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Sensitivity Study of Fiber Optic Ultrasonic Probe Based on the Modulation in the Refractive Index of Air

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ABSTRACT

In this report, a method of measuring intense ultrasonic field in air using a fiber optic probe is studied, where the modulation of optical reflectivity at the end of the optical fiber provides the absolute value of sound pressure through a change in the refractive index of air. The effects of humidity, temperature and atmospheric pressure on the absolute sensitivity of the probe are discussed, and the correction formula is presented for the absolute sound pressure. The measurements of standing wave fields exited between a piston transducer and a reflector and comparison with a commercial probe-type condenser microphone are carried out to confirm the theory. The error with the proposed probe was 8-14% compared with the B&K 4138 condenser microphone.

INTRODUCTION

In most aerial ultrasound applications, the wave length is short and the field exists in a small space[1]. We previously proposed to utilize the modulation of the optical reflectivity at the end of an optical fiber to measure the absolute value of sound pressure. We presented a formulation that showed the relationship between the sound pressure and the modulation in the reflected light intensity as well as a setup for the measurement[2]. In this report, by comparing with a commercial condenser microphone, a discussion about sensitivity is made.

PRINCIPLE AND SENSITIVITY

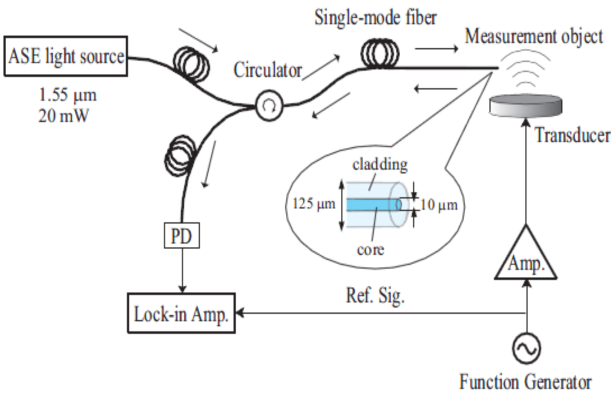

Figure.1 Principle and the optical setup.

A single-mode fiber is inserted in the sound field to be measured as shown in Fig.1. A broadband light centered at 1.55 μm is guided through the fiber and reflected at the end. The reflected light is returned through the same fiber, and detected by a GaAs photodiode(PD) via a circulator. The PD output is monitored using a lock-in-amplifier. We used the amplified spontaneous emission(ASE) noise of an Er-doped optical fiber amplifier (Furukawa ErFA1220) as the light source. The output power was maintained at 20 mW and the bandwidth of the spectrum was 40 nm. An SMF-28 compatible fiber was utilized: the diameter of the probe tip was 125 μm and its effective diameter for measurement was about 10 μm.

As reported in Ref.[2], the refractive index change of air Δn due to sound pressure can be expressed as a function of sound pressure p as

$$\Delta n = \frac{(n\ -1)p}{\rho c^2}, \qquad (1)$$

where ρ is the density, and c is the sound speed in air.

At the end of an optical fiber, guided light is reflected with the reflection coefficient R ,

$$R = \left(\frac{n_f - n}{n_f + n}\right)^2 = 0.04 \cdot$$

Here, the refractive index of the fiber $n_f = 1.46$ and the refractive index of air $n = 1.00$. The change rate of the reflection coefficient is given by

$$\frac{R' - R}{R} = \frac{2\Delta n}{n_f - n} . \quad (2)$$

Using eqs.(1) and (2), the modulation of the reflectivity on coefficient at the end of the fiber can be expressed as

$$\frac{R' - R}{R} = 2\frac{n - 1}{n_f - n}\frac{p}{\rho c^2} . \quad (3)$$

From this equation, we can obtain absolute sound pressure by measuring the AC and DC components of the reflected light intensities.

EFFECT OF HUMIDITY, TEMPERATURE AND ATMOSPHERIC PRESSURE

Sound speed and density are functions of the temperature, the vapor pressure and the atmospheric pressure.

$$c = 331.45\sqrt{(1 + \frac{T}{T_0})(1 + 0.3192\frac{p_w}{P_0})} , \quad (4)$$

where P_0 is the atmospheric pressure, p_w is vapor pressure of air, T is absolute temperature and $T_0 = 273.15$ (K). Humidity (%) is calculated by $P_W/P_S \times 100\%$ with saturated water vapor P_s .

