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Effect of handy microphone movement in mixed reality visualization system of sound intensity

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Abstract

We have proposed a system of real-time measurement and visualization for three-dimensional (3D) sound field by using mixed reality (MR) device. MR device enables effective visualization with depth perception using the 3D computer graphics (3DCGs) superimposed on the real world. Our system can superimpose 3D sound intensity data on the measurement points in the see-through head mounted display (STHMD). It helps us not only to understand the sound field but also to design it, to detect the source of noise, etc. Sound intensities are measured by freely and slowly scanning the sound field with a handy 4-ch microphone array. However, the measurement results of sound intensity would be affected by assuming a moving microphone array as fixed one. In this paper, we investigate the effect of microphone movement on sound intensity. To clarify the maximum of handy microphone speed to be assumed, microphone speeds were measured in measurement of sound field by using our proposed MR visualization system. Then, simulation experiments in a plane wave and a spherical wave were conducted to compare the sound intensities by fixed and moving microphone array at different speeds.

Keywords: Acoustic imaging, sound intensity, Doppler effect, Mixed reality(MR), Augmented reality(AR)

1 INTRODUCTION

The social request for comfortable sound environment has been increasing. To improve sound environment, it is important to understand physical phenomena of sound field. In particular, sound field visualization technologies help us to intuitively understand the sound field information, because the spatial behavior of sound propagation is suited for visual perception which has higher spatial resolution. They have been utilized for estimating a noise source, checking a sound energy flow, acoustically designing rooms, etc. In previous studies, many visualization methods were proposed by using such as beamforming method [1, 2], acoustic holography [3, 4, 5] and optical visualization [6, 7, 8].

As one of sound field visualization technology, we have proposed three-dimensional (3D) visualization systems for sound propagation with a handy 4-ch microphone array by using augmented reality (AR)/mixed reality (MR) and simultaneous localization and mapping (SLAM) [9, 10, 11, 12]. AR/MR refer to the technologies to merge the real world constructs with virtual constructs generated by computer [13]. It enables us to represent the depth information in vision while adjusting to the movement of viewpoint. Thus, the measured information is translated to a object of 3D computer graphics (3DCG) with spatial and sound information. Then, observers with a head mounted display (HMD) can watch many measurement results while freely changing the viewpoint in a space. In particular, the real-time measurement and visualization systems [9, 10, 12] enable us to place a 3DCG object of sound intensity at each measurement point by slowly moving a handy 4-ch microphone array for understanding the relationships between the measurement results and actual objects.

Recently, a system of real-time measurement for 3D sound intensity by using the optical see-through HMD (OSTHMD) with SLAM [12] achieves free movement of measurement positions in a broad area. By an assumption in our previous visualization methods, the velocity of moving 4-ch microphone array must be slow enough to ignore the Doppler effect. To visualize a wide range of sound field in a shorter time, it is preferable

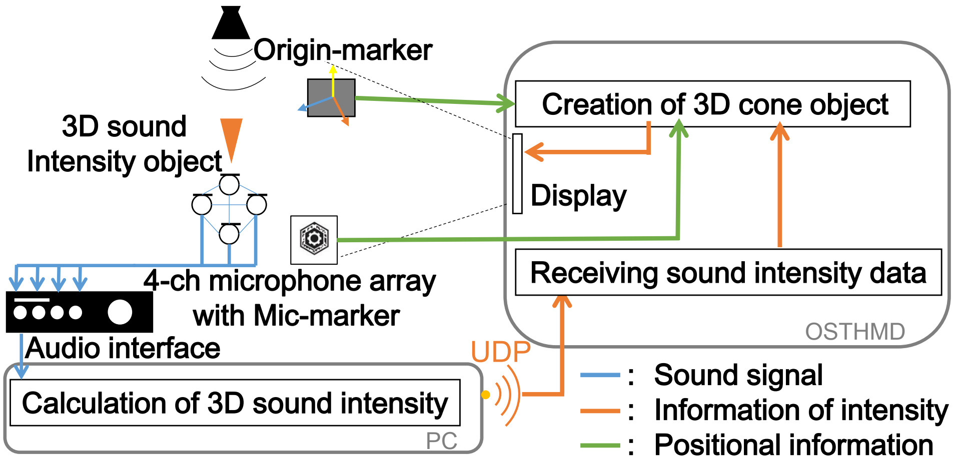

Figure 1. System overview. When a measured position and an intensity are transmitted to the OSTHMD, a 3D object is shown on the display of OSTHMD.

to measure the sound field moving the 4-ch microphone array at higher speed by removing Doppler effect.

