PAPER

Theoretical investigation on a microphone using optical reflection on curved surface

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Abstract: This paper proposes a microphone using a new principle, involving the optical reflection at the curved end surface of a thin glass rod or a glass fiber. This microphone uses the change in the optical total reflection area by the change in the refractive index by the sound pressure. The change ratio in the reflection area depends on the shape of the curved end. This paper investigates theoretically the effect of the curved end shape on the sensitivity for the spherical end and the parabola type end. The microphone is expected to have possibility of practical use, though the sensitivity is low. The sensitivity may be improved by the invention of curved end shape and the detection method. This microphone is expected to have good high frequency response as it can be made small and involves no mechanical vibration.

Keywords: Microphone, Refractive index, Optical reflection, Curved surface, Laser

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1. INTRODUCTION

Microphones are usually composed of two parts. One is the acousto-mechanical part and the other is the mechano-electric part. The acousto-mechanical part transforms the sound pressure into the mechanical vibration through a diaphragm which is vibrated by the sound pressure. The mechano-electric transducer transforms the mechanical vibration into the electric signal. The characteristics of a microphone depend on the refraction of sound and the vibration characteristics of the mechanical system. Ordinary microphones have complex mechanical structure and the frequency range is restricted by the characteristics of the mechanical vibration part. If a microphone with no diaphragm can be realized, most of the difficult problems restricting the characteristics of a microphone will be removed. A big advantage is expected to a microphone with no diaphragm. Therefore, the development of such a type of microphone is considered to be one of the important problems in the acoustics to expand the possibility in the acoustical measurement.

The laser and the optical fiber have been applied to

many fields of the measurements because of their excellent properties. They have properly employed in the measurement of the sound and vibration. A few research has been carried out on microphones for sound in air [1], one of which is a microphone with no diaphragm [2], though most of the microphones using optical fiber have been studied for hydrophone.

Several methods of acoustic field measurement using laser light emitted in the air have recently been reported. In these methods, the change of refractive index of air by the sound pressure is detected as the beam deflection or the change in wavelength or phase shift of laser light [3–6]. They can also be considered to be the microphones with no diaphragm, but they can measure the averaged sound pressure in some spatial extent. The measurement of the sound pressure in a narrow space is necessary for the acoustic measurement.

In this paper we propose the method for detecting the change in the refractive index of air by the sound pressure using the optical measurement technique and show the possibility of a microphone with no diaphragm. The fundamental principle of the proposed microphone and the investigation on the sensitivity of the system are described.

This microphone detects the sound pressure by mea-

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asuring the change in the intensity of reflected light using the total reflection at the boundary surface between the glass and the air.

2. PRINCIPLES

The proposed microphone is composed of a thin uniform glass rod. A light beam is emitted into the rod at an end and reflected at another end. The end where the light source is set is called as the end A and the other as the end B. The output of the microphone is obtained from the change in the reflected light. The rod is cut perpendicularly at the end A and has a curved shape at the end B. If the rod has an adequate shape at the end B, a part of the transmitted light penetrates the boundary surface and the other part is totally reflected. The intensity of the reflected light depends on the area of the total reflection. The area of the total reflection changes by the change in the refractive index of the surrounding air by the sound pressure. Thus the sound is detected by measuring the intensity of the light reflected at the end B.

The first problem is the relation between the sound pressure and the refraction coefficient. The next problem is the effect of the shape of the surface at the end B on the change in the area of the total reflection by the refraction coefficient.

2.1. Pressure and Refractive Index of Air

In a gaseous medium, the relation between the refractive index n_m and the density ρ is given by Lorentz-Lorentz's law as follows [7];

$$\frac{n_m - 1}{\rho} = K \quad \therefore n_m = 1 + K\rho \quad (1)$$

where K is a constant.

The equation of state of gas in the adiabatic change is

$$PV^\gamma = C \quad (2)$$

where P is the pressure of gas, V is the volume, γ is the ratio of specific heat and C is a constant. Considering the air of unit mass,

$$\rho = 1/V$$

accordingly,

$$\rho = \left(\frac{1}{C}\right)^{\frac{1}{\gamma}} P^{\frac{1}{\gamma}} \equiv aP^{\frac{1}{\gamma}} \quad (3)$$

where a is a constant. Substituting this equation into Eq. (1), the relation between the pressure and the refractive index of air can be expressed as follows;

$$n_m(P) = 1 + KaP^{\frac{1}{\gamma}} \equiv 1 + bP^{\frac{1}{\gamma}} \quad (4)$$

where b is a constant.

