EXTRACTION OF SOUND FIELD INFORMATION FROM FLOWING DUST CAPTURED WITH HIGH-SPEED CAMERA

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ABSTRACT

In this paper, we propose a measuring method of the sound field from high-speed movie of dust. The movements of dust in the sound field are affected by the sound vibration. We observe the dust using high-speed cameras. The movie is recorded by one high-speed camera in order to get the information of 2-D sound field and two high-speed cameras for 3-D. 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 to observe the sound field especially composed of low frequency components.

Index Terms**—** High-speed camera, 3-D records, Sound field, Dust

1. INTRODUCTION

Generally, a number of microphones are used for measuring sound fields. However, a sound field is affected by a microphone, which may have to set at various positions. A variety of methods to measure sound fields are studied today. For instance, laser Doppler vibrometer is used for measuring sound fields by the change of the sound pressure [1][2]. Also, high-speed cameras are used for observing the sound source and the sound field [3][4]. However, those methods require specific equipment such as spatially-spreaded particles or a high-power-laser. Besides used for art, cameras have been used for photogrammetric system. This is because cameras can observe what we see without contacting or destructing it.

In this paper, sound fields are observed through high-speed movies of dust, since sounds propagate through a medium inclusive of dust. Movements of medium enable us to observe intact sound field especially in particle velocities. We use phenomenon of light reflection, for example, the dust is visible in a spotlight in a theater. Using high-speed cameras, we can record the vibrations of a transient sound at two or more points within the range of the camera at the same time. When sound vibrations are recorded using a high-speed camera, a frame rate of camera correspond to sampling rate of A/D converter. From sampling theorem, a high-speed camera can record sounds which include less than half frequency of its frame rate.

2. MOTION OF A PARTICLE IN A MOVING FLUID

Dust cannot follow airflow completely because of fictitious force. Therefore, it is necessary to exemplify its capability to follow airflow [5]. When the fluid fluctuates, the particle velocity

$$u_p = \int_0^\infty [\eta\{\xi\cos(\omega t+\beta)+\lambda\sin(\omega t+\beta)\}]d\omega, \tag{1}$$

where $\eta = \sqrt{(1+f_1)^2+f_2^2}$ and $\beta = \tan^{-1}\{f_2/(1+f_1)\}$

in which η is amplitude ratio of the particle to the fluid velocity and β is phase angle. For the general case,

$$f_1 = \frac{\left\{1+\frac{9}{\sqrt{2}(s+1/2)}N_s\right\}\left(\frac{1-s}{s+1/2}\right)}{\frac{81}{(s+1/2)^2}\left(2N_s^2+\frac{N_s}{\sqrt{2}}\right)^2+\left\{1+\frac{9}{\sqrt{2}(s+1/2)}N_s\right\}^2}, \tag{2}$$

$$f_2 = \frac{\frac{9(1-s)}{(s+1/2)^2}\left(2N_s^2+\frac{N_s}{\sqrt{2}}\right)}{\frac{81}{(s+1/2)^2}\left(2N_s^2+\frac{N_s}{\sqrt{2}}\right)^2+\left\{1+\frac{9}{\sqrt{2}(s+1/2)}N_s\right\}^2}, \tag{3}$$

where $s=\rho_p/\rho_f$ and $N_s=\sqrt{\nu/\omega d^2}$. In which ρ_p is density of the particle, ρ_f is density of the fluid, d is diameter of sphere and ν is kinematic viscosity. The amplitude ratio of each frequency for each particle size is shown in Fig.1. The following capability is decreased with increasing frequency. In low-frequency, however, the dust is expected to follow the airflow well. It is presumed that the dust is composed of nylon which is approximately 100 µm - 300 µm in diameter and exists in the room.

3. EXPERIMENTS AND RESULTS

We measured sound fields by high-speed movies of dust. Figure 2 illustrates the recording and the analyzing process of the method. First, the flowing dust is recorded with high-speed cameras. Second, the movements of a particle of dust

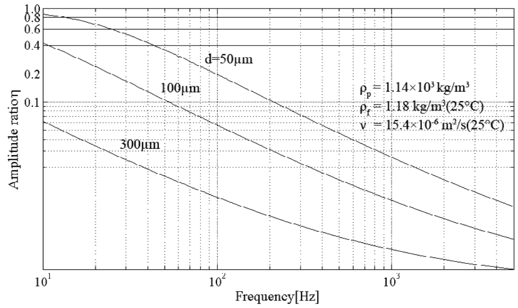

Fig.1. Amplitude ratio for particles.

