OPTICAL COMPUTERIZED TOMOGRAPHY SYSTEM FOR VISUALIZATION OF SOUND FIELDS USING MACH-ZEHNDER INTERFERENCE IMAGES DETECTED BY CHARGE COUPLED DEVICE

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Abstract

In this paper, we describe an optical computerized tomography (O-CT) system for visualization of sound fields using Mach-Zehnder interference images detected by a charge-coupled device (CCD). The system designed to use of the interference images and the CT method does not have scanning process in the optical system. The measuring object is the sound field pattern radiated from the piezoelectric transducer of 8.0 mm diameter applied to 1.4 MHz sinusoidal continuous waves. Comparing just before and after images of the interference fringes when the sound fields radiated, a distribution of the refractive index proportional to the sound pressure can be acquired from the difference of the two images. In addition, reconstructed images were acquired from 18 difference projection data when the sound fields were rotated. The system is effective method for the measurement of the sound fields because the probe does not be installed in the sound fields.

Introduction

Evaluating characteristic of ultrasonic transducer is one of key components for development of medical instruments. One of general methods for measuring a pattern of sound field generated from transducer is a combination of using hydrophone and mechanical scanning system. In this method, it is considered that the sound field is disturbed by the hydrophone and the spatial resolution is deteriorated due to the size of the sensor.

Non-destructive method as measurements without installing a sensor is useful to decide the above problems. Optical sensing is one of the non-destructive measurements and is useful for measuring the sound fields. In 1984, Lokberg measured the sound field characteristics both the amplitude and the phase in the air using TV holography [1]. In 1995, Neighbors measured the absolute sound pressure using a charge-coupled device (CCD) and Schlieren method at the focused ultrasonic beam driven at the frequency of 0.37 MHz [2].

The optical measurements of phase deviation in proportion to sound fields use the phenomena of the diffraction or the interference due to the influence that the sound fields affect change of the refractive index in the media. The merit of the measurement using diffraction phenomenon as Schlieren method, which is useful visualization method of sound fields, is to acquire high signal noise ratio (SNR) projection images of sound fields. However, in measuring the sound fields with a wide beam width, the acquired images do not represent correctly the integral data of the sound field, because the reception points of the light beams passing through the sound fields are different by location of diffraction. Therefore those images are difficult to be available for the primary data using CT method. On the other hand, the measurement using interference is affected by the rectilinear integral data of the sound field and is better suited linearly than using the diffraction. In addition, the measurement using a CCD makes possible quickly the acquirement of larger area than using a photo detector. In this paper, we describe an optical computerized tomography (O-CT) system for visualization of sound fields using Mach-Zehnder interference images detected by a CCD. We will obtain the tomographic image as three-dimensional distribution of the sound fields reconstructed from 18 projection data. The following are described measurement principle and result and summary.

Principle

Principle of measurement

Figure 1 shows the schematic diagram of interferometer. The light rays pass through the sound fields. The ultrasonic beam with the water tank is installed in one optical path of Mach-Zehnder interferometer. Although the change is not observed at the optical intensity even if the light passes through sound field radiated from the transducer in the water, the change of the sound pressure in the water yields the change of the refractive index and the phase deviation of the light beam. Optic and sound axes are defined a *y*-direction and a *z*-direction, respectively. The *x*-direction indicates the transversal direction of the sound. Sound wave defines a sinusoidal plane wave that propagates in the *z*-direction. The refractive index of water is given by

$$n = n_0 + \kappa\ p(x, y, z, t). \qquad (1)$$

$$\kappa = \frac{(n_0 - 1)\left(n_0^{\,2} + 1.4\,n_0 + 0.4\right)}{\left(n_0^{\,2} + 0.8\,n_0 + 1\right)\rho_0 c_s^{\,2}}. \qquad (2)$$

where n_0 is refractive index without sound field in the medium, ρ_0 is density of the medium, c_s is velocity of sound in the medium, p is amplitude of the sound