2.2. Sensitivity of Sound Pressure Detection

Two types of the shape of the surface at the end B are investigated in this paper. The first one is the spherical surface. The second one is the parabolic surface.

This paper assumes for the theoretical analysis that the plain light wave travels parallel to the axis of the glass rod of uniform material. Such the wave is considered to be approximately realized when the length of the glass rod is much longer than the diameter of the rod. The wave characteristic of light is ignored as the diameter is much longer than the wave length of the light. The reflection of returned light at the end A is also ignored because the returned light should be guided to the light sensor. But the measurement method of the returned light is not yet determined. So, it can be said in this stage that this paper investigates only the possibility of the measurement of sound by this type of microphone.

2.2.1. Spherical surface end

Figure 1 shows the shape of the spherical end of the cylindrical glass rod of radius R where a reflection path of an incident ray I is drawn. The nomenclatures for calculation are also shown in the caption for Fig. 1. The direction of the ray I is assumed to be parallel to the axis of the glass rod. The distance between the ray I and the axis is y and the incidence angle of the ray to the spherical surface is θ . If $y \geq h$, θ exceeds the critical incidence angle θ_c and the incident ray I is totally reflected at the surface and the reflected light is again totally reflected at the other point on the surface as the incidence angle is unchanged in a spherical surface. Therefore, the ray I is totally reflected and returns to the rod if $y \geq h$. The intensity of the returned light is proportional to the area of the total reflection. The total reflection area depends on the refractive index of the surrounding air which is changed by the sound pressure. Therefore, the sound pressure can be measured by using the

Fig. 1 Principle of sound pressure measurement (spherical surface).

reflected light.

The microphone sensitivity is estimated by the change due to the sound pressure in the intensity of the total reflected light which is proportional to the area between the radius h and the radius R in the cross section of the glass rod.

The total intensity of the catoptric light, S is expressed as a function of h as follows;

$$S(h) = I(\pi R^2 - \pi h^2) = I\pi(R^2 - h^2) \quad (5)$$

The angles, θ and θ_c , are

$$\theta = \sin^{-1}\left(\frac{h}{R}\right), \quad \theta_c = \sin^{-1}\left(\frac{n_m}{n_0}\right) \quad (6)$$

Therefore, when $\theta = \theta_c$,

$$\sin^{-1}\left(\frac{h}{R}\right) = \sin^{-1}\left(\frac{n_m}{n_0}\right) \quad \therefore h = \frac{n_m}{n_0} R \quad (7)$$

Substituting this equation into Eq. (5)

$$S(n_m) = I\pi \left\{ R^2 - \left(\frac{n_m}{n_0} R \right)^2 \right\} = W \left(1 - \frac{n_m^2}{n_0^2} \right) \quad (8)$$

where $W = I\pi R^2$ is all the amount of incident light.

And substituting Eq. (4) into Eq. (8), we obtain the following equation.

$$\begin{aligned} S(P) &= W \left\{ 1 - \frac{n_m^2(P)}{n_0^2} \right\} \\ &= W \left\{ 1 - \frac{\left(1 + bP^{\frac{1}{\gamma}} \right)^2}{n_0^2} \right\} \end{aligned} \quad (9)$$

The pressure sensitivity $\sigma_S(P)$ is obtained as the efficiency of change in $S(P)$ by the pressure P as follows;

$$\begin{aligned} \sigma_S(P) &= \frac{1}{W} \frac{dS(P)}{dP} = -\frac{2b}{n_0^2 \gamma} P^{\left(\frac{1}{\gamma}-1\right)} \left(1 + bP^{\frac{1}{\gamma}} \right) \\ &= -\frac{2}{n_0^2 \gamma P} n_m(P) \{ n_m(P) - 1 \} \end{aligned} \quad (10)$$

2.2.2. Parabolic surface end

Figure 2 shows the shape of the parabola type end of cylindrical glass rod of radius R where the path of an incident and reflected rays is drawn. The direction of the incident ray I is parallel to the axis of the glass rod. The direction of the ray reflected twice at the end surface is also parallel to the axis as the surface is parabola. The distance between the incident ray I and the axis x of the glass rod is h . Using x - y coordinate written in this figure, the ray I travels on the line $y = h$.

The coordinate of the focal point F of the parabola is $(p, 0)$. That is, the distance from the tip of the glass rod to the focal point is p . Every incident ray parallel to the rod axis passes the focal point after reflected.