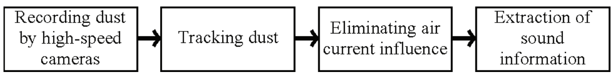

Fig.2. Recording and analyzing process.

are tracked by template matching between the recorded image and a sample image of a dust. Dust is set on the location where correlation value is the highest of all values. When dust is recorded by the stereo camera system, 3-D coordinates are calculated using the information of right and left images. Finally, we reduce the influence of air current from the movement of dust so that the original sound field information is extracted.

We did three experiments in this method. Measurements of its frequency response, the sound field which mainly contains pure sound and the sound field which contains both pure sound and sound of Japanese drums. In all experiments, the active speakers (YAMAHA MSP-7) are used for generating the sound field. To analyze the data, we set x-axis as rightward, y-axis as downward and z-axis as backward from high-speed cameras. In this study, it is assumed that sound propagates the direction perpendicular to the speaker, and the axis perpendicular to the speaker is referred to as speaker-axis.

3.1. Frequency response

As a basic experiment, its frequency characteristic was measured. As shown in Fig.3, a high-speed camera was located beside the speaker driven by TSP (Time-Stretched-Pulse). TSP is a test signal of acoustical measurement method [6]. Then, we recorded dust which exists between the speaker and the camera. A halogen light was set under the space. Other conditions are shown in Table 1.

Figure 4 shows the frequency characteristic calculated from the measured TSP signal. Regarding more than 100 Hz components, the level decreases same as Fig.1. This experiment explains that this method is useful for the measurement of low-frequency sounds.

3.2. Sound field with one sound source

The sound field generated by one speaker was measured. Two high-speed cameras and the speaker were located as

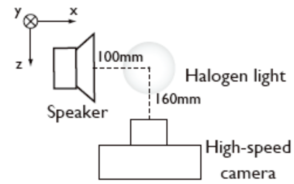

Fig.3. Experiment condition of frequency response measurement (overhead view).

Table 1. Detail of experiment in frequency response measurement.

High-speed camera	EXILIM EX-F1 (CASIO)
Focal length	36 mm
Frame rate	600 fps
Pixel count	432×192 pixels
Sound Pressure Level	100 dB (at the middle point)

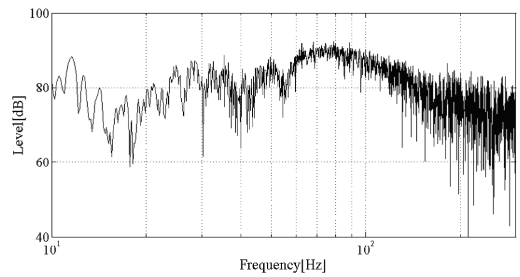

Fig.4. Frequency characteristic.

Fig.5. In this time, the speaker was driven by 125 Hz pure sound. A halogen light is set under the space. Other conditions are shown in Table 2.

Figure 6 shows the dust movement including air currents. Figure 7 and 8 show the dust vibration waveform on speaker-axis and frequency analysis result, respectively. To analyze the frequency component, GHA (generalized harmonic analysis) was used. From these results, it is clear that 125 Hz component is included in the sound field.

3.2.1. Generalized harmonic analysis

GHA is a one of frequency analyses method. To extract pure tones from an original sound, so as to minimize residual energy between the original sound and the pure tone. The analysis result is unaffected by the window function and the length of the analytic section [7] [8].

When a continuous signal $x_0(t)$ is in the length of the analytic section $L(t)$, Fourier modulus

$$S(f) = \frac{2}{nT}\int_0^{nT} x_0(t)\sin(2\pi ft)dt \quad (4)$$

$$C(f) = \frac{2}{nT}\int_0^{nT} x_0(t)\cos(2\pi ft)dt \quad (5)$$

are calculated, where f is any frequency, T is wave period, n is integer and $nT \leq L$.

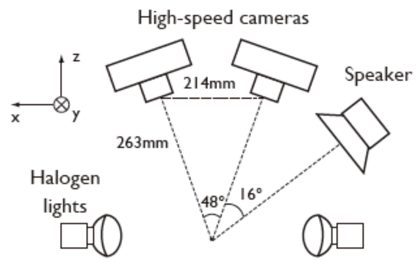

Fig.5. Condition of experiment
with one sound source (overhead view).