Density ρ in dry air can be expressed as

$$\rho_0 = \frac{1.293}{1 + 0.00367T}P_0 . \quad (5)$$

The density ρ under humidity is expressed as

$$\rho = \rho_0\sqrt{1 - 0.378\frac{p_w}{P_0}} . \quad (6)$$

Using eqs.(4)-(6), the sensitivity constant of the modulation in eq.(3) $2\frac{n - 1}{n_f - n}\frac{1}{\rho c^2}$ is calculated at 1 atm for various temperature and humidity as shown as in Fig.2. The refractive index of air $n = 1.0002732$ at optical wavelength of 1.55 μm is used in this calculation.

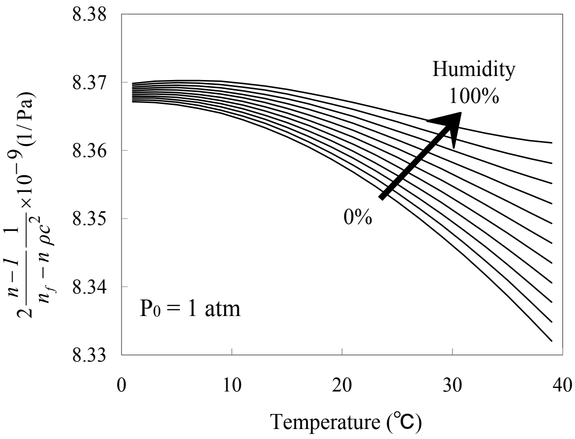

Figure.2 The sensitivity constant of the reflection coefficient at 1 atm for various temperature and humidity.

The sensitivity varies only 0.5% for the humidity and temperature range in Fig.2. But it changes approximately 4% for the atmospheric pressure range from 980 to 1010 hPa in dry air in Fig.3.

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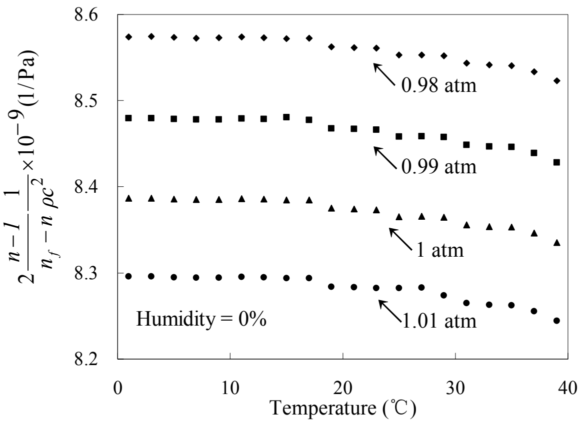


Figure.3 The sensitivity constant of the reflection coefficient in dry air for various temperature and atmospheric pressure.

On the other hand, the refraction index of air has a complicated relationship with the temperature, the vapour pressure and the atmospheric pressure as well. A formulation about the relationship presented by Owens[4] is

$$\begin{aligned}(n-1)\times10^8 = &\frac{P_s}{T}\left[2{,}371.34 + \frac{683{,}939.7}{(130-\sigma^2)} + \frac{4{,}547.3}{(38.9-\sigma^2)}\right] \\ &\times\left[1 + P_s\left(57.90\times10^{-8} - \frac{9.3250\times10^{-4}}{T} + \frac{0.25844}{T^2}\right)\right] \\ &+ \frac{P_w}{T}\left[6{,}487.31 + 58.058\sigma^2 - 0.71150\sigma^4 + 0.08851\sigma^6\right] \\ &\times\left\{1 + P_w\left[1 + \left(3.7\times10^{-4}\right)P_w\right]\times\left[\begin{matrix}-2.37321\times10^{-3} + \frac{2.23366}{T} \\ -\frac{710.792}{T^2} + \frac{7.75141\times10^4}{T^3}\end{matrix}\right]\right\}\end{aligned} \quad (7)$$

where σ is wave number（μm^{-1}）, P_s is the atmospheric pressure in dry air (hPa), T is temperature (K), Pw is vapour pressure (Pa). Using the optical wavelength of 1.55 μm, the refraction index of air can be obtained.

