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F1.2 Parallel-Wrapped Optical Fiber Interferometric Ellipsoidal Shell Acoustic Sensors

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Introduction

High sensitivity interferometric acoustic sensors have been demonstrated using optical fiber interferometry and ellipsoidal shells. A new push-pull winding scheme has been tested in which circular windings of optical fiber are bonded to the pole(s) and to the equator of an ellipsoidal shell. Previous push-pull ellipsoids incorporated one leg of the interferometer around the equator and the second around the meridional circumference. In the new scheme the polar leg replaces the equatorial leg while maintaining the desired push-pull performance.

A thin oblate ellipsoidal shell produces surface strains of opposite sign when subject to a uniform pressure loading. Generally, if the aspect ratio, a/b, exceeds the quantity, (2 - v)1/2, where v is Poisson's ratio, the meridional circumferential strain will be compressive, while the equatorial circumferential strain will be tensile [Ref. 1-3]. If one winds optical fiber around these two principle circumferences, the differential strains can be detected in a push-pull fashion in the legs of an optical fiber interferometer. In this meridional / equatorial winding configuration, the two optical fibers comprising the legs of the interferometer cross at both the equator and crown of the shell, hence, we refer to this transducer as a "cross-wrapped" ellipsoidal shell. An illustration of the "cross-wrapped" ellipsoidal shell is provided in Figure 1a.

A disadvantage in the orientation of the optical fibers in the "cross-wrapped" design is that when using "squat" shells (large aspect ratio) a problem exists in exceeding the maximum bend radius of the optical fiber in the meridional leg as it crosses the equator. This restriction has motivated the discovery of a new winding approach that maintains the desired push pull detection and alleviates the bend radius limitation by using two "parallel" circular windings of optical fiber. A fiber optic oblate push pull flextensional transducer can be obtained by using a parallel fiber wrapping technique in which one leg is wound on the equator of the ellipsoid and the second circular (parallel) fiber winding is wound or bonded to the poles of the oblate ellipsoid. An illustration of the "parallel-wrap" design is provided in Figure 1b.

Theoretical Sensitivity

The acoustic sensitivity of an interferometric transducer is the amount of relative phase induced between the legs of the interferometer per unit pressure applied to the transducer. The major contribution of phase change arises from the axial strain in the optical fiber(s). The axial strain also induces a change in the index of refraction of the optical fiber, resulting in a contribution to the total phase modulation that is approximately 20% of direct length change contribution and of opposite sign. If we make the assumption that all of the optical fiber in one leg is placed on the "true" equator of the ellipsoid and that all of the optical fiber in the second leg is placed near the pole at a radial distance x perpendicular to the axis of rotation of the ellipsoidal shell, then the acoustic sensitivity of the "parallel-wrapped" optical fiber ellipsoidal shell transducer can be shown to be [Ref. 3]

$$\Delta \phi \over \rho = \Xi \frac{2\pi n a^2 \pi}{\lambda} \left[ \frac{a^2 + (1 - v) x - b (2 - v)}{b^2} \right].$$

(1)

The multiplicative factor, $\Xi$, accounts for the reduction in sensitivity due to the photoelastic effect and is approximately equal to 0.80, $\xi$ is the interferometer configuration parameter which accounts for the number of passes of light through the sensing fiber before it combines interferometrically, n.
is the index of refraction of the optical fiber core, \( \lambda \) is the vacuum wavelength of the light, a is the semi-major axes of the ellipse, b is the semi-minor axes (the axis of rotation for an oblate spheroid), E is the Young's modulus, \( \nu \) is Poisson's ratio, and x is the Cartesian coordinate equal to the radius of the circular wrap of optical fiber near the pole of the shell.

Figure 1. Illustration of a) "cross-wrapped" ellipsoid, b) "parallel-wrapped" ellipsoid.