Table 2. Detail of experiment with one sound source.

High-speed camera	FASTCAM SA5 (Photron)
Focal length	50 mm
Frame rate	4000 fps
Pixel count	1024×1024 pixels
Sound Pressure Level	110 dB (at the middle point)

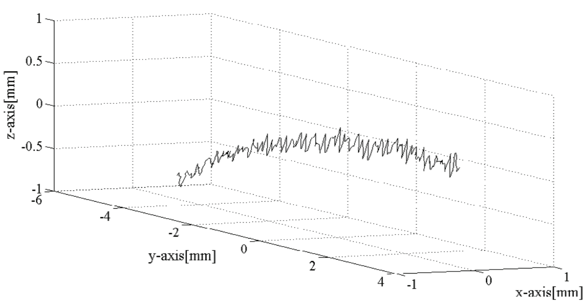

Fig.6. Movement of dust.

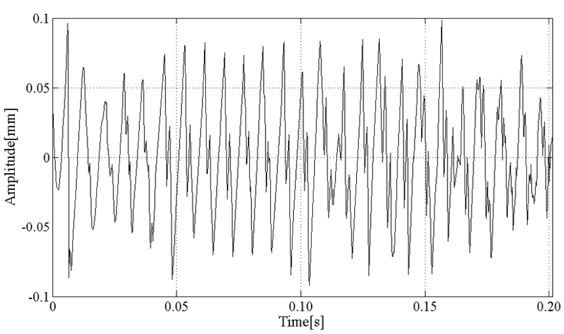

Fig.7. Vibration waveform of dust.

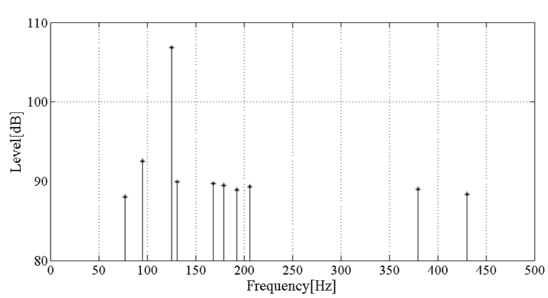

Fig.8. Result of frequency analysis.

Based on this, residual energy on each frequency

$$E(f) = \int_0^L \varepsilon(t,f)^2 dt \quad (6)$$

is calculated. The residual $\varepsilon(t,f)$ is given by

$$\varepsilon(t,f) = x_0(t) - S(f)\sin(2\pi ft) - C(f)\cos(2\pi ft). \quad (7)$$

Then, the frequency f_1 which has its minimum energy and the factor $S_1(f_1)$, $C_1(f_1)$ are set up. We subtract its frequency component from the original wave

$$x_1(t) = x_0(t) - S_1(f_1)\sin(2\pi f_1 t) - C_1(f_1)\cos(2\pi f_1 t), \quad (8)$$

and the calculation (4) - (8) are repeated for it.

The original signal is combined as

$$x_0(t) \approx x(t) = \sum_{k=1}^{N} \{S_k(f_k)\sin(2\pi f_k t) + C_k(f_k)\cos(2\pi f_k t)\}. \quad (9)$$

Also, the power spectral $P(f_k)$ is estimated as

$$P(f_k) = S_k^2 + C_k^2. \quad (10)$$

3.3. Sound field with two sound sources

The sound field generated by two speakers was measured. Two high-speed cameras and the speakers were located as Fig.9. Speaker-L was driven by sound of Japanese drums and Speaker-R was driven by 80 Hz pure sound. Other conditions are shown in Table 3.

The vibration waveform of the dust on speaker-L-axis is shown in Fig.10. Speaker-L was driven by sound of Japanese drums. This sound vibration is also affected by 80 Hz pure sound from speaker-R. Figure 11 shows the vibration waveform of the dust without the 80Hz component on speaker-L-axis. On the other hand, the vibration waveform of speaker-L's cone at the same time is shown in Fig.12. It is known that the sound field generated a speaker is reconstructed by vibrations of speaker cone [3]. As shown in Fig.11 and 12, the vibration waveform of the dust on speaker-L-axis is in agreement with the speaker-L's cone vibration waveform. Figure 13 and 14 show the frequency components of vibration waveform of dust on each speaker-axis and speaker-L's cone, respectively. As shown in Fig.13 and 14, the dust vibration in speaker-L-axis contains speaker-L's cone vibration, more than in speaker-R-axis. As a result, the components and the directions of the sound field can be obtained from high-speed movie of dust.

