HIGHLY DIRECTIVE MEASUREMENTS OF AIR-BORNE ULTRASOUND BY DETECTING THE OPTICAL REFRACTIVE INDEX OF AIR

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Abstract

To obtain narrower beam width for sound field measurements, we need wider aperture for receiving the sound. In this report, the authors propose to create the large aperture using an optical interferometer to detect the optical path length modulation caused by sound pressure. A commercial laser Doppler velocimeter (LDV) is used as the interferometer, and the relationship between the sound pressure and the LDV output is mentioned in the first part of the report. The validity of the principle is confirmed through two experiments of ultrasonic fields in air. Then, a method to obtain a very sharp directivity is discussed. The receiving aperture is created by extending one arm of the optical interferometer. A very narrow beam width less than ten degrees is obtained both at ultrasonic and audible frequency.

Introduction

Highly directive microphone is utilized to discriminate necessary sound source among many undesired signals, or to suppress high level ambient noise. However, to obtain very narrow beam width for sound field measurements, we need a large aperture for receiving the sound. The aperture is formulated by using a parabolic reflector or array system in conventional highly directive microphones. To achieve such a sharp beam width less than ten degrees in full width half maximum, for example, the aperture diameter becomes about ten times of the wavelength of the sound to be detected. The large aperture will become obstacle in practical use.

A part of authors have proposed a method to measure air-borne ultrasound by detecting refractive index modulation of air[1]. The change in optical path length due to sound pressure is measured by using an optical interferometer in the method. A commercial laser Doppler velocimeter (LDV) is utilized as the optical interferometer. Instead of vibration velocity/amplitude, the optical path length change along the laser beam launched from the LDV head is measured. This means that the sound pressure averaged over the laser beam is the output of the system, and the laser beam is a line sensor for sound field. Consequently, the directivity of the system is determined by the geometrical arrangement of the laser beam. We newly propose to create a large aperture by using the LDV laser beam to obtain a very sharp directivity for sound measurement in air.

First, in this report, the detection principle and the relationship between the sound pressure and the optical refractive index modulation are reviewed. Second, let us confirm the feasibility of the detection principle through two measurements of ultrasonic fields in air. The method to create the large aperture by extending and folding the LDV laser beam many times is described. The authors succeed in obtaining sharp beam width less than ten degrees at both ultrasonic and audible frequencies.

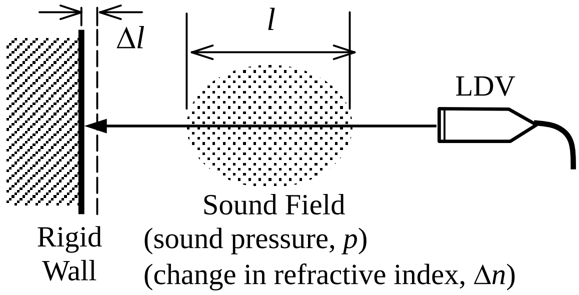

Fig. 1 Basic setup for sound pressure measurement by optical interferometry.

Methods for detecting sound field

Figure 1 illustrates the basic setup for the measurement. The laser beam of LDV crosses the field of sound pressure p, and is reflected by a rigid wall located behind the sound field. The optical refractive index of air is n, and the beam overlaps with the field for the length of l. The modulation of optical path by the change in refractive index Δn is measured as a displacement of the rigid wall Δl:

$$\Delta n \cdot l = n \Delta l \,. \tag{1}$$

The LDV system is so designed that the output electrical signal may correspond directly to the vibration velocity v_{LDV}. Then, the refractive index change Δn is expressed as

$$\Delta n = \frac{n}{2\pi f l} v_{LDV} \,. \tag{2}$$

On the other hand, let us assume the following relationship between the sound pressure p and the change rate of volume $\Delta V/V$,

$$\frac{\Delta V}{V} = -\frac{\Delta n}{n-1} \,. \tag{3}$$

By using the fundamental equations of sound field:

$$\frac{p}{P_0} = -\gamma \frac{\Delta V}{V}, \qquad P_0 \gamma = c^2 \rho \,, \tag{4}$$