Fig. 4 shows the variation ratio of refractive index of air on the basis of atmospheric pressure 1013.3 hPa, temperature 293 K and humidity 50%. The variation ratio of refractive index of air can be expressed as

$$\frac{\left| n_{P_0+\Delta P, T_0+\Delta T} - n_{P_0, T_0} \right|}{n_{P_0, T_0} - 1},$$

where ΔP is the change of pressure on the basis of atmospheric pressure (1013.3hPa), ΔT is the change of temperature on the basis of the temperature 293K. The basis of humidity is 50%.

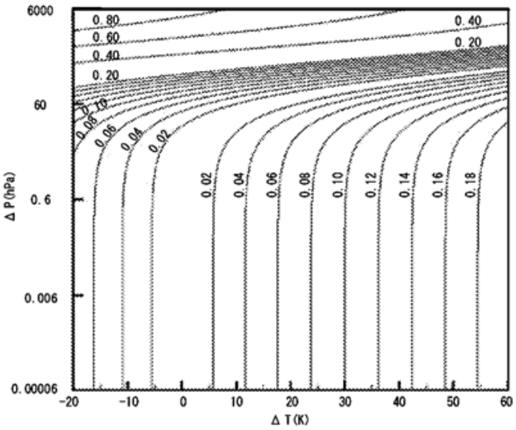


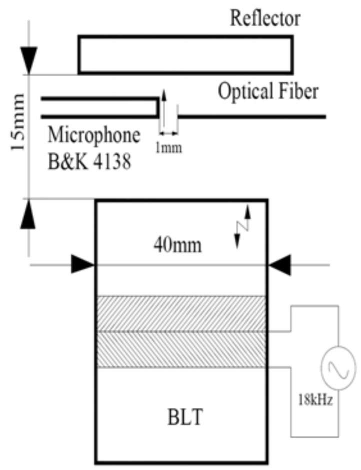
Figure.4 Variation ratio of refractive index of air by temperature and pressure.

The change of refractive index of air on the condition of the difference of pressure less than 0.6 hPa depends on the difference of temperature. In contrast, if the difference of pressure is more than 60 hPa, the pressure will have a great effect on the refractive index of air.

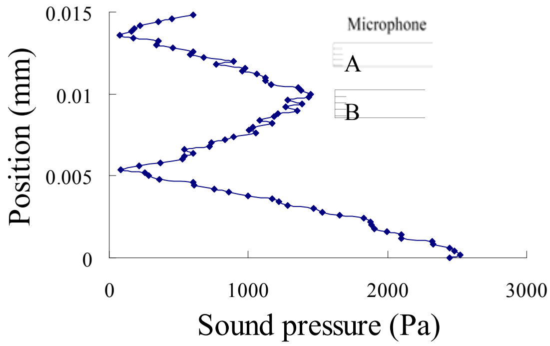
MEASUREMENTS OF THE SENSITIVITY

Experimental setup is shown in Fig.5(a). A standing wave field generated between a piston transducer and a reflector was measured. The distance between these devices was about a wavelength of the sound field of 18 kHz which is the resonance point. The diameter of the piston surface was 40 mm. The temperature was 26.8℃, the humidity was 65% and the atmospheric pressure was 1003 hPa. The sensitivity constant is calculated to be 8.4×10^{-9} /Pa. The vibration velocity of the piston is about 1.6 m/s and the peak sound pressure is in the order of 100-3000 Pa. The vertical distribution of the sound pressure measured by the fiber is shown in Fig.5(b).

For the sake of evaluating the absolute sensitivity experimentally, we compared the fiber with a commercial 1/8 inch condenser microphone (B&K Type 4138). We set the microphone between antinode and node (position A in Fig.5(b)), and at antinode(position B) , respectively. The fiber optic probe was faced with the microphone with an interval of about 1 mm inside the ultrasonic field as illustrated in Fig.5(a). The fiber probe is so thin that the sound pressure distribution across the diaphragm of the 1/8 microphone can be measured. The absolute sound pressures estimated from the optical reflectivity modulation using the theory stated before are summarized in Fig.6. Here, the sound pressure measured by the fiber represents the averaged value over the diameter of the microphone.



(a)



(b)

Figure.5 (a), Experimental setup; (b), Measurement of standing wave field.