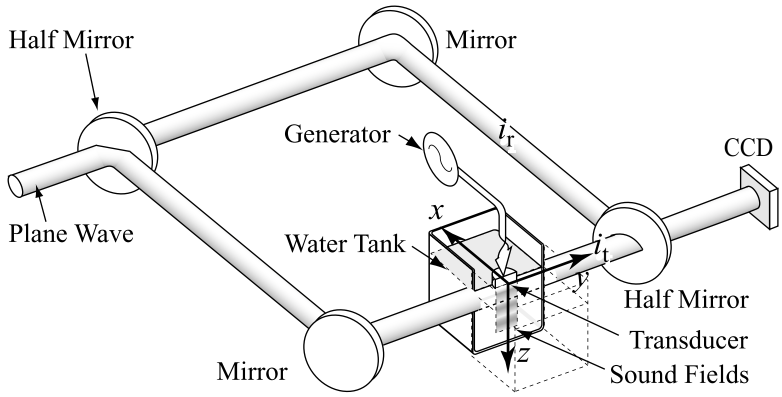

Figure 1 : Schematic of Mach-Zehnder interferometer for optical measurement of sound fields via a CCD. Light beam is diffracted after passage through sound fields.

pressure. κ is proportionality constant concerned between amplitude of the sound pressure and change of the refractive index [3]. The plane waves emitted from the light source is divided into two paths by the half mirror. The interference phenomenon is occurred due to the superposition of two coherent lights i_t and i_r. The interference images are detected by a CCD. The optical intensity I caused by the interference between the test light beam i_t and the reference light beam i_r is given by

$$\begin{aligned} I &= \left| i_t + i_r \right|^2 \\ &= \left| i_t \right|^2 + \left| i_r \right|^2 + 2\sqrt{\left| i_t \right|^2 \left| i_r \right|^2} \cos \phi(x,z,t) . \end{aligned} \tag{3}$$

where $\phi(x,z,t)$ is a phase deviation between i_t and i_r. The phase deviation is changed mainly by the refractive index in the water and is given by

$$\begin{aligned} \phi(x,z,t) &= \phi_0(x,z) + \frac{2\pi}{\lambda} n_y(x,z,t) \\ &= \phi_0(x,z) + \frac{2\pi}{\lambda} \int n(x,y,z,t)\, dy \\ &= \phi_0(x,z) + \phi_n(x,z) + \phi_y(x,z,t) . \end{aligned} \tag{4}$$

$$\begin{cases} \phi_n(x,z) = \dfrac{2\pi}{\lambda} \displaystyle\int n_0(x,y,z)\, dy, \\ \phi_y(x,z,t) = \dfrac{2\pi\,\kappa}{\lambda} \displaystyle\int p(x,y,z,t)\, dy . \end{cases} \tag{5}$$

where $\phi_0(x,z)$ is a initial phase of interference system, $n_y(x,z,t)$ is a refractive index occurred by the water tank, $\phi_n(x,z,t)$ is a phase deviation concerned the propagation of the test light beam. $\phi_y(x,z,t)$ is a phase deviation concerned the change of the sound fields, λ is light wavelength. The assumption that the terms $\phi_0(x,z,t)$ and $\phi_n(x,z,t)$ are not changed by generating the sound shows that the phase deviation $\phi_y(x,z,t)$ represents the sound fields information.

Change of light intensity due to the diffraction grating by ultrasonic beam

When the CCD for obtaining the images is used effectively, it is possible to extract the mean value for a fast change in I [4]. The optical intensity I' acquired by the CCD is given as

$$I' = \bar{I}, \tag{6}$$

When the sound fields of frequency ω radiated from the transducer are assumed as the plane waves at a finite width D, the term $\phi_y(x,z,t)$ in eq. (4) is given by

$$\phi_y = \frac{2\pi\,\kappa\, pD}{\lambda} \sin(\omega t). \tag{7}$$

The phase term in eq. (3) is expanded as

$$\begin{aligned} \cos(\phi_0 + \phi_n + \phi_y) &= \cos(\phi_0 + \phi_n)\cos\{\xi \sin(\omega t)\} \\ &\quad - \sin(\phi_0 + \phi_n)\sin\{\xi \sin(\omega t)\} \\ &= \cos(\phi_0 + \phi_n) J_0(\xi) \\ &\quad - 2\sin(\phi_0 + \phi_n) J_1(\xi)\sin(\omega t) \\ &\quad + 2\cos(\phi_0 + \phi_n) J_2(\xi)\cos(2\omega t) - \cdots, \end{aligned} \tag{8}$$

where $\xi = 2\pi\,\kappa\, pD/\lambda$ is the change of the phase deviation. Then, equation (8) is rewritten by following expression due to the operation that the terms included ω become "0" by the mean function of the CCD.

