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A photonic wall pressure sensor for fluid mechanics applications

M. Manzo, T. Ioppolo, U. K. Ayaz, a) V. LaPenna, and M. V. Ötügen
Southern Methodist University, Dallas, Texas 75205, USA

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In this paper, we demonstrate a micro-optical wall pressure sensor concept based on the optical modes of dielectric resonators. The sensing element is a spherical micro-resonator with a diameter of a few hundred micrometers. A latex membrane that is flush mounted on the wall transmits the normal pressure to the sensing element. Changes in the wall pressure perturb the sphere’s morphology, leading to a shift in the optical modes. The wall pressure is measured by monitoring the shifts in the optical modes. Prototype sensors with polydimethylsiloxane micro-spheres are tested in a steady two-dimensional channel flow and in a plate wave acoustic tube. Results indicate sensor resolutions of ~20 mPa and bandwidth of up to 2 kHz. © 2012 American Institute of Physics.

I. INTRODUCTION

In recent years, several optical devices have been proposed based on the excitation of optical modes of dielectric micro-resonators. These optical resonators with spherical, cylindrical or toroidal geometries vary in size from a few micrometers to several hundreds of micrometers and exhibit very large optical quality factors Q = λ/δλ (λ is the excitation wavelength and δλ is the linewidth of the excited optical mode). The optical modes are typically called morphology dependent resonances or whispering gallery modes (WGM) and, as their name implies, they are highly sensitive to the morphology of the resonator. The WGM-based optical devices have been proposed in spectroscopy,1 micro-cavity laser technology,2 and optical communication, such as switching,3 filtering,4 wavelength division, and multiplexing.5 Optical modes (WGM) of spherical resonators have been tuned by mechanical strain6 and by heating,3 demonstrating their potential as actuators. Several sensor concepts have also been proposed for biological applications,7–9 trace gas detection,6,10 impurity detection in liquids,10,11 force,12,13 pressure,14 temperature,15 wall shear stress,16,17 electric18 and magnetic fields.19,20

The WGMs of dielectric resonators can be excited, for example, by coupling light from a tunable laser through an optical fiber.13 In the transmission spectrum through the optical fiber, these optical modes are observed as narrow dips in the intensity of the light. The large optical Q-factors observed with spherical WGM resonators make them attractive for sensor applications since the Q-factor is directly related to measurement resolution. The smaller the resonance linewidth, δλ, the higher the resolution in the detection of a WGM shift caused by an external effect. Q-factors as high as 1010 have been reported in the literature for dielectric micro-spheres,21 thus making these spheres excellent candidates for high-resolution sensing applications.

Significant attention has been focused on MEMS-based pressure sensors in the past several years. Based on their electric readout, MEMS pressure sensors are typically collected into three groups: piezoelectric,22–33 piezoresistive,34–40 and capacitive.41–46 Pressure sensors utilizing the piezoelectric transduction are reported to have durability, high sensitivity, and low noise. In addition, they do not require an external power source to operate. A drawback of piezoelectric sensors is that they tend to have a limitation on the measurement bandwidth (typically limited to a few kHz). Capacitive sensors offer high sensitivity and dynamic range; however, they have high impedance, which requires an impedance buffer to be integrated close to the sensor. Piezoresistive sensors generally have low sensitivity and require temperature compensation for accurate measurements.

In this paper, we demonstrate a novel wall pressure sensor based on dielectric micro-spheres and uses the WGM transduction technique. The changes in the fluid pressure acting on a membrane attached to the sphere perturb the shape of the sphere causing a shift in its WGM. The proposed WGM-based wall pressure sensor shows promise for high sensitivity with high dynamic range. The sensor is immune to electromagnetic interference, which can impede the operation of MEMS sensors. In addition, the performance characteristics (sensitivity, bandwidth and dynamic range) can be optimized by using sensor materials (dielectric sphere) with different mechanical properties (Young’s modulus, loss tangent, etc.).

