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Finite element analysis of stress influence on reflection type fiber optic probe hydrophone output

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1. Introduction

Demands for sound pressure measurement under sever situation like high temperature or high intensity cavitation increases. However, conventional hydrophones are hard to be applied to such a severe environment. The authors have attempted to employ a Fiber Optic Probe Hydrophone (FOPH), which is expected to be durable under cavitation and has excellent heat and chemical resistance.[1, 2)]

A lot of reports on FOPH application are already reported.[3, 4)] The author also investigated the influence of cavitation bubble corruptions from 20kHz to 400kHz. The principle of FOPH measurement is based on diffraction index change in the proportional to media density variation. Until now, the authors have considered diffraction index change in front of the probe. Since some sound propagates through the fiber, light intensity inside the fiber is also affected by the optical fiber deformation. In this report, the effect of stress inside the fiber on the sensitivity of FOPH was investigated using finite element analysis (FEM).

2. Conventional Sensitivity Equation

The configuration of the differential FOPH circuit used in this study is shown in **Fig. 1**. The ASE (Amplified Spontaneous Emission) light source bifurcated by a photocoupler produces reflected light at the tip of an optical fiber placed in a liquid. The reflection intensity changes with the change in refractive index due to sound pressure fluctuations and is converted to a current by a photodiode. The I-V converter converts the reflected light into a voltage value, which passes through an amplifier and is measured by an oscilloscope for data acquisition. Conventionally, the observed voltage is converted to sound pressure by the sensitivity formula S_F V/Pa using Eykman's formula.

$$S_F = -\frac{4n_f R_w P P_{loss} S_{PD} R_F A(n_w - 1)(n_w{}^2 + 1.4n_w + 0.4)}{(n_f{}^2 - n_w{}^2)(n_w{}^2 + 0.8n_w + 1)c^2\rho} \quad (1)$$

where n_f is the refractive index of unstressed optical fiber core, n_m is the refractive index of the medium, R_w is the reflectance at the interface between the end surface of the optical fiber and the medium, R_F is the feedback resistance of the I-V conversion circuit, S_{PD} is the sensitivity of the photodiode, A is the amplification factor of the amplifier circuit, P is the output of the ASE light source, P_{loss} is the optical loss due to the connecting connector, c is the speed of sound, and ρ is the density of the medium. Since each parameter value is known, we obtain the sensitivity $S_{SF} = -0.2075$ V/MPa in water for FOPH by ignoring the deformation inside the fiber.

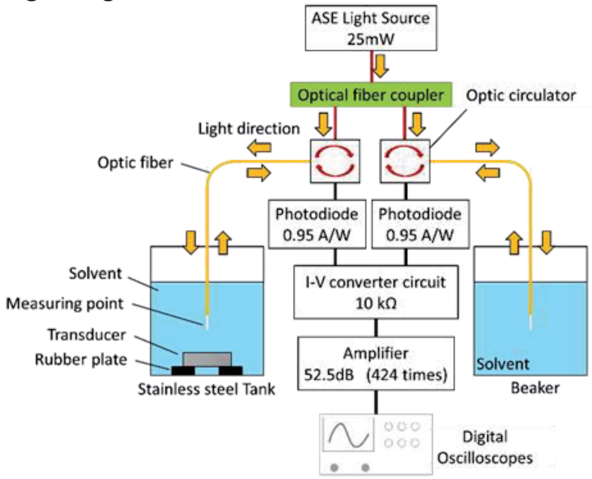

Fig.1. FOPH configuration

3. Sensitivity Considering Fiber deformation

When an external force is applied to glass or plastic, photoelastic effect occurs. It is well known that stress on an optical fiber changes the refractive index of the optical fiber core n_f.[5)] Sound pressure of which ultrasonic wave propagates through the fiber also exerts stress on optical fibers and thus changes n_f. However, the sensitivity equation S_F in Eq.(1) is derived assuming that n_f is independent of sound pressure. Therefore, we must examine the effect of stress due to sound pressure on n_f.

Assume that only the axial stress component σ_z is directly related to the optical intensity variation inside the axisymmetric fiber and that other stress components does not affect the optical intensity.[5)] Assuming a linear elastic body, the refractive index change of the optical fiber core due to the stress exerted by sound pressure can be expressed as follows.

$$\frac{\Delta n_f}{\Delta P} = -C_2 A_\sigma \quad (2)$$

In quartz glass, $C_2 = 4.39 \times 10^{-6}$/MPa and A_σ is

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the proportionality constant of σ_z due to sound pressure.[5ff)] Then, the sensitivity equation S_{SF}, considering the effect of stress due to sound pressure, is rederived by the following equation.

$$S_{SF} = \frac{4n_m R_W P P_{loss} S_{PD} R_F A}{n_f^2 - n_W^2} \cdot \left(-C_2 A_\sigma\right) + S_F \quad (3)$$

Since all parameters except A_σ are known, the sensitivity can be calculated considering the stress by finding A_σ.