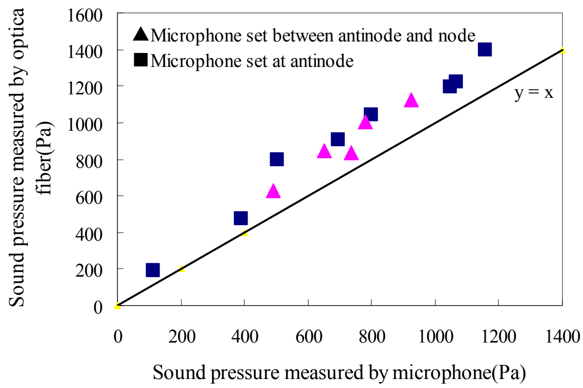


Figure.6 Comparison with microphone (B&K 4138).

The results obtained with fiber probe were 8-14% higher than that with B&K 4138.

Another experiment about the comparison between the microphone (B&K Type 4138) and the optical fiber at various frequencies (18.7kHz, 22kHz, 23kHz, 24kHz, 25kHz, 26.3kHz, 30kHz, 31kHz, 32.1kHz, 33kHz, 35.2kHz)was carried out. The maximum frequency which the microphone can measure is 36 kHz. Experimental setup is shown in Fig.7. The distance between the piston transducer and the reflector was about the diameter of the microphone. The temperature was 25.8℃, the humidity was 25% and the atmospheric pressure was 1013.3 hPa. The sensitivity constant is calculated to be 8.12×10^{-9} /Pa. The absolute sound pressures estimated from the optical reflectivity modulation using the theory stated before are summarized in Fig.8.

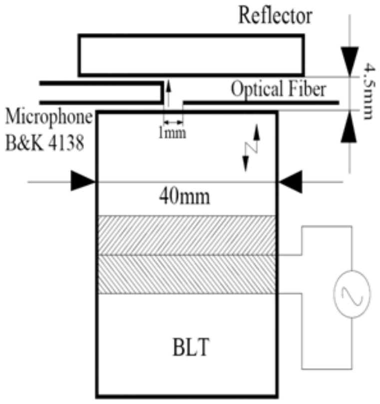


Figure 7. Experimental setup

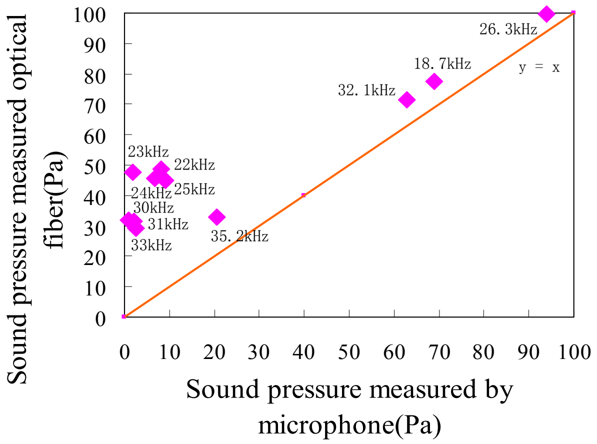


Figure.8 Comparison with microphone (B&K 4138) at various frequencies.

The results obtained with the fiber probe were still 10% higher than that with B&K 4138. The results with the fiber probe for less than 60 Pa in sound pressure showed unstable values. This might be the lower limit for the sound pressure measurement using the setup utilized in the experiment.

CONCLUSIONS

The dynamic range of the optical fiber in this experiment is about 60Pa~3000Pa. In addition, absolute sensitivity of the fiber optic probe for sound pressure measurement was discussed by comparing the theoretical value with the measured one using a commercial 1/8 condenser microphone. The error was +8~14% for 18~35 kHz standing wave field in air.

The cause of the error is left for future study. Unwanted acoustic responses of the optical components such as circulator should be eliminated.

REFERENCES

[1] Y. Ito. Jpn. J. Appl. Phys. 42, 2990 (2003)

[2] H. Takei, T. Hasegawa, K. Nakamura and S. Ueha. Jpn. J. Appl. Phys. 46(7B), 4555-4557 (2007)

[3] J.C.Owens. Optical refractive index of air-Dependence on pressure, temperature and composition[J]. Applied Optics, Vol. 6, No. 1, pp. 51-59, 1967. 1