II. SENSOR DETAILS

A. Measurement principle

The sensor concept is based on the whispering gallery optical mode shifts of a dielectric sphere. The optical mode shifts are due to the perturbations of the sphere morphology caused by the fluctuations in pressure exerted on the sphere by the fluid. By tracking the WGM shifts, the flow pressure can be measured. The optical scheme to monitor sphere optical modes is similar to that described in our earlier work (see Refs. 12 and 13). The WGMs are excited by coupling light from a tunable diode laser into a micro-sphere using a single-mode optical fiber as shown in Fig. 1. The optical fiber serves as an input/output port for the micro-sphere. In order to
facilitate light coupling between the sphere and the fiber, a section of fiber is tapered by heating and stretching it until the nominal diameter of the fiber is $\sim 10 \mu m$. The tapered section, which has a length of $\sim 1$ cm, is brought into contact with the sphere. Light from a tunable distributed feedback (DFB) laser with a central wavelength of $\sim 1.3 \mu m$ is coupled into one end of the optical fiber and the other end is terminated at a photodiode. The wavelength of the laser is swept over a narrow range ($\sim 0.1$ nm) and the optical modes are observed as sharp dips in the transmission spectrum through the fiber (as depicted in Fig. 1). Any external effect, such as pressure, that perturbs the morphology of the sphere (shape, size or refractive index) induces a blue- or redshift of the dips in the transmission spectrum. By monitoring these shifts, the physical effect causing the perturbation in the sphere morphology can be determined.

Ray optics provides a simple description of the WGM of spheres. Laser light tangentially coupled into a micro-sphere in the fashion shown in Fig. 1 travels along the interior surface of the sphere through multiples of total internal reflections (provided that the sphere’s refractive index is greater than that of the surrounding medium). When the total round trip traveled by the light is a multiple integer of the laser wavelength, a WGM of the sphere is excited. For the case of $a \gg \lambda$ (where $a$ is the sphere radius and $\lambda$ is the vacuum wavelength of the laser light),

$$2\pi n_0 a \approx l\lambda.$$  \hspace{1cm} (1)

Here, $n_0$ is the sphere refractive index and $l$ is an integer (circumferential mode number). Any perturbation to the size or the refractive index of the sphere will lead to a shift in the optical modes as

$$\frac{d\lambda}{\lambda} = \frac{dn_0}{n_0} + \frac{da}{a}. \hspace{1cm} (2)$$

Thus, an external effect (such as pressure) that perturbs the sphere’s morphology can be detected by monitoring the WGM optical modes of the transmission spectrum.

The optical quality factor, $Q$, is a factor in determining the measurement resolution; smaller $\delta\lambda$ lead to smaller minimum measurable WGM shift. The typical quality factor associated with the polydimethylsiloxane (PDMS) spheres used in this study is $Q \sim 10^6$. Such high $Q$-factors cannot be reached by planar interferometric systems, such as Fabry-Perot instruments and Bragg gratings, which typically render smaller $Q$ values.

B. Sensor design

Figure 2 is a schematic of the prototype sensor. It is a circular cylinder with an outer diameter of $\sim 25$ mm and plugs into the test section wall with the top measurement surface flush with the wall. The active components of the sensor are a PDMS micro-sphere and a latex membrane. The nominal thickness of the membrane is in the range between 50 $\mu m$ and 75 $\mu m$ and transmits the fluid pressure to the sphere. The edge of the membrane is sandwiched between two circular brass plates of 300 $\mu m$ thickness using loctite epoxy as adhesive. The opening at the center of the brass plates is 1.4 mm. The pressure acting on this 1.4 mm diameter section of the membrane is transmitted to the sphere at the contact point between the sphere and the membrane. A change in the wall pressure either compresses or decompresses the sphere perturbing its equatorial diameter on the plane normal to the wall surface. A higher fluid pressure leads to the compression of the sphere, resulting in a redshift of the WGM. Conversely, a lower pressure de-compresses the sphere leading to a blueshift of the WGM. As shown in Fig. 2, the plate-membrane system is mounted on a cylindrical case of
The PDMS sphere is a mixture of polymer base and a curing agent (Sylgard 184 elastomer kit). The polymer base is a viscous fluid. However, when it is mixed with the curing agent, polymer chains form cross-links leading to the solidification of the mixture. The stiffness of the cured mixture can be varied by using different base-to-curing agent ratios; larger base-to-curing agent ratios lead to softer spheres. We carried out experiments with several different spheres having base-to-curing agent mixing ratios ranging between 10:1 and 60:1 by volume. The sphere diameter was kept constant (∼900 μm) throughout. As indicated in Fig. 1, the sphere is in contact with the tapered section of an optical fiber. One end of the fiber is connected to a DFB diode laser and the other end is terminated at a photodiode.

