DETECTION OF ULTRASONIC FIELDS IN AIR WITH AN OPTICAL HETERODYNE PROBE

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INTRODUCTION

The air-coupled ultrasonic transducers and their applications to ranging, robotic vision and nondestructive testing etc. have been widely studied in recent years. Further studies should be concentrated on (1) the improvement of the sensitivity and bandwidth of the transducers, (2) the prediction and measurement method of the radiation pattern. Much attention has been paid to the former problem about the transduction. However, the second problem, related to the measurement techniques of acoustic pressure distribution, is not well studied.

The characterization of the ultrasonic fields with the frequency less than 50 kHz may be taken by using microphones. For higher frequencies, the measurement can be done by using another air-coupled ultrasonic transducer. But in both cases, the directivity functions of the transducer and the receiver are in convolution. Besides, the scattering effect of the receiver should be also taken into account. Therefore, the difficulty in characterizing ultrasonic fields in air lies in the absence of high frequency, wide bandwidth and miniature microphones.

Optical methods have been proposed to detect the acoustic waves in air. Holm et al. used an optical deflection method and the tomography algorithm to reconstruct the acoustic field[1,2]. Jia and co-authors proposed an optical heterodyne interferometer to detect the ultrasonic wave in water and in air[3]. In this paper, we combine the ideas of Holm and Royer, and propose a simple method to obtain the acoustic pressure distribution by differentiating the overall optical diffraction signal as a function of the position of the reflector in the sound field. The experimental method and apparatus will be described. The result of the acoustic pressure distribution of a 42 kHz transducer will be given. Finally, the possibility of the absolute determination of the acoustic pressure distribution will be discussed.
Fig. 1. Illustration of interaction between laser beam and acoustic wave.

EXPERIMENTAL METHOD AND APPARATUS

Consider a He-Ne laser beam passing through the ultrasonic wave in air, as shown in Fig. 1. A miniature mirror with an area of 1 mm x 1 mm is inserted in the way of the optical beam, and can be moved along x direction in the acoustical field.

The optical refraction index will be changed as a result of the expansion and contraction of the propagating medium, i.e. the air. We can write the variation of the optical phase, i.e. the phase difference of the optical phase of the laser beam when the ultrasonic wave is on and when it is off, as following

\[ \psi = \frac{4 \pi \mu}{\lambda} \int_0^{L_x} p(x,t) \, dx \]  

where \( \phi \) is the optical phase difference, \( p(x,t) \) is the acoustical pressure, \( \lambda \) is the optical wavelength, \( p \) the acoustic pressure, \( \mu \) the elasto-optic coefficient (in air, \( \mu = 2.7 \times 10^{-9} \text{m}^2/\text{N} \)), \( L_x \) is the length that the laser beam covers the ultrasonic field.

Suppose that the ultrasonic field is monochromatic, i.e.

\[ p(x,t) = p_0(x) e^{i \omega t} e^{-i \omega t} \]  

where \( \omega \) is the frequency of the ultrasonic wave.

Then we have

\[ \psi = \psi_0 e^{-i \omega t} \]  

with

\[ \psi_0 = \frac{4 \pi \mu}{\lambda} \int_0^{L_x} p(x,t) \, dx \]
The phase shift $\psi_0$ can be measured with an asymmetrical optical heterodyne interferometer\[4,5\].

The block diagram of the system is shown in Fig. 2. The interferometer with dove prism is compact. The key part of the system is about 10 cm. The advantage is that the air disturbance can be avoided in the experiment.

The output of the photodiode in the interferometer is

$$V(x) = A_1 \sum_{N=0}^{\infty} J_N(\psi) \cos\left[2\pi (f_B \pm N f_A) t + \phi_L\right]$$  \hspace{1cm} (5)

in which $f_B$ is the frequency of the Bragg Cell in the interferometer, $f_A$ is the signal frequency, $\phi_L$ is a fixed phase difference of the laser probe system. If it is only the $f_B + f_A$ component of the signal in (5) to be demodulated, and in the case of $\psi << 1$ (it is generally the case for the measurement of ultrasonic wave in air). We have

$$V(x) = A_2 \psi_0(x)$$
$$= A_2 \int_0^x p_0(x) e^{\phi(x)} \, dx$$ \hspace{1cm} (6)

$A_1$ and $A_2$ are constants. In our system, we use an amplitude limiter so that the variation due to the laser intensity fluctuation can be neglected. If the reflector is moved along the $x$ direction, for different position $x$, we have

$$p_0(x) e^{\phi(x)} = \frac{dV(x)}{dx}$$ \hspace{1cm} (7)

Therefore, the acoustic pressure (amplitude $p$ and phase $\phi$) can be obtained for the point $x$.

