Evaluation of Damping Ratio in a Glass-Based Guided-Wave Optical Microphone with a Diaphragm

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ABSTRACT

In a guided-wave optical microphone with a diaphragm used as a vibration plate, damping of diaphragm vibration is very significant in order to realize broad flat frequency response. In this study, a glass-based guided-wave optical microphone without a damping structure was experimentally examined to evaluate the damping ratio as the first phase in the optimization of damping. Damping ratio and resonance frequency were successfully evaluated to be 0.009 and 3.5 kHz, respectively, for a fabricated microphone with a diaphragm of 20 mm × 20 mm × 0.15 mm.

Keywords: microphone, diaphragm, damping, frequency response, integrated photonics, glass waveguide

1. INTRODUCTION

In clinical Magnetic Resonance Imaging (MRI) and functional MRI (fMRI), microphones are useful tools for patient-to-physician communication. Dynamic microphones based on the electromagnetic effect however, cannot be used under the strong magnetic fields during MRI operation. Also, condenser microphones are also unacceptable in the MRI scanner room since the metal parts of the microphones degrade the MR image. On the other hand, microphones using lightwave sensing technology are available even in high magnetic fields such as an MRI, because such optical microphones are not susceptible to electromagnetic interference and do not require metal parts. A number of optical microphones have been developed to detect sound waves even under strong electromagnetic fields.[1,2] Our group has also demonstrated silicon-based and glass-based guided-wave optical microphones, consisting of a diaphragm and a waveguide across the diaphragm.[3,4] The guided-wave optical microphones have advantages such as alignment-free and stout configurations, compactness and lightness, in addition to immunity to electromagnetic interference.

Incidentally, frequency response is an important specification in microphones, and damping of the vibration plate is essential to properly avoid resonance. As a background study, we experimentally examined the damping ratio for a glass-based optical microphone which did not contain a damping structure. The results would provide beneficial information toward the goal of realizing a damping ratio of 0.707. A guided-wave optical microphone with a diaphragm of 20 mm × 20 mm × 0.15 mm was fabricated, and its damping ratio was evaluated both from the frequency response (frequency domain measurement) and from the step response (time domain measurement). In the frequency response, damping ratio was determined to be 0.009 from the resonance characteristics around the first resonance frequency. Also, in the step response, damping ratio was evaluated to be 0.009 from the transient output after the applied acoustic sound is turned off. The reasonable damping ratios were successfully obtained from both frequency and time domain measurements.

2. PRINCIPLES OF SENSOR OPERATION

A glass-based guided-wave optical microphone consisting of a diaphragm and a single-mode optical waveguide on the diaphragm is shown in Fig. 1. A shielding plate with a small hole is required to protect the bottom of the diaphragm from diffracted sounds. The microphone is placed between a pair of crossed polarizers, which can be replaced with polarization-maintaining fibers. The input polarizer is oriented at 45° with respect to the polarizations of the fundamental TM-like and TE-like modes. As a result, the lightwave is coupled to both guided modes at equal intensities. When acoustic sound is applied to the diaphragm, the diaphragm is distorted corresponding to the instantaneous sound pressure. The distortion causes strain, which produces a change in the refractive index of the waveguide on the diaphragm by the

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elasto-optic effect. The index change yields phase retardation in the lightwave, which propagates in the waveguide. Since phase retardation is dependent on the guided modes, phase difference between the two modes is a function of the pressure difference due to the applied sound. The lightwave has linear, elliptic, or circular polarization at the end of the waveguide, corresponding to the induced phase difference. The crossed output polarizer converts the polarization-modulated light into intensity-modulated light. The intensity of the lightwave passing through the output polarizer varies corresponding to the instantaneous acoustic pressure.

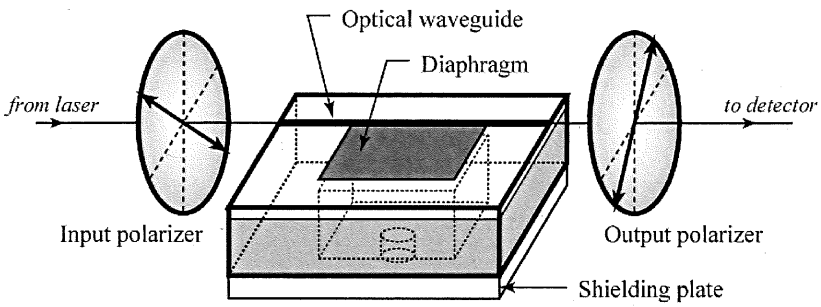

Figure 1 Configuration of a glass-based guided-wave optical microphone, which is placed between a pair of crossed polarizers.