$$\cos(\phi_0 + \phi_n + \phi_y) = \cos(\phi_0 + \phi_n) J_0(\xi). \tag{9}$$

Additionally, we have to consider the influence of the diffraction when the test light beam passes through the sound fields. Due to the diffraction phenomenon, the change of refractive index behaves as the diffraction grating when the light beam passes through the sound fields in the water. The following equation, when the optical intensity of the incident light is assumed to be "1", shows the optical intensity of mth order diffracted light [5]

$$I_m = J_m^{\,2}(v), \tag{10}$$

where J_m is mth order Bessel function of the first kind, v is a parameter of Raman-Nath diffraction and is given as

$$v = \frac{2\pi\ \kappa\, pD}{\lambda}. \tag{11}$$

The parameter v is equal to ξ. It is probably that the light beam passing through the sound fields is affected by the changes both the phase deviation and the diffraction depended on the Raman-Nath parameter.

In this paper, the parameters ξ and v assumes the change of the phase deviation and the light intensity, respectively. It is assumed that i_t is comparable to the zeroth order optical intensity of Raman-Nath diffraction. Combining eq. (3), (9) and (10), I' in eq. (6) is rearranged by

$$I' = J_0^2(v) + |i_r|^2 + 2\sqrt{|i_r|^2}\, J_0(v)\cos\,(\phi_0 + \phi_n)\, J_0(\xi_y), \quad (12)$$

Therefore, it is possible that the refractive index in proportion to the sound information is estimated from the change of the optical intensity of the interference fringe. The estimation is calculated from the difference of the interference images with or without sound fields.

Measurements and Results

Measurement and Estimation

The experimental setup is shown in Fig. 2. The light source is a 632.8 nm He-Ne Laser (05LHP151 / Melles Griot). The light rays are made parallel by the plano-convex lens (*f* = 500 mm). The piezoelectric transducer (NEPEC 21 / TOKIN) is an 8.0 mm aperture in diameter at the frequency of 1.4 MHz. The sound fields formed using the transducer applied to the sinusoidal continuous wave generated by a function generator （33120A/Agilent Technologies） and a 40 dB power amplifier （4055/ NF ELECTRONIC）. In the interferometer, the mirrors M_1 and M_2, the half mirror H_1 and H_2 are 130 mm in diameter, respectively. Images of interference fringes were detected by the CCD (CS3440 / Tokyo Electronic Industry). The water tank and the transducer are installed in one optical path of Mach-Zehnder interferometer. The depth of the water tank is 200 mm. In order to the prevention of the reflection of the ultrasonic beam, an absorber set in the bottom of the water. To acquire multiple projection images as the primary data of the CT method, the transducer is fixed at a rotational stage, and the sound fields is rotated.

Figure 3 shows the images of measurement by the CCD and the projection data estimated from two images. Figure 3(a) and 3(b) respectively are the images without sound fields and with sound fields. Figure 3(c) is estimated distribution of the sound fields from the comparing the intensities between figs. 3(a) and 3(b). The brightness in Fig. 3(c) is normalized to the max value of the distribution. The area of the images is 25 mm (V)×25 mm (H). The sound axis is laid on the center of the images. From the result of Fig. 3(c), we confirmed that the the optical intensity changing region exists in the vicinity of the sound axis with approximately 7mm width.