In this experiment, we move the reflector in step by step with an increment of $\Delta x$ about 1 mm, and calculate numerically the acoustic pressure according to (7).
The fact that the pressure is obtained by the differentiation may cause some errors, because a small noise will produce a big deviation from the real value. To solve the problem, we filter numerically the received signal, then calculate the differentiation. The results will be given in the next section.

EXPERIMENT RESULT AND DISCUSSION

The transducer used in experiment is a commercial 42 kHz transducer in flexural mode, with a diameter of 10 mm. The transduction element PZT is mounted in a cylindrical housing of $\phi$ 15mm x 10mm.

To verify the proposed method, the linearity between the acoustic pressure and the output of the experiment system is measured. The electric excitation voltage is about 1-10 volt (p-p). In this range, the PZT is supposed to have a linear response. Then the system output versus excitation voltage is obtained as the reflector is fixed at a certain place. The measured result is plotted in Fig 3.

The input voltage can easily be increased. The dynamic range is higher than that demonstrated in Fig.3, which is estimated about 60 dB. That is generally sufficient for the characterization of air transducers.

As it is mentioned above, the technique permits to measure not only the amplitude distribution, but also the phase distribution. It is demonstrated in Fig. 4, in which the acoustic pressure is obtained in the sectional plane perpendicular to the axis of the transducer and at about 7 cm from the surface of the transducer.

In Fig.5, the distribution of the acoustic pressure for different distance from the surface of the transducer is presented. It is shown that the main lobe is relatively narrow and the side lobes are relatively high in comparison with a piston-like transducer. We suppose that it is due to: 1) the nonuniform excitation of the surface of the transducer in flexural mode, 2) the effect of the reflection from the housing, by considering its size, limits the
Fig. 4. The amplitude and phase distribution of the 42 kHz transducer. The transducer is excited by the voltage of 12 Vp-p and measured at the distance of 8 cm.

Fig. 5. The acoustic pressure distribution of the 42 kHz transducer. The distances are 7cm, 9cm, 11cm, 13cm, 15cm and 18cm.

expanding of the sound beam.

The acoustic pressure in Fig. 4 and Fig. 5 is plotted in arbitrary unit. However, it is possible to use this technique to determine the acoustic pressure absolutely. For simplicity, we consider the case of a plane progressive wave

\[ p(x,t) = p_A \sin(2\pi f_A t) \]

where \( p_A \) is the amplitude of the acoustics pressure. Thus, the phase variation of laser beam can be written, according to (1), as following

\[ \psi(t) = \frac{4\pi \mu L p_A}{\lambda} \sin(2\pi f_A t) \]
where \( L \) is the width of the ultrasonic wave. So the corresponding output signal \( i(t) \) at the photodiode of the interferometer is

\[
i(t) = A_\lambda \cos(2\pi f_\lambda t + \frac{4\pi \mu L p_A}{\lambda} \sin 2\pi f_\lambda t)
\]  

(8)

Eq. (8) is just the expression of a frequency-modulated signal. Its maximum frequency deviation is

\[
\Delta f = \frac{4\pi \mu L p_A}{\lambda} f_\lambda
\]  

(9)

Now, if a frequency-modulated signal with given modulation ratio, or the maximum frequency deviation is applied to the demodulation system, the relationship between the maximum frequency deviation of the input signal and the output signal can be established. It is shown in Fig. 6.

According to Fig. 6 and Eq. (9), the acoustic pressure can be estimated. If we have \( V = 80 \text{ mV} \), \( L = 2 \text{ cm} \), we have \( \Delta f = 0.1 \text{ kHz} \). Therefore \( p_A = 4 \text{ Pa} \).

The above analysis for a plane progressive wave can easily be extended to the general case, \( p_A L \) should be replaced by the integration of the acoustic pressure \( p(x) \) over the distance \( L_x \), as described above. By differentiating the output signal the corresponding pressure at any point the pressure can be obtained. The acoustic pressure of the measured transducer in Fig 4 is about 1 - 10 Pa.

Therefore, the optical heterodyne interferometer can be used for the absolute calibration of the acoustic field, as it does for the absolute calibration of vibration amplitude in [4,5].

In conclusion, we presented a simple method to characterize the ultrasonic fields in air. The size of the reflector can be reduced in dimension to decrease further scattering effect. The method described in this paper can be easily extended for the pulsed ultrasonic fields which is now in progress.
ACKNOWLEDGMENT

This work is supported by the Foundation for Young Scientists of the National Education Commission of China.

REFERENCES