3. DESIGN AND FABRICATION

Microphones require extremely high sensitivity to detect pressure of less than 1 mPa and broad frequency range from 20 Hz to 20 kHz. Unfortunately, for the glass-based guided-wave optical microphone, sensitivity increases with an increase in side length or a decrease in thickness of the diaphragm, while resonance frequency decreases. Since it is difficult to achieve both higher sensitivity and a broader frequency range, one of these conditions may need to be sacrificed in order to satisfy the other when designing the guided-wave optical microphone.

This study placed more weight on sensitivity than resonance frequency from the viewpoint of the S/N ratio. To detect normal speech, the target value of sensitivity was set at 2.5 mrad/Pa and above, and resonance frequency at 3 kHz or higher. Using a chart for design assistance, diaphragm dimensions were determined to be 20 mm× 20 mm× 0.15 mm.[4] According to the theoretical calculations, phase sensitivity and resonance frequency were 2.5 mrad/Pa and 3.4 kHz, respectively.

A schematic drawing of the fabricated optical microphone with actual dimensions is shown in Fig. 2. The microphone was built using two glasses: a Corning #0211 glass as a diaphragm plate and a soda-lime glass with a 20 mm×20 mm square hole to support the diaphragm plate. First, a thin aluminum film was evaporated on a Corning glass with a thickness of 0.15 mm. A waveguide pattern was engraved by photolithographic process on the aluminum film. Then, the glass was immersed in KNO_3 for two hours at 400°C to form the single-mode channel waveguides. The waveguides were adjusted to be parallel to the diaphragm edge, and then the two substrates were bonded by UV adhesion. Finally, a shielding plate with a small hole was attached to the microphone.

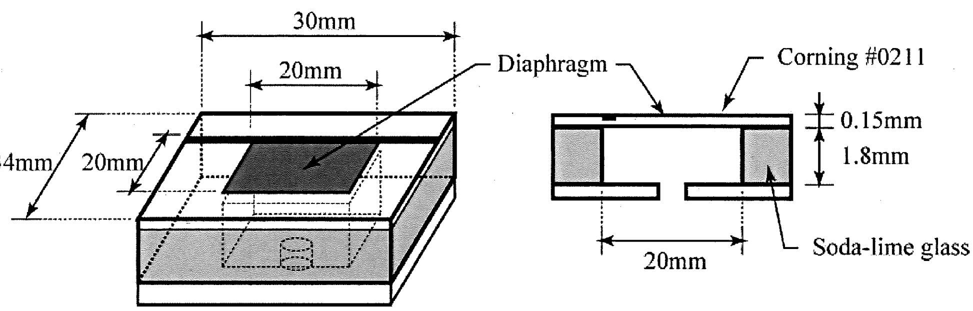

Figure 2. Schematic diagram of the fabricated optical microphone with actual dimensions.

4. EVALUATION OF DAMPING RATIO BY FREQUENCY DOMAIN MEASUREMENT

4.1 Theory

For a two dimensional diaphragm with an acoustic pressure load p, the differential equation for displacement w of the diaphragm is often expressed as

$$h\rho\frac{\partial^2 w}{\partial t^2}+D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2\partial y^2}+\frac{\partial^4 w}{\partial y^4}\right)=p(x,y,t), \qquad (1)$$

where h, ρ and D are thickness, density and flexure rigidity of diaphragm, respectively.[5] Unless the damping force can be neglected, a variable for the damping force must be added to eq. (1). Frequency response can be derived by solving eq. (1) with an additional variable due to the damping force. However, analytically solving the differential equation is quite laborious even for a simple rectangular diaphragm. For simplicity, the following second-order differential equation of a well-known single-degree-of-freedom system is introduced to obtain a frequency response.