Fig. 2 Principle of sound pressure measurement (parabolic surface).

h_1 is the value of y coordinate for a ray of incident angle θ_c the critical angle. The y coordinate of the point of the second reflection of this incident ray is $-h_2$. There is the relation $\theta + \phi = \pi/2$ between the incidence angles θ and ϕ . After the second reflection the ray travels backward. Both θ and ϕ should exceed the critical angle θ_c for the backward traveling light to exist. If ϕ is less than θ_c , the ray penetrates the surface at the second reflection point and there is no backward traveling light. ϕ is equal to θ_c for the incident ray which travels on $y = h_2$. The incident ray does not travel to the backward direction if $h > h_2$.

Therefore, the value of h is between h_1 and h_2 for the backward traveling light to exist and the area of the total reflection becomes the cross section of the rod between h_1 and h_2 .

And the next condition,

$$\theta_c < \frac{\pi}{4}, \quad (11)$$

is necessary for the existence of reflected light.

The tangents of the incident angle at the point A and B are as follows;

$$\tan \theta = \frac{h}{2p}, \quad \tan \phi = \frac{2p}{h} \quad (12)$$

Using Eq. (6),

$$\tan \theta_c = \frac{\sin \theta_c}{\sqrt{1 - \sin^2 \theta_c}} = \frac{\left(\frac{n_m}{n_0} \right)}{\sqrt{1 - \left(\frac{n_m}{n_0} \right)^2}} = \frac{h_1}{2p} \quad (13)$$

Therefore, h_1 and h_2 are expressed as following equations.

$$h_1 = 2p \frac{\left(\frac{n_m}{n_0}\right)}{\sqrt{1 - \left(\frac{n_m}{n_0}\right)^2}}, \quad h_2 = \frac{4p^2}{h_1} = 2p \frac{\sqrt{1 - \left(\frac{n_m}{n_0}\right)^2}}{\left(\frac{n_m}{n_0}\right)} \quad (14)$$

Then the total intensity of the catoptric light S is obtained as the function of h as follows;

$$S(h) = I\pi(h_2^2 - h_1^2) \quad (15)$$

$S(h)$ is also expressed as the function of refractive index of air as follows;

$$S(n_m) = 4p^2\pi I \left\{ \frac{1 - \left(\frac{n_m}{n_0}\right)^2}{\left(\frac{n_m}{n_0}\right)^2} - \frac{\left(\frac{n_m}{n_0}\right)^2}{1 - \left(\frac{n_m}{n_0}\right)^2} \right\} \quad (16)$$

$$= \left(\frac{2p}{R}\right)^2 W \left(\frac{n_0^2 - n_m^2}{n_m^2} - \frac{n_m^2}{n_0^2 - n_m^2} \right)$$

Since n_m is a function of the pressure, the efficiency of change in S due to the pressure is expressed as the function of P .

$$\frac{dS(P)}{dP} = -2W \left(\frac{2p}{R}\right)^2 n_0^2 n_m(P) \frac{dn_m(P)}{dP} \times \left\{ \frac{1}{n_m^4(P)} + \frac{1}{[n_0^2 - n_m^2(P)]^2} \right\} \quad (17)$$

Using Eq. (10), therefore, the pressure sensitivity $\sigma_P(P)$ is obtained as the following equation.

$$\sigma_P(P) = \frac{1}{W} \frac{dS(P)}{dP}$$

$$= \sigma_S(P) \left(\frac{2p}{R}\right)^2 n_0^4 \left\{ \frac{1}{n_m^4(P)} + \frac{1}{[n_0^2 - n_m^2(P)]^2} \right\} \quad (18)$$

2.3. Estimation of the Sensitivity

2.3.1. Spherical surface end

To estimate the sensitivity of sound pressure detection, we use

$$n_0 = 1.4567, \quad n_m(P_0) = 1.0002716, \quad \gamma = 1.403 \quad (19)$$

at an atmospheric pressure ($P = P_0 = 1,013$ hPa) and 20°C in temperature. Then, substituting Eq. (19) into Eq. (10), we obtain

$$\sigma_S(P_0) = -1.802 \times 10^{-9} \quad [\text{Pa}] \quad (20)$$

Although n_m contains a constant b , we do not need to know the value of b because $n_m(P_0)$ is used for the calculation of the sensitivity at an atmospheric pressure.

The value in Eq. (20) indicates that the sensitivity is too low to use this microphone for an ordinary use, but it is

possible to use it as a pressure sensor in high-pressure region.

2.3.2. Parabolic surface end

As the radius of the rod R is made larger than h_2 , following equation is obtained.

$$\left(\frac{2p}{R}\right)^2 = \frac{1}{q^2} \frac{\left\{\frac{n_m(P_0)}{n_0}\right\}^2}{1 - \left\{\frac{n_m(P_0)}{n_0}\right\}^2} = \frac{0.892}{q^2} \quad (21)$$

Where, $R = qh_2$ ($q > 1$).