Separation of regions of compressional and tensile strain: Nodal circles

It is of interest to determine the coordinate at which the circular strain changes sign. This "nodal circle" will set the practical limit to which optical fiber of a given interferometric leg could be wrapped while still exploiting the intrinsically differential nature of the interferometer. The location of the nodal circle in terms of the x coordinate of the ellipse can be shown to be [Ref. 3]

\[
\frac{x_n}{a} = \sqrt{\frac{1 - \nu}{2 - \nu} \left( 1 - \frac{b^2}{a^2} \right)}.
\]

(2)

The \( \theta \)-strain or circular strain (normalized by the factor \( \frac{P}{2E} \)) is plotted versus \( \phi \) in Figure 2, where \( \phi \) is the angle between the radius of curvature (to a meridional segment) and the axis of revolution, b. The \( \theta \)-strain is plotted on the same graph as a function of the true azimuthal polar angle, \( \phi_{\text{polar}} \). Note that the strain does indeed change sign reaching a relative maximum at the equator (\( \phi_{\text{polar}} = \phi = \pi/2 \) radians). Also note that for a given strain, \( \phi \leq \phi_{\text{polar}} \), and that the strain is relatively constant near the pole in the range \( \pm 0.5 \) radians in \( \phi_{\text{polar}} \). The relationship between \( \phi \) and \( \phi_{\text{polar}} \) is given below

\[
\phi_{\text{polar}} = \tan^{-1}\left( \frac{a^2 \tan \phi}{b^2} \right)
\]

(3)
The normalized $\theta$-strain plotted versus $\phi$ (the angle associated with the radius of curvature) and plotted as a function of the polar angle, $\phi_{\text{polar}}$ for a Poisson's ratio $= 0.4$ and an aspect ratio, $a/b = 2$.

**Fabrication**

An oblate spheroidal shell was constructed using Stycast™ 1266 castable epoxy to test the parallel wrap fiber optic detection scheme. The aspect ratio of the finished oblate spheroidal shell, $a/b$, was 1.96, with the major axis equal to 10.36 cm (outer diameter) and the minor axis equal 5.28 cm (outer diameter). The actual shell thickness of the Stycast™ spheroid varied from a high of 0.91 mm (0.036 inches) at the both the equator and the poles to a low of 0.81 mm (0.032 inches) between the pole and the equator of the shell. In the azimuthal direction, the shell thickness was uniform with variations less than 0.001 inches. The finished polar coil of optical fiber had an inner radius of 1.6 cm and an outer radius of 3.9 cm and a total length of 4.00 meters of active fiber. The fiber on the equator consisted of 12 turns of optical fiber for a total active equatorial length of 3.83 m.

**Optical sensitivity measurements**

The optical fiber was first wound around and then epoxied to the equator of the ellipsoid, keeping the second leg detached from the sensor, in order to obtain sensitivity measurements of the individual leg of the interferometer. The acoustic sensor (with temporary reference leg wrapped as a pancake coil to be later mounted on the pole of the ellipsoid) was inserted into a cylindrical coupler calibrator. Using a fringe counting calibration measurement technique, the measured acoustic sensitivity of the single interferometric leg was found to be $0.99 \pm 0.02 \text{ rad/Pa}$. Data was obtained in the frequency range from 30 to 100 Hz. Noting the radian path length of the 4.02m equatorial leg, we arrive at a normalized sensitivity based on measurement of $\Delta \phi/\phi \Delta p = 1.14 \times 10^{-8} \text{ Pa}^{-1}$ or $-279.2 \text{ dB re } \mu\text{Pa}^{-1}$.
The second leg of the interferometer was then epoxied to the pole (one pole only) and the push-pull performance of the alternative winding scheme was fully tested. A photograph of the sensor placed in the calibrator is shown in Figure 3. The average overall sensitivity using both legs was determined to be 1.44 rad/Pa. The push pull performance was clearly demonstrated since the addition of the second leg increased the sensitivity from 0.99 to 1.44 rad/Pa for a net increase of 0.45 rad/Pa. The normalized sensitivity, obtained by dividing the radian path length by the average interferometer leg length, is -276 dB re μPa⁻¹.

Figure 3. Photograph of the fiber optic oblate ellipsoidal acoustic sensor inside the calibrator with the polar and equatorial legs attached to the sensor.

REFERENCES