$$m\ddot{x}+c\dot{x}+kx=F_0\sin\omega t, \qquad (2)$$

where m, c and k are mass, damping coefficient, and spring constant, respectively. Also, $F_0\sin\omega t$ represents periodic driving force acting on the mass. Eq. (2) is rewritten as

$$\ddot{x}+2\gamma\dot{x}+\omega_0{}^2x=(F_0/m)\sin\omega t, \qquad (3)$$

where $\gamma=c/2m$ and $\omega_0=\sqrt{k/m}$. The solution of eq. (3) is given by

$$x=X\sin(\omega t-\phi), \qquad (4)$$

if the short-lived transient oscillation is sufficiently decayed. In the equation, ϕ denotes phase lag of the vibration against the sinusoidal force. In addition, amplitude X of the steady vibration with an angular frequency of ω is expressed as

$$\frac{X}{x_{st}}=\frac{1}{\sqrt{\{1-(\omega/\omega_0)^2\}^2+\{2\zeta(\omega/\omega_0)\}^2}}=\frac{1}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}}, \qquad (5)$$

where $x_{st}=F_0/k$ is the static displacement of the mass caused by constant force F_0. Also, λ is the frequency ratio ω/ω_0 , and ζ is called the damping ratio, defined by γ/ω_0 .

Figure 3 shows X/x_{st} as a function of the frequency ratio λ, that is, the frequency response, when damping ratio ζ is 0.2, 0.7 and 1.2. If damping is light, that is, ζ is smaller than 0.7, the resonance peak clearly appears. In this case, the angular frequency of the resonance peak is closer to ω_0, and X/x_{st} at the peak is approximately equal to $1/2\zeta$. When ζ is equal to or greater than 0.7, the resonance peak disappears. In the case of $\zeta=0.7$, the frequency response has the largest flat region, so is often referred to as the optimum damping condition. In this study, since there is no damping structure and ζ is much smaller than 0.7, damping ratio can be evaluated from the resonance curve in the frequency response.

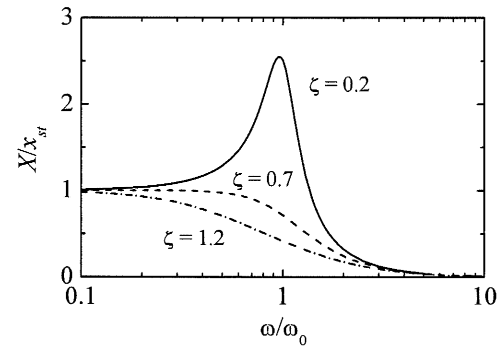

Figure 3. Frequency responses calculated using eq. (5) in the cases of ζ = 0.2 (weak damping), 0.7 (critical damping) and 1.2 (strong damping).

4.2 Experiments

The experimental setup to examine frequency response is illustrated in Fig. 4. In the experiment, a sound pressure of 2 Pa (100 dB-SPL) was applied to the fabricated microphone by a speaker with a diameter of 80 mm. Sound frequency ranged from 1 kHz to 20 kHz. A linearly polarized He-Ne laser at 633 nm was used as the light source. Polarization of the laser beam was set at 45° to the microphone surface, eliminating the need for an input polarizer. Output light from the microphone was passed through a pinhole to extract only the guided-wave light. Also, lock-in detection with a bandwidth of 1 Hz was used for the measurement of this frequency response.

Frequency response of the fabricated microphone is indicated in Fig. 5. Since the microphone has no damping structure, resonance appears in the frequency response. The first resonance frequency was determined to be 3.5 kHz from Fig. 5, and the measured resonance frequency closely agrees with the theoretical value of 3.4 kHz. Moreover, the fabricated sensors showed a flat response over the frequency range sufficiently less than the measured resonance frequency.

The frequency response extracted around the first resonance is shown in Fig. 6. In the figure, dots denote measured data, and the solid line represents the calculated curve of eq. (5) when $\zeta = 0.009$. Since the curve agrees well with the measured data, damping ratio ζ is evaluated to be 0.009.

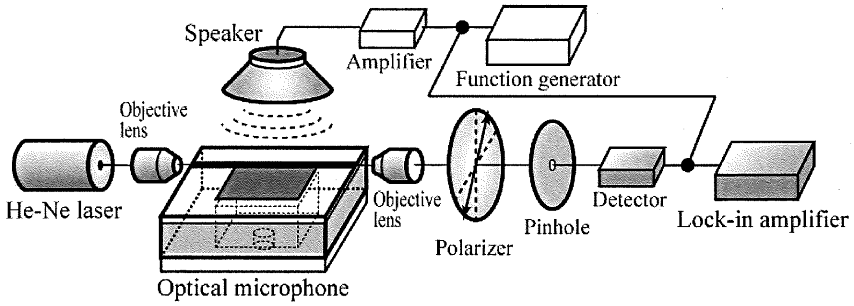

Figure 4. Experimental setup to examine frequency response of the guided-wave optical microphone.