C. Opto-electronic setup

The opto-electronic setup for the sensor system is shown schematically in Fig. 3. The distributed feedback laser with a nominal wavelength of 1.3 μm is current tuned over a range of about 0.1 nm. The laser controller is driven by a function generator that provides it with a sawtooth waveform input. The bias and amplitude of the waveform determine the laser’s central wavelength and tuning range, respectively. The output of the laser is split into two single mode fibers with 90%–10% power ratio. At the other end, the output of each fiber is coupled into a fast photodiode (PDA10CS by Thorlabs). The fiber carrying the higher laser power goes through the sensor and interrogates the sphere’s modes (signal). The light through the other fiber is used as a reference. By normalizing the signal with the reference, the effect of temporal variations in laser intensity is eliminated. The output of the signal and reference photodiodes are pre-amplified and fed into a 14-bit analog-to-digital converter (A/D) to be analyzed on a personal computer (PC). The A/D is triggered by the same function generator that provides input to the laser controller.

D. Signal processing

Changes in the flow pressure on the top side of the membrane of the sensor (Fig. 2) deform the sphere, causing WGM shifts in the transmission spectrum. Short segments of typical transmission spectra for three gage pressures (0, 44, and −22 Pa) are shown in Fig. 4. The sensor in this case has a 950 μm diameter 10:1 PDMS sphere. The positive gage pressure causes a redshift in WGM dip and the negative gage pressure causes a blueshift. Signal processing software (developed in-house) tracks these shifts in the spectrum at each scan of the laser and determines the corresponding flow pressure. Each scan of the laser results in a single pressure measurement. In the present study, the laser is scanned (and transmission spectrum is captured) at different rates for steady and unsteady measurements. The laser is scanned at 100 Hz for the steady measurements and at 10 kHz for the dynamic measurements (resulting in pressure data rates of 100 samples/s and 10 ksamples/s, respectively). Digitized data are stored on the PC for post-processing to determine pressure.

The digitized signal (transmission spectra) for each laser scan is first normalized by the optical reference to remove the effect of laser power fluctuations. Then, a cross-correlation technique is used to determine the WGM shift at time t = t₀ + Δt relative to a reference spectrum that is acquired at time t₀ that represents zero gage pressure (Fig. 3). The location of the largest peak in the resulting cross-correlation function is then compared to that of the autocorrelation peak of the reference spectrum (obtained at t₀) to determine the WGM shift value. This shift is then used to determine the gage pressure through a calibration constant.
respectively, the force acting on the sphere is

$$F_s = \frac{k_m P \pi R^2}{k_s + k_m},$$

(3)