Substituting this equation and the values in Eq. (19) into Eq. (18), the sensitivity in parabola type surface is obtained as follows;

$$\sigma_P(P_0) = \frac{7.21}{q^2} \sigma_S(P_0), \quad (q > 1) \quad (22)$$

If q is chosen close to 1, the sensitivity becomes about seven times higher than that in the case of spherical surface.

2.4. Effect of Surrounding Conditions

Since the refractive index of air changes by the change in the surrounding conditions such as temperature, atmospheric pressure, humidity and concentration of CO_2 , the sensitivity can be affected by those conditions.

The refractive index of air is approximately given by the following equation around the industrial normal state (temperature: 20°C , atmospheric pressure: 760 mmHg, vapor pressure: 10 mmHg, concentration of the CO_2 : 0.03%) for the red light of He-Ne laser [8].

$$(n_m - 1) \times 10^6 = 271.30 - 0.93(\theta - 20) + 0.36(p - 760) - 0.05(f - 10) + 0.02(k - 3) \quad (23)$$

where θ is the temperature in $^\circ\text{C}$, p and f are the atmospheric pressure and the vapor pressure in mmHg, respectively, and k is the concentration of the carbon dioxide in 0.01% unit. In these conditions, the temperature and the atmospheric pressure affect the refractive index much larger than the other conditions do.

Using Eq. (23), the sensitivity in the spherical surface at the industrial normal state is obtained as follows;

$$\sigma_S(P_0) = -1.800 \times 10^{-9} \quad [\text{Pa}] \quad (24)$$

When the temperature rises 1°C from the industrial normal state, the sensitivity in the spherical surface is given by substituting the value of the refractive index obtained from Eq. (23) at 21°C in temperature into Eq. (10). The sensitivity at 21°C is obtained by the numerical computation as follows;

$$\sigma_S(P_0) = -1.793 \times 10^{-9} \quad [\text{Pa}] \quad (25)$$

The difference between Eq. (24) and Eq. (25) is about 0.4%. And the efficiency of change in temperature at $20^\circ\text{C}(\theta_0)$ can be calculated as follows;

$$\begin{aligned}\sigma_S(\theta_0) &= \frac{1}{W} \frac{dS(n_m)}{d\theta} \bigg|_{\theta=\theta_0} = \frac{1}{W} \frac{dS(n_m)}{dn_m} \frac{dn_m}{d\theta} \bigg|_{\theta=\theta_0} \\ &= -\frac{2}{n_0^2} n_m(\theta_0) \times (-0.93 \times 10^{-6}) \\ &= 0.877 \times 10^{-6} \quad [\text{Pa}]\end{aligned}\quad (26)$$

It is found that the change of the temperature has an effect upon the refractive index, which causes the changes in the amount of reflected light. But the sensitivity of the sound pressure detection is almost independent of the temperature if the change is slow.

Calculating the sensitivity at 1,023 hPa in atmospheric pressure,

$$\sigma_S(P_0) = -1.7998 \times 10^{-9} \quad [\text{Pa}] \quad (27)$$

The difference between Eq. (24) and Eq. (27) is about 0.01%. Hence, the sensitivity of the sound pressure detection is almost independent of slow change of the atmospheric pressure.

The same conclusion can be made for the change of the humidity and the concentration of carbon dioxide.

3. CONCLUSION

This paper proposes a microphone which detects the change in the refractive index of air due to the sound pressure using the optical total reflection on the curved end surface of a glass rod. The feasibility of this type of microphone is proved in this paper.

The pressure sensitivity is investigated theoretically for the spherical end and the parabolic end. The sensitivity of the microphone whose end shape is a parabola type is higher than that of a spherical type in seven times. But the sensitivity of the microphone of parabolic type is only about 10^{-8} /Pa, this value shows that the practical use of the microphone is limited in a high-pressure region. The sensitivity should be much improved for the ordinary use. The practical use of this type of microphone depends on a remarkable improvement in the sensitivity. The sensitivity should be much improved if we use only the changing part of the reflected wave.

It is shown that the change in the surrounding conditions, such as temperature, atmospheric pressure or humidity, has almost no effect on the pressure sensitivity if their fluctuations are slow, although the change of those conditions affect the refractive index much larger than the sound pressure.

According to our successive investigation, we have found a promising method to improve the sensitivity. We are going to establish the new method for improving the sensitivity and to carry out the experimental investigation.

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