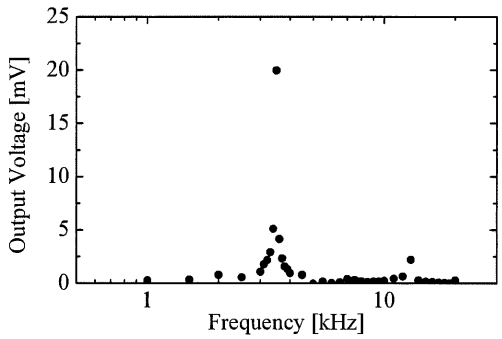

Figure 5. Frequency response of the fabricated microphone in a frequency range of 1-20 kHz, with a constant applied sound pressure of 2 Pa

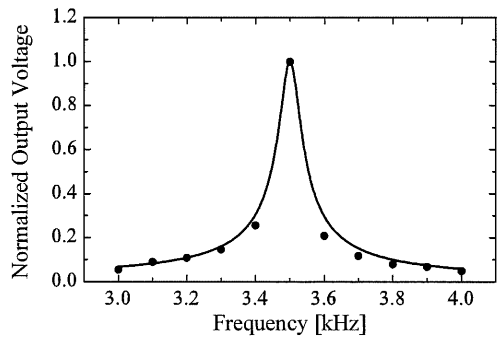

Figure 6. Frequency response around the first resonance frequency. The solid line shows the calculated frequency response for a damping ratio ζ of 0.009.

5. EVALUATION OF DAMPING RATIO BY TIME DOMAIN MEASUREMENT

5.1 Theory

Damping ratio can also be determined from the step response, that is, the transient output after the applied acoustic sound is turned off. The step response is calculated from the following differential equation under proper boundary conditions.

$$\ddot{x} + 2\gamma\dot{x} + \omega_0{}^2 x = 0 . \tag{6}$$

When damping ratio ζ is less than 1, transient output exhibits free decaying vibration, and displacement can be expressed as

$$x = Ae^{-\zeta\omega t}\cos(\omega_d t - \phi), \tag{7}$$

where $\omega_d = \omega_0\sqrt{1-\zeta^2}$ and ω_0 is the resonance angular frequency. Also, A and ϕ represent initial amplitude and initial phase, respectively, and are determined by initial displacement, initial velocity, etc. Damping ratio ζ can be determined by the curve fitting of the measured step response.

Moreover, the damping ratio of an under-damped system can also be evaluated from logarithmic decrement δ of a measured step response, that is, a measured decaying vibration. Logarithmic decrement δ is defined as

$$\delta = \frac{1}{n}\ln\frac{x_1}{x_2}, \tag{8}$$

where x_1 and x_2 are the amplitude maxima of two points exactly n cycles apart. From eqs. (7) and (8), the relation between the logarithmic decrement and the damping ratio is derived as follows.

$$\delta = \frac{1}{n}\ln\frac{Ae^{-\zeta\omega t_1}}{Ae^{-\zeta\omega t_2}} = \frac{1}{n}\ln\frac{Ae^{-\zeta\omega t_1}}{Ae^{-\zeta\omega(t_1+nT)}} = \frac{1}{n}\ln e^{\zeta\omega nT} = \zeta\omega T = \zeta\omega\frac{2\pi}{\omega_d} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}. \tag{9}$$

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}}. \tag{10}$$

T in eq. (9) represents the period of the free decaying vibration.

Incidentally, the logarithmic decrement method may not be suitable for estimation of the damping ratio unless the peak amplitudes are exactly determined due to noise. Even for noisy signals, the damping ratio can be estimated using the Hilbert transform, which is defined as the following convolution.

$$\tilde{x}(t) = H[x(t)] = x(t) * \frac{1}{\pi t} = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(t)}{t-\tau}d\tau, \tag{11}$$

where $H[\cdot]$ and * represent the Hilbert transform operator and the convolution symbol, respectively. Here, analytic signal $x_a(t)$ is introduced as

$$x_a(t) = x(t) + j\tilde{x}(t) \equiv A(t)e^{j\theta t}, \tag{12}$$

where j is the imaginary unit. $A(t)$ is called an instantaneous envelope, and $\theta(t)$ is an instantaneous phase. The instantaneous envelope signal is given by

$$A(t) = \sqrt{\{x(t)\}^2 + \{\tilde{x}(t)\}^2}. \tag{13}$$

Using envelope signal $A(t)$, instantaneous damping ratio can be expressed as

$$\zeta = -\frac{1}{\omega}\cdot\frac{d\{\ln A(t)\}}{dt}. \tag{14}$$

Therefore, if the regression line of the natural logarithm of envelope signal $A(t)$ is obtained, damping ratio ζ can be determined from the slope of the regression line.