Using plate theory for a clamped thin plate the spring constant of the membrane can be expressed as

$$k_m = \frac{16\pi E t^3}{3R^2(1 - \nu^2)},$$

(4)

where $\nu$, $E$, and $t$ are the Poisson’s ratio, Young’s modulus, and thickness of the membrane. The spring constant for the sphere can be estimated using Hertz contact theory. In a previous study, we used Hertz contact theory to estimate the deformation of a sphere under compressive force between two plates. Here, we will carry out a similar analysis to estimate the response of the current pressure sensor. Figure 6 is a schematic showing the deformation of the sphere sensor under uniform pressure. The deformation of the sphere can be obtained by solving Navier equation,

$$\nabla^2 u + \frac{1}{1 - 2\nu} \nabla(\nabla \cdot u) = 0,$$

(5)

where $u$ is the displacement of a given point within the sphere. For the azimuthally symmetric loading, assuming frictionless contact between the sphere and membrane, the solution of

Eq. (5) is

$$u_r = \sum_n \left[ A_n(n + 1)(n - 2 + 4\nu)r^{n+1} + B_n(nr^{n-1}) \right] P_n(\cos \theta),$$

(6)

where $r$ and $\theta$ are the radial and polar coordinates, respectively (Fig. 6); $u_r$ is the radial component of displacement; $P_n$ is the Legendre polynomial; $A_n$ and $B_n$ are constants determined by the boundary condition at the sphere surface. Stress distributions within the sphere can be derived from Eq. (6) as

$$\sigma_{rr} = 2G \sum [A_n(n + 1)(n^2 - n - 2 - 2\nu)r^n + B_n(nr^{n-2})] P_n(\cos \theta),$$

(7a)

$$\sigma_{r\theta} = 2G \sum [A_n(n^2 + 2r - 1 + 2\nu)r^n + B_n(n - 1)r^{n-2}] \frac{d P_n(\cos \theta)}{d \theta},$$

(7b)

where $G$ is the shear modulus of the sphere material. The pressure force exerted by the membrane on a sphere of radius $a$ can be expressed as

$$P(\theta) = \frac{3F_S}{2\pi a_0^2} \sqrt{a_0^2 - a^2 \sin^2(\theta)} \sin \theta d\theta,$$

$$a_0 = \left[ \frac{3F_S(1 - \nu^2)}{4E} \right]^{1/3}.$$

(8)

In this equation, $a_0$ is the radius of contact area as shown in Fig. 6 and $E$ is the Young’s modulus. The boundary conditions for the stress are as follows (see Ref. 13): The normal stress at sphere surface within the contact area is $\sigma_{rr} = -P(\theta)$ and is zero elsewhere. The stress distribution can be obtained by expanding the stress at the contact area as a Legendre series in the spherical coordinates with coefficients (Ref. 13)

$$H_n = \int_0^{\pi/2} P_n(\cos \theta) \frac{3F_S}{2\pi a_0^2} \sqrt{a_0^2 - a^2 \sin^2(\theta)} \sin \theta d\theta.$$

(9)

Here, $F_S$ is the force acting on the sphere expressed in Eq. (3). The radial deformation of the sphere at $\theta = \pi/2$ can be obtained by satisfying the boundary conditions. Then, using Eq. (2), the sensitivity of the pressure sensor can be expressed as

$$\frac{d\lambda}{dP} = \frac{k_s \lambda R^2}{k_s + k_m} \sum_n \frac{H_n}{4GF_S(n^2 + 2n + n + v + 1)} \times \left[ 2 - 4n^2 + v(4n^2 - 2n - 4) \right] P_n(0).$$

(10)

The radius of the latex membrane is $R \approx 0.7$ mm, and its thickness is in the range $t = 50–75$ $\mu$m. This yields a spring constant of $k_m = 7.38$ and 18.73 N/m for $t = 50$ $\mu$m and $75$ $\mu$m, respectively. For the $900$ $\mu$m diameter 60:1 mixing ratio PDMS micro-sphere used for the sensor, the Hertz contact theory yields a spring constant $k_s \approx 1.64$ N/m.