4. CONCLUSIONS

In this paper, we extracted the sound field information from high-speed movies of dust. The sound field measuring method using the high-speed camera has the advantage of being able to measure a transient sound and multipoint measurement. Our results of waveforms and the frequency analyses confirm that the sound field information was extracted from the movements of the dust. Moreover, the frequency response of this method is measured and it shows this method is useful for low-frequency sounds.

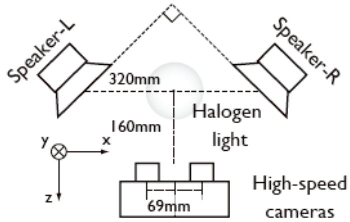

Fig.9. Condition of experiment
with two sound sources (overhead view).

Table 3. Detail of experiment with two sound sources.

High-speed camera	EXILIM EX-F1 (CASIO)
Focal length	36 mm
Frame rate	300 fps
Pixel count	512×384 pixels
Sound Pressure Level	114 dB (at the middle point)

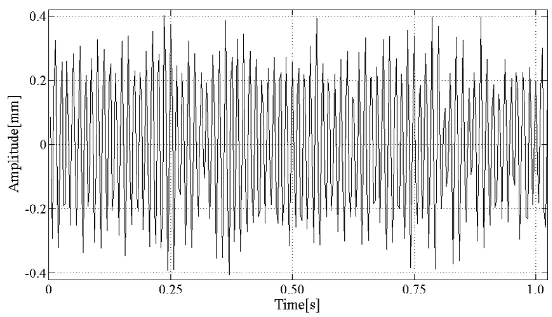

Fig.10. Vibration waveform of dust
on speaker-L-axis.

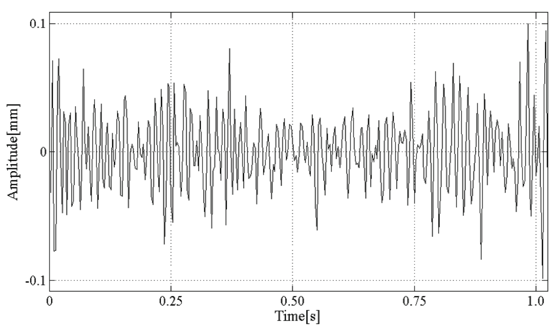

Fig.11. Vibration waveform of dust
on speaker-L-axis without 80 Hz.

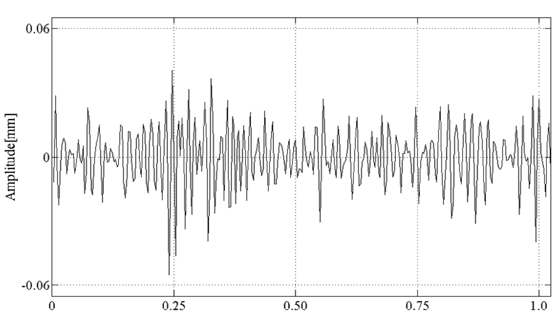

Fig.12. Vibration waveform of speaker-L's cone.

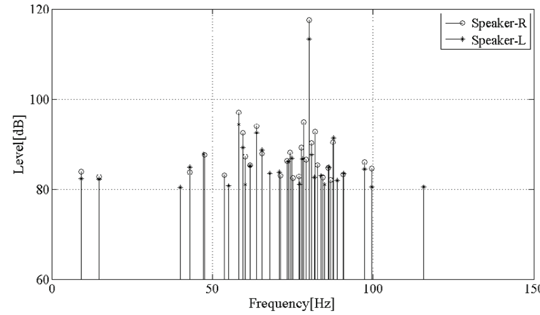

Fig.13. Frequency analysis of dust on speaker-axis.

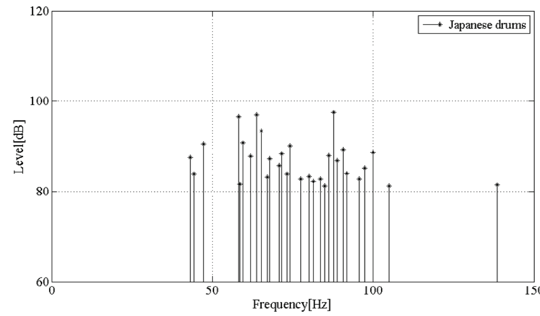

Fig.14. Frequency analysis of speaker-L's cone.

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