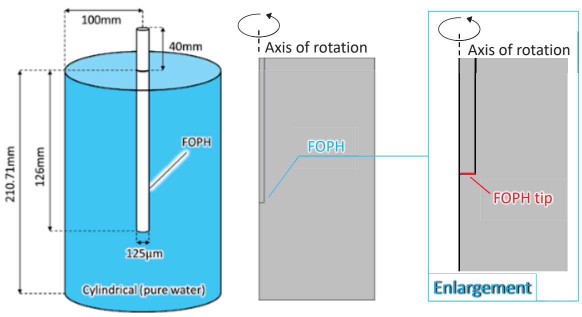
4. Result of Finite Element Analysis (FEM)

A linear acoustic-structure coupled harmonic analysis was carried out using FEM (COMSOL Multiphysics, KEISOKU Engineering, Inc.). The analytical model shown in **Fig. 2** is the axisymmetric cylindrical shape to reduce computational cost, FOPH diameter is 125 µm in the same as the clad diameter and FOPH material is quartz glass. The medium is water. The boundary conditions are as follows: the cylinder sides are fixed boundaries, the top surface (water surface) is a free boundary, and the boundary between the FOPH and the water is an acoustic-structure boundary. Sound pressure is set on the bottom of the cylindrical shape. Assuming the short optical fiber, the standing wave might generate inside the fiber.

The value of σ_z is calculated while changing the observation points shown in **Fig. 3**(b) in the axial direction of the optical fiber. The frequency of incident sound is 35.5kHz. Due to short fiber, the standing wave appears along Z direction. Since FEM analysis is linear, the axial stress σ_z is proportional to incident sound pressure on the radiation surface that changes from 1Pa to 400kPa. The result is shown in **Fig. 4**. In Fig. 4, horizontal is sound pressure at tip of FOPH and vertical is maximum σ_z inside the fiber.

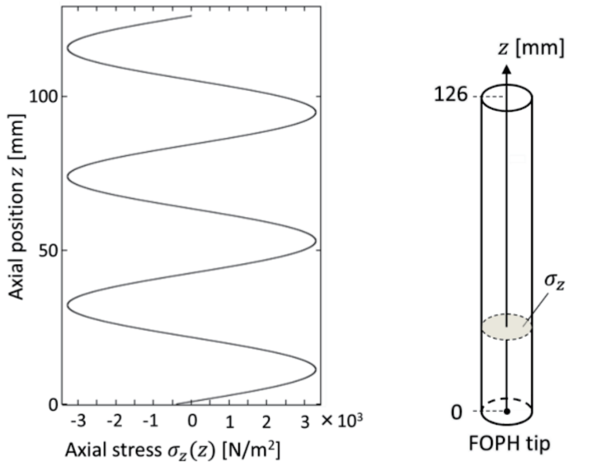
$$-C_2 A_\sigma = -3.4 \times 10^{-5} [/\mathrm{Pa}] \quad (4)$$

As a resutl, a sensitivity $S_{SF} = -0.32$ V/MPa in Eq.(3). The obtained results is a most severe case because of assumption of the standing wave in the fiber. The variation of sensitivity is almost 50%.



(a)Assumed model (b)Axisymmetric geometry

Fig.2. Analytical model



(a) Result (b) Observation change

Fig.3. FOPH position and Axial stress

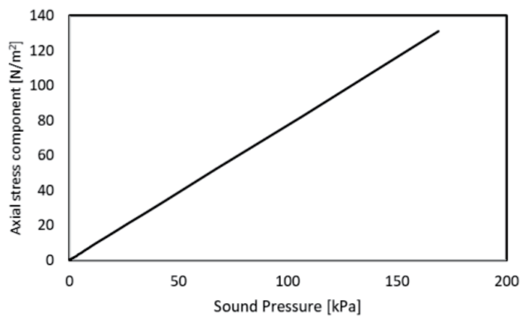


Fig.4. Sound Pressure and Axial Stress

6. Conclusion

The effect of stress insider the fiber on the sensitivity of FOPH was investigated using FEM. Assuming the standing wave generation inside the fiber, the variation of sensitivity is not negligible. In the future, we plan to investigate the accuracy of the measurement result under severe environment.

Acknowledgment

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