IV. SENSOR CALIBRATION

The optical pressure sensors were calibrated in a test chamber which is a simple piston-cylinder device (Fig. 7).
Each sensor was mounted on the dead end of the cylinder and the transmission spectra are recorded as the pressure in the chamber is varied by moving the piston. The chamber pressure was monitored independently by using a pressure transducer (PX277 by Omega). Figure 8(a) presents a typical time variation of the calibration data. In this case, the micro-sphere used is a ∼900 μm diameter 60:1 PDMS. Initially, the pressure chamber has atmospheric pressure. The piston is first moved forward to increase the pressure in the chamber and then moved back to reduce it.

Figure 8(a) shows strong qualitative agreement between the WGM shifts and the pressure recorded by the transducer. The corresponding calibration curve is presented in Fig. 8(b).

The analytical prediction using Eq. (10) is also shown in the figure for membrane thicknesses of $t = 50 \mu m$ and 75 μm. The calibration (experimental data) yields an average sensitivity (or gain factor) of $d\lambda/dP = 6.674 \text{ pm/Pa}$. Note that sensitivity is a function of sphere diameter and Young’s modulus of the material. The sensitivity is lower for sensors with smaller base-to-mixing agent ratio PDMS spheres due to the larger Young’s moduli. With a conservative assumption that the minimum measurable WGM shift is $\delta\lambda = \lambda/Q$, typical WGM sensor resolution can be expressed as

$$
\delta p = \frac{\lambda}{Q} \left( \frac{d\lambda}{dp} \right)^{-1}.
$$

Sensor resolution given in Eq. (11) can be further improved by utilizing better signal processing methods. For example, the signal processing method described in Sec. II D provides a shift detection resolution of ∼0.13 pm. For our studies, this is equivalent to having a sensor Q-factor of $10^7$ for Eq. (11). With this tracking method, the sensitivity provided in Fig. 8(b) results in a pressure resolution of ∼20 mPa.

V. RESULTS

Proof-of-concept experiments were carried out to validate the optical wall pressure sensor under steady and unsteady flow conditions. A two-dimensional channel flow is used for the steady flow experiments while the unsteady experiments were carried out in a plane wave acoustic tube.

A. Steady flow experiments

The sensor is tested in a two-dimensional airflow channel that is shown schematically in Fig. 9.

The height and span of the channel are 4.76 ± 0.05 mm and 160 mm, respectively, resulting in an aspect ratio of ∼33. This large cross-sectional aspect ratio ensures a two-dimensional flow in the span-wise mid-section. The test section is far enough from the entrance (800 mm) so that the flow in the test region is fully developed for most of the flow rates considered. The optical pressure sensor and a pressure tap are flush mounted on two opposite walls. The streamwise pressure is measured using a piezotransducer (PX277 by Omega). The flow is driven by a suction fan placed at the outlet of the channel. The fan is driven by a dc motor connected to a variable voltage supply. The flow rate can be continuously varied by varying the voltage input to the dc motor. Figure 10
FIG. 10. Results of channel flow experiment. (a) Time variation of WGM shift and wall pressure measured by piezotransducer; (b) comparison of optical sensor results with that of piezotransducer.

shows a typical experimental result with the setup of Fig. 9. The WGM shifts and the corresponding wall pressures measured by the transducer as the flow rate is slowly increased and then decreased are shown in Fig. 10(a). The ramping up and down of the flow rate is slow enough to consider the flow as steady. The pressure measurement by the optical sensor is determined using the calibration curve of Fig. 8(b). The solid line ($y = x$) in Fig. 10(b) indicates a perfect match between the optical sensor and the pressure transducer. The measured pressure by the optical sensor is about 10% higher than that indicated by pressure transducer. A likely cause of this discrepancy is the induced cavity flow effect at the optical sensor surface. As indicated in Fig. 2 and Sec. II B, the active part of the sensing surface is a circular cavity with diameter 1.4 mm and edge height 0.3 mm rendering an aspect ratio of 4.7. For the next iteration of the sensor, a number of design options can be implemented to reduce or eliminate the cavity effect. These include using a thinner ring on the outside surface of the membrane, tapering the inner edge of this ring or implementing a combination of both.