where, P_0, γ, ρ, and c are the atmospheric pressure, the ratio of the two specific heats, density and the sound speed, respectively, sound pressure p can be rewritten as

$$p = \frac{n}{n-1}\frac{c^2\rho}{2\pi f l}v_{LDV}\,. \qquad (5)$$

This can be calculated as below for air (n=1.0002764 at 1 atm, 15℃, 640 nm, c=340.6m/s, ρ=1.226kg/m^3) for practical use:

$$p[\mathrm{Pa}] = 8.19\times10^4 \times \frac{v_{LDV}\,[\mathrm{mm/s}]}{f\,[\mathrm{kHz}]\times l[\mathrm{mm}]}\quad . \qquad (6)$$

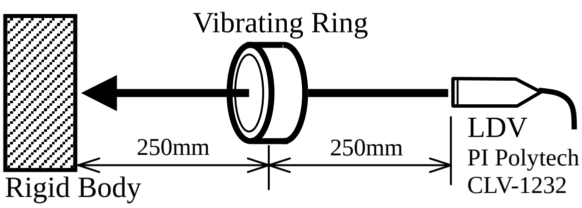

Fig. 2 Setup for measuring the standing wave field excited inside a vibrating ring.

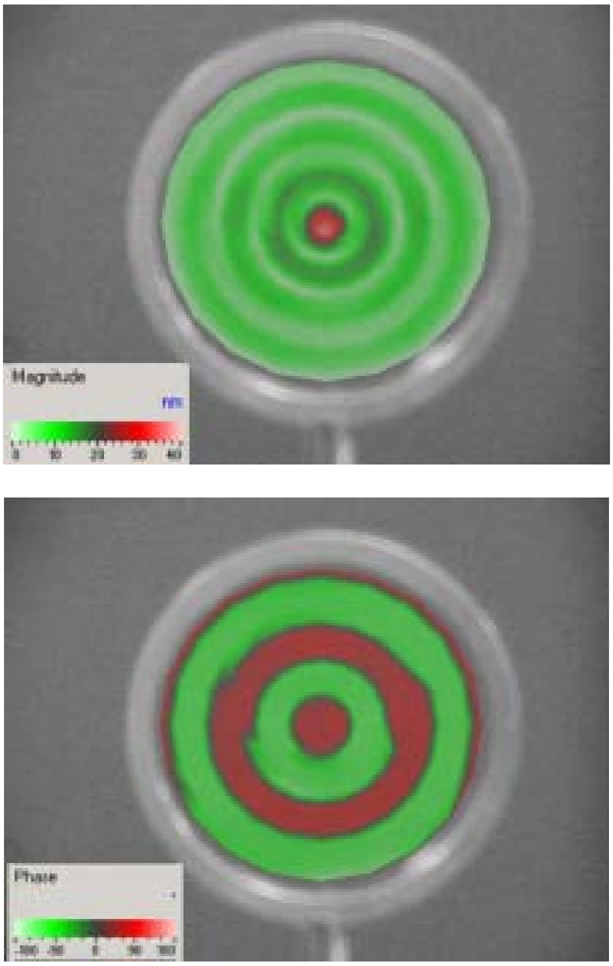

Fig. 3 Results for the inside of the vibrating ring visualized by the present method: upper picture, amplitude; lower, phase.

Confirming the principle

Standing wave field

A vibrating aluminum ring, 61.3 mm in outer diameter, 53.4 mm in inner diameter, and 30.0 mm in depth, was used as a sound source at 27.2 kHz as illustrated as Fig. 2. It vibrated radially with an excitation at one point by a Langevin transducer and a horn. The fundamental uniform expansion mode was excited at this frequency, and an axial symmetric sound pressure field with four nodal circles was built up inside the ring. The laser beam propagated almost parallel to the axis of ring. The light reflected by the aluminum block was received by the LDV head. In this setup, the vibration system and the aluminum block were acoustically isolated each other with rubber sheets, and the distances between the ring, the block and the LDV head were large enough to eliminate the effect by air-borne field.

