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ACOUSTICAL LETTER

Extraction of sound field information from high-speed movie of flowing dust

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1. Introduction

In this paper, we propose a measuring method of the sound field using a high-speed movie of dust. The dust movement is considered to be related to the sound vibration. We observe the dust movement using two high-speed cameras in order to acquire information of the 3-D sound field. The influence of air current is reduced from the movement of dust so that the sound field information is extracted. The experimental results indicate that this method is effective for observing the sound field.

Generally, a number of microphones are used for measuring sound fields. However, a sound field is affected by the presence of a microphone, which may have to be set at various positions. Various measuring methods of acoustic imaging and understanding are being studied today. For instance, a laser Doppler vibrometer (LDV) is used for measuring a sound field by observing the change in the sound pressure [1–3], and acoustic TV, which consists of a microphone array and a parabolic reflector, are used for the real-time measurement of sound source information [4]. However, the method with LDV needs the stationary sound played because the sound field must be scanned. The method involving the use of the microphone array and parabolic reflector cannot measure sound field information because its purpose is sound source observation. A high-speed camera is also used for observing the sound source and the sound field by particle imaging velocimetry (PIV) [5,6]. However, those methods require specific equipment such as spatially spreaded particles or a high-power laser.

The purpose of this study is to obtain sound field information from a high-speed movie of dust. To measure the sound field more simply, we use the phenomenon of light reflection, for example, as when dust is visible in a theater spotlight. It is considered that knowing the dust movement enables us to observe the sound field particularly in particle velocities. We examine our method using high-speed movies of dust and comparison with the vibration of a speaker cone.

2. Extract sound information

Since sounds propagate through the air via changes in air density, dust movement is related to sound vibration. For this reason, the sound field information can be obtained from the dust movement. The recording and analyzing process is shown in Fig. 1. First, the flowing dust is recorded using high-speed cameras. Second, the movements of a particle of dust are tracked by template matching between the recorded image and a sample image of particle dust. Dust settles at a location where the correlation value is the highest of all values. Then, 3-D coordinates are calculated from right and left camera images. Finally, we reduce the influence of air current from the dust movement so that the original sound field information is extracted.

High-speed cameras can simultaneously record the sound vibrations at two or more points within the range of the camera. In this method, the frame rate of a high-speed camera corresponds to the sampling rate of the A/D converter. According to the sampling theorem, a high-speed camera can record sounds that include less than half the frequency of its frame rate. In theory, auditory sounds can be fully recorded by a high-speed camera that records more than 40 thousand frames per second. We set the x-axis as rightward, the y-axis as downward, and the z-axis as backward in the view of high-speed cameras. An axis perpendicular to the speaker is referred to as the speaker-axis.

3. Estimation of 3-D location

Using two cameras, not only 2-D information of the photographic subject but also depth information are recorded [7]. The cameras are set at the same height and parallel to each of the optical axes, as shown in Fig. 2, where "b" refers to a baseline length, which is the length between the left camera and the right camera, and "f" refers to the focal length of the camera. Figure 2(a) illustrates the positional relationship between cameras and the photographic subject, and Fig. 2(b) illustrates overhead view of Fig. 2(a). We define the coordinate systems, $x_l - y_l$ coordinate systems and $x_r - y_r$ coordinate systems, with their origins at the center of each camera image. The $x_l - y_l$ plane and the $x_r - y_r$ plane represent the left camera image and the right camera image, respectively.

From the similarity rule in Fig. 2(b),

$$f : x_{rl} = z_l : (x_l - b), \tag{1}$$

$$x_{rl} z_l = f(x_l - b). \tag{2}$$

Similarly, that calculated in the y-z plane is

$$f : y_{rl} = z_l : y_l, \tag{3}$$

$$y_{rl} z_l = f y_l. \tag{4}$$

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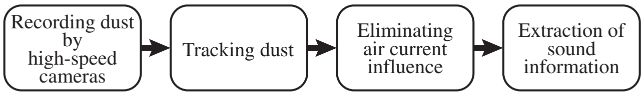

Fig. 1 Recording and analyzing process.

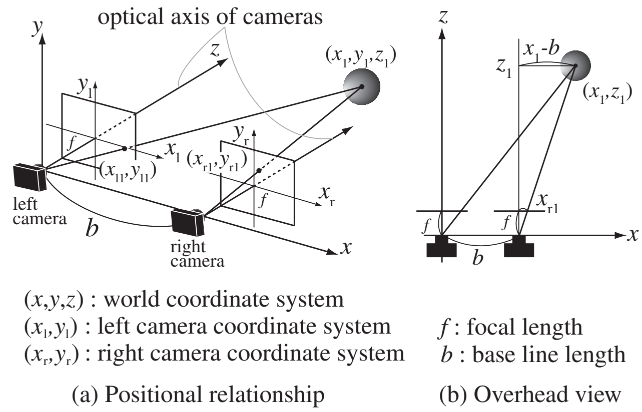

Fig. 2 Estimation of 3-D location.

