composite material.

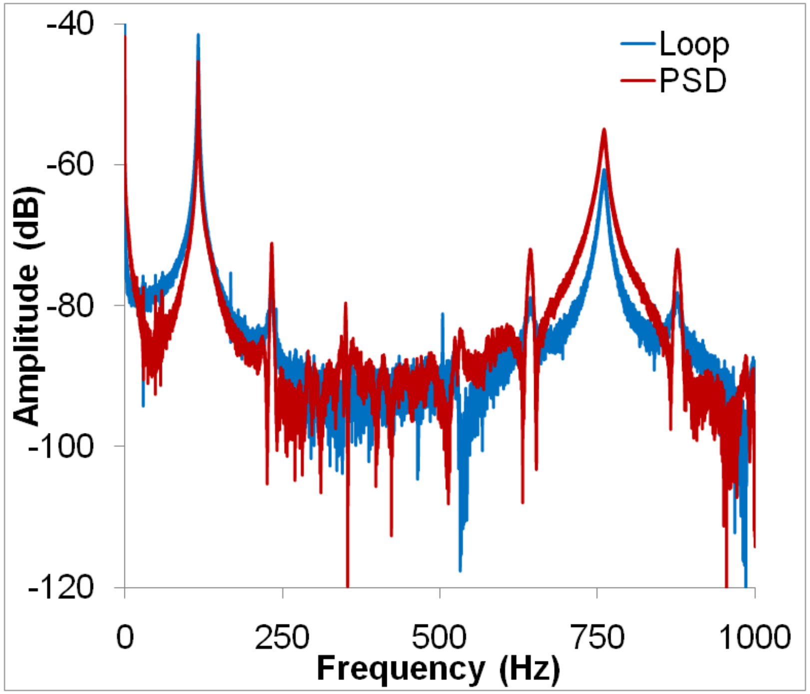
Vibration Measurement



- The Vibration measurements are accurate and match with the frequency of the shaker
- No fatigue or hysteresis is observed for over 10,000 cycles

Results and Discussion





- The system is tested with and without optical fiber sensor using only a PSD
- Then the output of the sensor is related to the PSD measurements

Conclusions

- A low-cost, high sensitivity loop-sensor has been developed for stress or strain measurement
- The sensor can be used in dual measurement ranges for displacement
- The sensor shows survivability in large number of loading cycles
- Use of loop-sensor for vibration measurement is possible
- Potential applications in chemical sensing

Acknowledgements

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- Dr. Volkan Otugen's group at Southern Methodist University, Dallas