Two-dimensional image of the sound field can be obtained easily by utilizing a scanning LDV system (PI polytec PSV-300). Fig. 3 shows the results for the inside of the vibrating ring. Here, in this experiment, the scanning region was confined inside the ring, though sound field existed also outside the ring, in order to reduce the measurement time. It should be noted that the pictures in Fig. 3 indicate the averaged value along the laser beam.

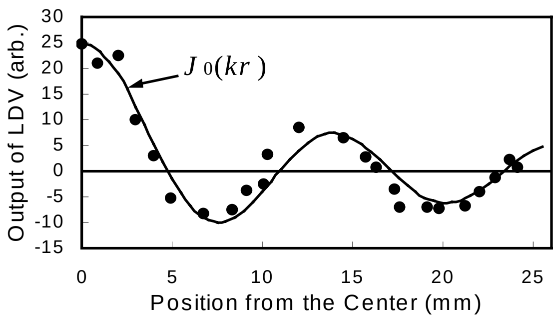

Fig. 4 Distribution along the radius of ring.

The distribution along the radius is extracted and shown in Fig. 4 with the theoretical curve. The results agree well with the expected value.

Radiation field

Next, the field in front of a piston vibrator was measured by using the present method. The equipment was the same as before, but the sound source was the end surface of Lagevin transducer. The diameter was 20 mm, and the surface vibrated almost uniformly at 28.2 kHz. The measured region is indicated in Fig. 5. The pictures for the amplitude and phase composed from the scanned data are shown in Fig. 6. The phase along the central line from the vibrator surface is shown in Fig. 7. It is successfully observed from the linear change of the phase that the sound field is propagates from the vibrator surface.

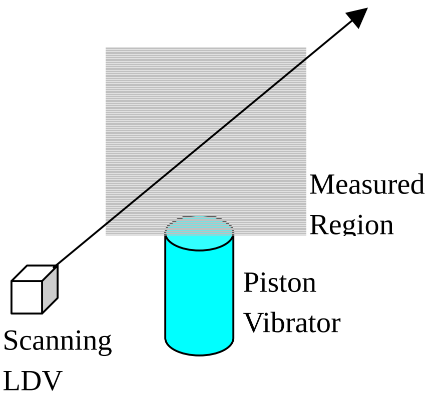

Fig. 5 Measured region for radiation field of a piston vibrator.

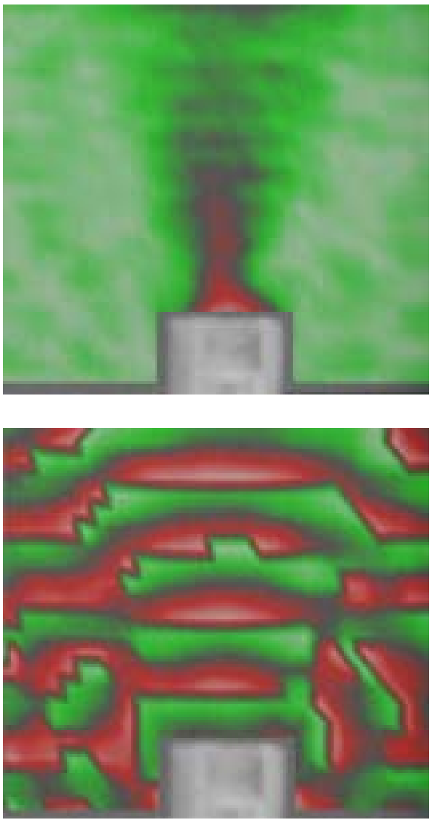

Fig. 6 Results for the radiation field: upper picture, amplitude; lower, phase.

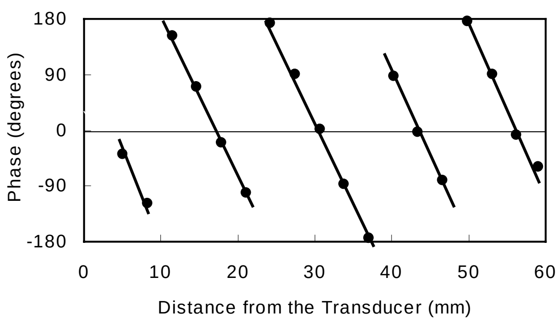

Fig. 7 Phase vs. the distance from the vibrator.