The estimation is calculated from comparing the change of the terms corresponding to the phase deviation. The intensity I'' is assumed as the value

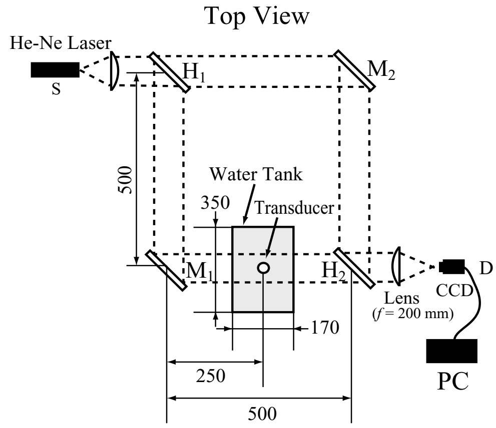

Figure 2 : Experimental arrangement of the Mach-Zehnder interferometer.

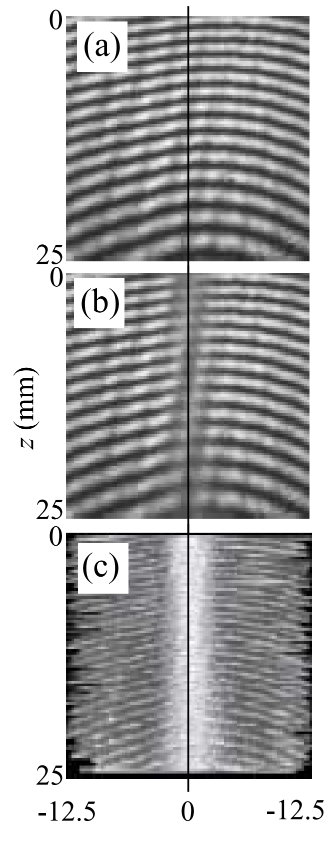

Figure 3 : Experimental result of the ultrasonic beam measured for the interference system. (a) and (b) are interference images without or with sound fields, respectively. (c) is an estimated projection distribution from comparing between (a) and (b).

extracted the third term of eq. (12) concerning the change of phase deviation and is given as

$$I'' = 2\sqrt{|i_r|^2}\, J_0(v)\cos\,(\phi_0 + \phi_n)\, J_0(\xi), \quad (13)$$

The terms i_r and $\phi_0+\phi_n$ are depended on the position of z, and the terms v and ξ are depended on the change of the sound fields. When the optical intensity I'' is monotonously decreased, the parameters v and ξ is increased. Therefore the proportion of decreasing the intensity I'' yields the estimation of the proportion of increasing the parameters v and ξ. From this operation, sound fields information is estimated from the two images.

Reconstruction using O-CT method

The multipule projeciton data for using the CT method was acquried from the oparetion rotating the transducer. We obtained 18 estimated results as projection data. Figure 4 shows the reconstruction image obtained from 18 projeciton data. The tomographic image represents under 15 mm from the surface of the transducer. The area of image is 25 mm x 25 mm. The brightness is normalized to the max value of the distribution. The distribution confirm more brightness in the vicinity of the center. We could obtain the one of projection data about a few seconds. It is useful feature to obtain these projection data at once required for the reconstruction of three dimensional distribution.

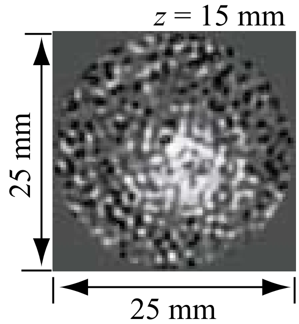

Figure 4 : Tomographic image reconstructed from 18 projection data. The area of image is 25 mm x 25 mm.

Conclusions

An O-CT system for visualization of sound fields using Mach-Zehnder interference images detected by a CCD was described. Although visualizations of the sound fields using the diffraciton as the schlieren method were useful to obtain the high SNR projection images, those images did not represent the width of the distribution of the sound fields. On the other hand, the measurement using the interference is better suited linearity than using diffraciton. In this paper, in order to obtain the sound fields information, the interference image using the Mach-Zehnder interferometer was detected by the CCD, the projection data of sound fields was estimated from the two interference images with or without sound fields. Additionally, rotating the sound fields, the multiple projection data were acquired for using the CT method. We could obtain the tomographic distribution from 18 projection data. The tomographic distribution is under 15 mm from the surface of the transducer. We could obtain the one of projection data about a few seconds. The O-CT system is useful to obtain these projection data required for the reconstruction of three dimensional distribution at once.

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