B. Unsteady flow experiments

The unsteady measurements are carried out in a plane wave acoustic tube that is designed and built in-house specifically for this purpose (Fig. 11). The setup consists of a ~183 cm long clear acrylic tube with wall thickness of 3 mm and diameter of ~12.7 cm. On one end of the tube, a JBL 2446 J speaker is placed to drive the acoustic waves. A conical foam section is placed to fill the other end as shown. The purpose of the conical acoustic foam is to absorb the acoustic energy and prevent wave reflections at the tube’s end. A 3 mm diameter microphone (Brue & Kjaer 4138) and the WGM wall pressure sensor are flush mounted opposite to one another at a distance of 0.38 m from the speaker. Signals from the WGM sensor and the microphone are acquired simultaneously by the analog-to-digital converter.

First, the performance of the plane wave tube was tested to ensure that acoustic waves are planar at the measurement location. This is accomplished by driving the speaker with 1 mW input power and comparing the microphone response at the measurement location to that provided by the speaker manufacturer for plane wave response. Two sets of measurements are taken to validate the plane wave tube’s response and their averaged result is plotted in Fig. 12. As shown in the figure, the variation of sound pressure level with acoustic frequency is in good agreement with the manufacturer’s specification indicating a nearly planar wave front at the measurement location.

Next, wall pressure measurements were carried out in the plane wave tube. The acoustic waves create an oscillating flow with streamwise velocity $u = u(t)$ at the measurement location. This way, the optical sensor is tested for dynamic response not just as a microphone (for acoustic pressure) but also as a wall pressure sensor under unsteady flow conditions. The speaker was driven sinusoidally and the frequency is varied between 300 Hz and 2 kHz. Measurements from WGM pressure sensor and the microphone are recorded simultaneously. Figure 13 shows representative results for two sensors; one with a 60:1 mixing ratio PDMS sphere and the other with...
a 40:1 PDMS sphere. Both spheres had a diameter of 900 μm. The figure shows measurements at 400 Hz (with 60:1 PDMS sphere) and 1.8 kHz (40:1 PDMS sphere) of flow oscillation frequency. At both frequencies the waveform pairs indicate a good agreement between the optical sensor output and the pressure transducer. The results also indicate that the sensor with 60:1 mixing ratio PDMS sphere (Fig. 13(a)) has a larger amplitude response to the applied pressure than that of the 40:1 sensor (Fig. 13(b)). Thus, the former with the softer sphere offers better sensitivity.

VI. CONCLUSION

A novel photonic wall pressure sensor concept based on the whispering gallery optical mode shifts of dielectric microspheres is proposed. A prototype sensor was developed and tested successfully in steady and unsteady flows. The mechanical properties of the dielectric sphere define the performance characteristics of the sensor including sensitivity and bandwidth. Several base-to-curing agent mixing ratio PDMS spheres ranging between 10:1 and 60:1 by volume were used to validate the sensor prototype. Larger mixing ratios result in softer spheres and higher sensitivities. For the 60:1 sphere sensor, a sensitivity of $|\Delta \omega| = 6.674 \text{ pm/Pa}$ is obtained. For a given device sensitivity, the measurement resolution is determined by the smallest measurable WGM shift, $\delta \omega$. This in turn, is dependent on the optical quality factor, $Q$, and the number of digitized samples for each scan of the transmission spectrum. For the present spheres with quality factors in the range $Q \sim 10^5$–$10^6$, we obtained $\delta \omega \approx 0.13 \text{ pm}$ resulting in a pressure resolution of 20 mPa. As in many other sensors, sensitivity and bandwidth present a tradeoff. Higher sensitivities result in lower measurement bandwidth. Therefore, high bandwidth measurements may require stiffer spheres (lower base-to-mixing ratio PDMS) resulting in reduced measurement resolution. In the unsteady measurements, acoustic frequencies were extended up to 2 kHz with no observable degradation in the sensor performance.

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