Discussion on the directivity

The directivity of the method was measured under the far field condition. First, the measurement was done in the plane parallel to the LDV laser beam. The set-up and the results are shown in Fig. 8. Theoretically, the directivity pattern is described by a *sinc* function, since the LDV laser beam acts as a line sensor. The theoretical expectations are added in the figure. The experimental results agreed well with the theory, and the beam width became narrower as the length *L* of LDV laser beam.

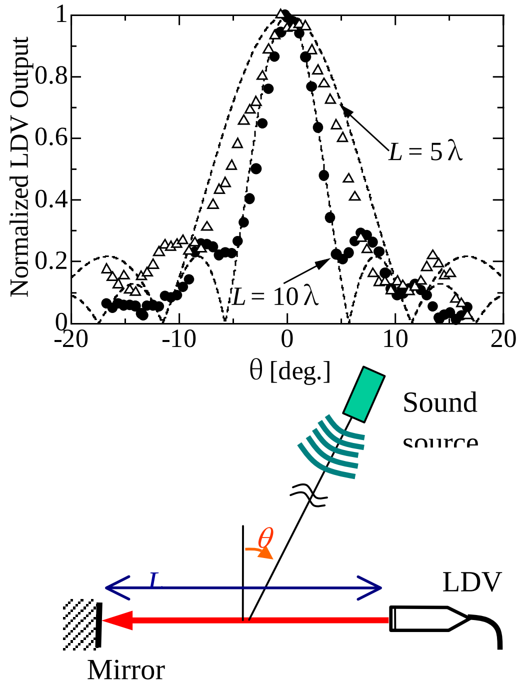

Fig. 8 Directivity in horizontal direction.

Next, the directivity for two parallel beams was investigated using the set-up illustrated in Fig. 9. The LDV laser beam was folded by a corner reflector with the spacing of *d*. The directivity pattern was measured in the plane perpendicular to the two beams. In this arrangement, the set-up is equivalent to the pair of point sensors. The results are shown in Fig. 10. The cancellation occurred in some directions as expected theoretically.

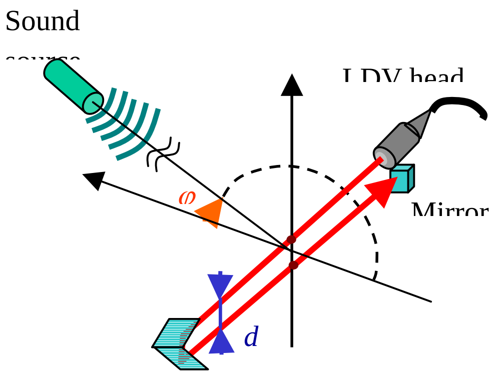

Fig. 9 Experimental setup for the directivity measurements in the plane vertical to the laser beams.

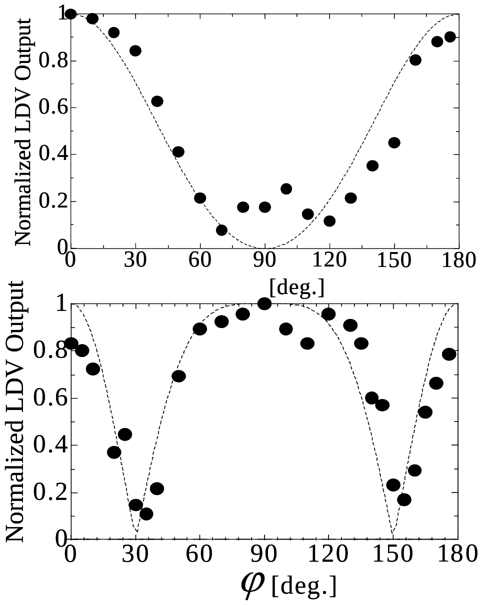

Fig. 10 Directivity patterns measured using the set-up of Fig. 9: upper figure shows the results in the case that *d* is equal to half a wavelength of the sound, while lower is the results when *d* is equal to the wavelength.