5.2 Experiments

The experimental setup to measure step response is illustrated in Fig. 6. In the experiment, acoustic sound at a resonance frequency of 3.5 kHz was first applied to the fabricated microphone. Sound pressure was set to be 2 Pa (100 dB-SPL). Next, the applied sound was momentarily turned off. Output power of the fabricated microphone was recorded on a PC through an AD converter before and after the applied sound was turned off. Measured transient output is shown as dots over a period of 5 ms after the applied sound is turned off in Fig. 8. The solid line represents the computer projection of the measured output using eq. (7). According to the curve fitting, the damping ratio was evaluated to be 0.0093.

The output signal shown in Fig. 8 was quite noisy, so it was difficult to evaluate the damping ratio by the logarithmic decrement method. In this study, the damping ratio was also determined using the envelope signal by the Hilbert transform described above. The natural logarithm of the envelope signal as a function of time is shown in Fig. 9. Although the plots are slightly scattered, they tend to decrease linearly and the regression line shown in the figure agrees well with their tendency. Slope of the regression line is –0.207. Since resonance frequency ω is 3.5 kHz, the damping ratio can be calculated using eq. (14) to be 0.0094.

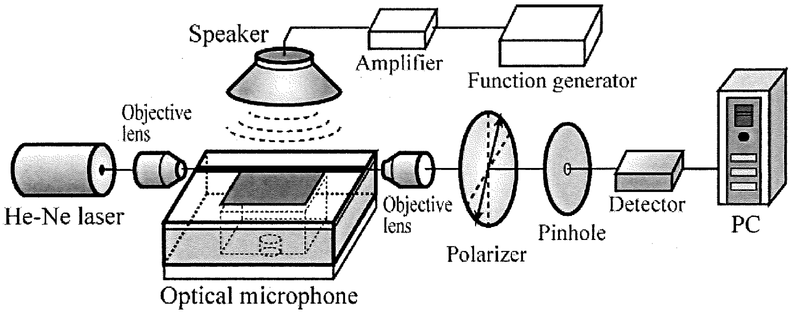

Figure 7. Experimental setup to examine frequency response of the guided-wave optical microphone.

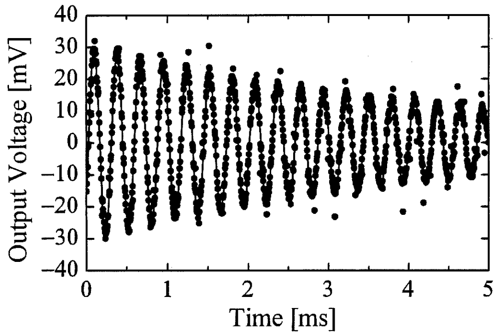

Figure 8. Transient output of the fabricated microphone after the applied acoustic sound is turned off.

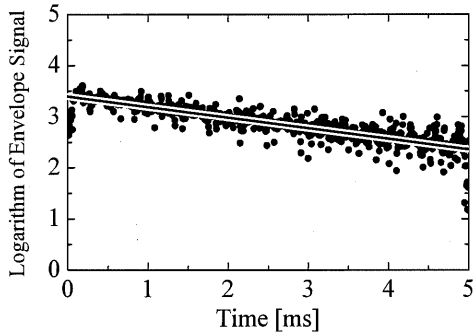

Figure 9. Natural logarithm of the envelope signal of the measured transient output shown in Fig 8.

6. CONCLUSIONS

A glass-based guided-wave optical microphone with a diaphragm of 20 mm×20 mm×0.15 mm and without a damping structure was fabricated. Frequency response and step response were experimentally examined to obtain the damping ratio. The damping ratio was reasonably evaluated to be approximately 0.009 by both frequency and time domain measurements.

ACKNOWLEDGMENTS

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