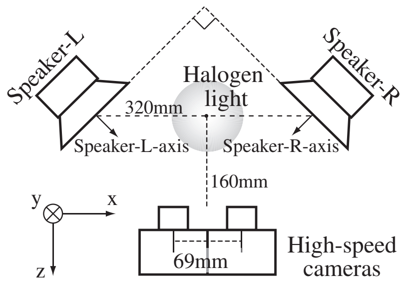

Fig. 3 Condition of experiment with two sound sources (overhead view).

Table 1 Detail of experiment.

High-speed camera	EXILIM EX-F1 (CASIO)
Powered monitor Speaker	MSP-7 (YAMAHA)
Focal length	36 mm
Frame late	300 fps
Pixel count	512 × 384 pixels
Sound pressure level	114 dB

Equations on the left camera image are calculated the same as the right camera image,

$$y_{l1}z_1 = fx_1, \tag{5}$$

$$y_{l1}z_1 = fy_1. \tag{6}$$

From Eqs. (2), (4), (5), and (6),

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \frac{b}{(x_{l1} - x_{r1})} \begin{pmatrix} x_{l1} \\ y_{l1} \\ f \end{pmatrix}. \tag{7}$$

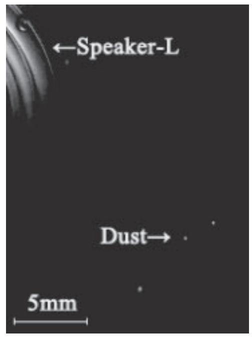

Fig. 4 Observed image of left camera.

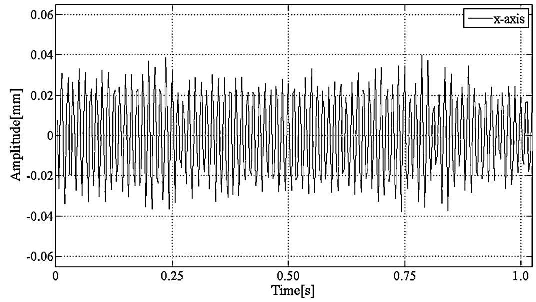

Fig. 5 Vibration waveform of dust on x-axis.

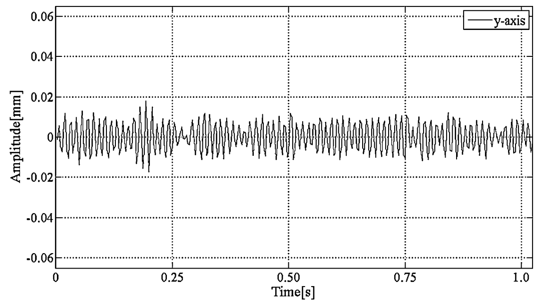

Fig. 6 Vibration waveform of dust on y-axis.

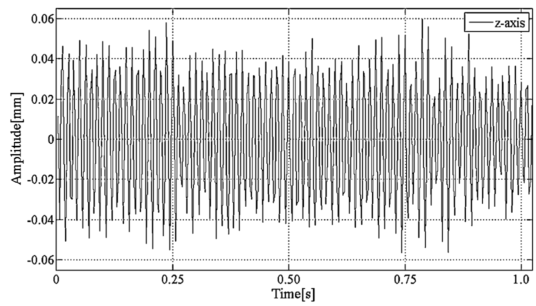

Fig. 7 Vibration waveform of dust on z-axis.

The 3-D location is calculated using right and left camera images.

4. Measuring sound field of two sound sources

A sound field generated using two speakers was measured

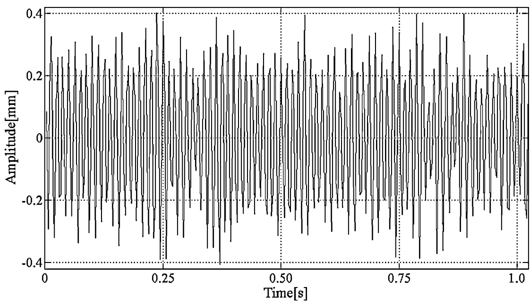

Fig. 8 Vibration waveform of dust on speaker-L-axis.