Super directivity

As confirmed in the previous section, the directivity depends on the geometrical arrangement of the LDV laser beams. Consequently, to obtain a two-dimensionally confined sharp directivity, a two-dimensionally large aperture sensitive to sound pressure. We tried to create a rectangular aperture by returning LDV laser beam many times using many steering mirrors as shown in Fig. 11. The spacing between adjacent beams was small enough to avoid the generation of grating lobes. The aperture dimensions were 150 mm in height and 120 mm in width. The directivity measured at 28 kHz was summarized in Fig. 12. The beam width was less than ten degrees in both horizontal and vertical directions. We also obtained the similar sharp directivity at 2 kHz with the aperture of 1.2 m in height and 1.5 m in width.

Conclusions

The authors have proposed a new method to obtain very narrow directivity for sound measurements in air. The large receiving aperture was created by one arm of an optical interferometer. The pencil beam with the beam width less than ten degrees has been achieved both at ultrasonic and audible frequencies. The present method is useful not only for obtaining such a super directivity, but also for measuring high intensity and short wavelength air-borne ultrasound. High power ultrasound in air is used in industry[2], and we need a new measurement technique without inserting sensors.

Acknowledgement

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References

[1] K. Nakamura, M. Hirayama, and S. Ueha, "Measurements of Air-Borne Ultrasound by Detecting the Modulation in Optical Refractive Index of Air," Proc. IEEE Ultrasonics symposium, Munich, Germany, Oct. 2002.

[2]*for example*, Y. Ito et al, *Jpn. J. Appl. Phys*. Vol.38, Part 1, No.5B, pp.3312-3315, 1999.

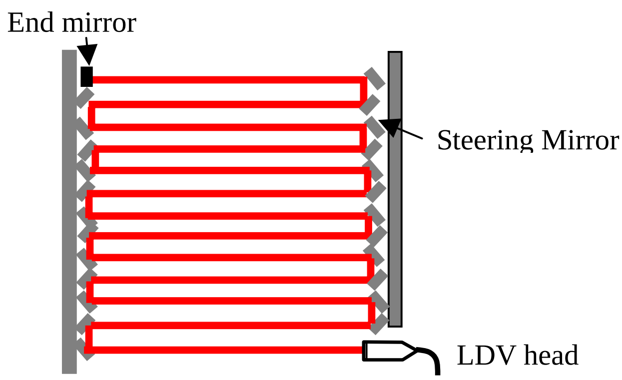

Fig. 11 Set-up for pencil beam.

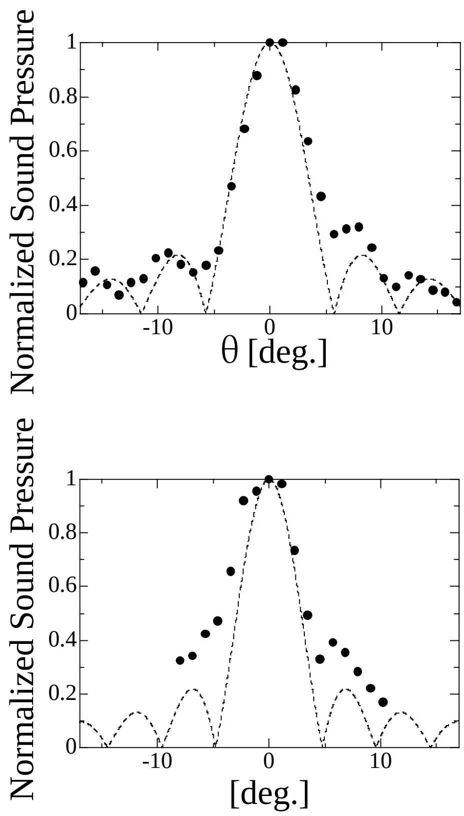

Fig. 12 Directivity in horizontal (upper) and vertical directions (lower).