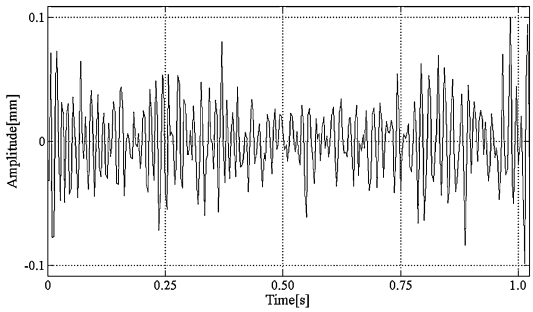

Fig. 9 Vibration waveform of dust on speaker-L-axis without 80 Hz.

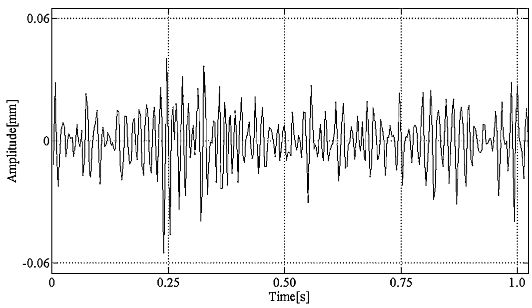

Fig. 10 Vibration waveform of speaker-L's cone.

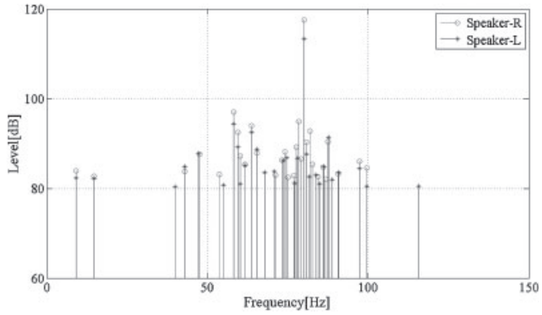

Fig. 11 Frequency analysis of dust on speaker-axis.

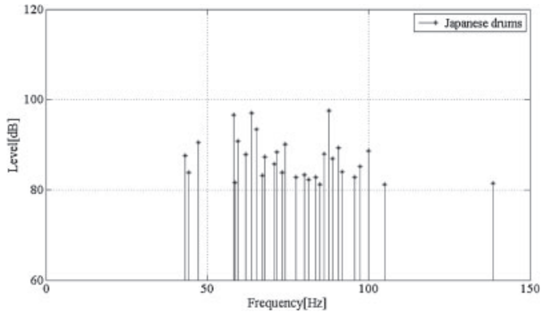

Fig. 12 Frequency analysis of Speaker-L's cone.

from high-speed movies of dust. Two high-speed cameras and the powered monitor speakers were located as shown in Fig. 3. Speaker-L was driven by the sound of Japanese drums and Speaker-R was driven by 80 Hz sinusoidal sound. Other details are shown in Table 1 and the observed image of the left camera is shown in Fig. 4.

Figures 5 to 7 show the vibration waveforms of dust on each of the three axes. The vibration waveform of dust on the speaker-L-axis is shown in Fig. 8. Speaker-L was driven by the sound of Japanese drums. This vibration waveform is also affected by 80 Hz sinusoidal sound from speaker-R. Figure 9 shows the vibration waveform of dust without the 80 Hz component on the speaker-L-axis. Meanwhile, because the sound from a speaker can be reproduced by the movies of speaker's cone [5], the vibration waveform of speaker-L's cone at the same time is shown in Fig. 10. As shown in Figs. 9 and 10, the vibration waveform of dust on speaker-L-axis is in agreement with speaker-L's cone vibration waveform. The result of the frequency analysis of the dust vibrations on each speaker-axis and the vibration of speaker-L's cone are shown in Figs. 11 and 12, respectively. To analyze the frequency component, generalized harmonic analysis (GHA) was used [8]. As shown in Figs. 11 and 12, the dust vibration on the speaker-L-axis contains speaker-L's cone vibration more than the dust vibration on the speaker-R-axis. As a result, the components and the directions of the sound field were obtained from high-speed movies of dust.

5. Conclusions

In this paper, we extracted the sound field information from high-speed movies of dust. The advantages of this method are the simpler measurement of the sound field and greater accuracy without microphones. The sound field generated by two speakers was measured in this method. From the result of the waveforms and the frequency components, it is confirmed that the sound field information can be obtained from the movement of dust. In our future study, we will examine the relationship between dust and the particle velocity, improve S/N, and search for the direction of sound sources.

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