For sound sources moving at high speed, many de-Dopplerization methods have been proposed with multiple microphones [2, 4, 5]. In this system, the Doppler effect on sound intensity is caused by moving the microphone array. In addition, average of sound intensities over analysis time is measured by a microphone array at a fixed position. However, a moving microphone array integrates sound intensities over time and the path of moving microphone.

In this paper, the effect of the Doppler shift on sound intensity when moving the microphone array, is quantitatively investigated by simulation. Next chapter provides an overview of the system used in this paper. Then, the moving velocity of the microphone was measured with our proposed system. Based on these results, 3D sound intensity due to the movement of the microphone array is formulated. Finally, the numerical simulation is conducted to compare the effects that a plane and spherical wave received.

2 MEASUREMENT AND VISUALIZATION SYSTEM

2.1 System overview

In this paper, we investigate the influence of moving the microphone array in the real-time measurement and visualization system [12]. Figure 1 shows the system overview. Microsoft HoloLens [14] is used as OSTHMD. SLAM installed at HoloLens makes the spatial map of the measured place and understand the position of observer in the spatial map. Based on the spatial map and observer's position, 3DCG representing 3D sound intensity is superimposed to be fixed to the corresponding position on the real space. When the AR marker installed at the 4-ch microphone array is detected by a camera of OSTHMD, the microphone positional information is sent sequentially to PC which is connected with the microphone array. Similarly, the sound signals are obtained sequentially, and are calculated to the sound intensity by cross-spectral method [15]. Sound intensity I_r between two microphones could be expressed as follows:

$$I_r = \frac{1}{2\pi\rho\Delta r}\int_{f_1}^{f_2} \frac{G_{12}(f)}{f} df, \tag{1}$$

where ρ is the atmospheric density, Δr is the distance between microphones, f_1 and f_2 are the lower and upper frequencies of the analyzed frequency range respectively, and G_{12} is the cross spectrum of two sound signals. Figure 2 shows a 4-ch microphone array we used. Six sound intensities that represent as I_{01}, I_{02},

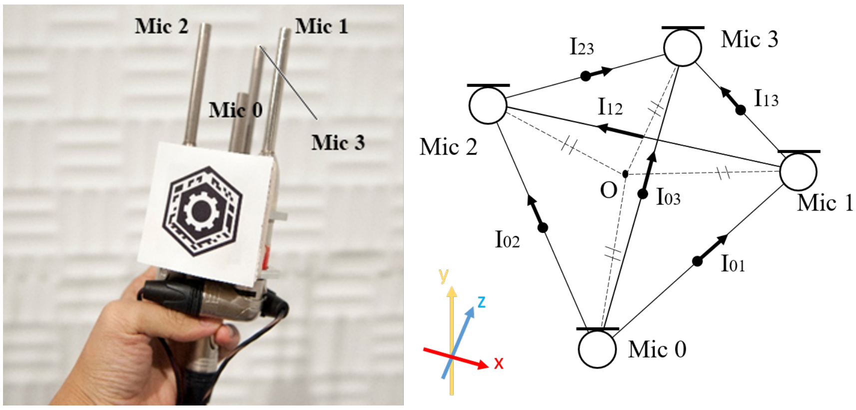

Figure 2. Image of the 4-ch microphone array. I_{01}, I_{02}, I_{03}, I_{12}, I_{13} and I_{23} represents the sound intensity between two microphones. By combining these intensities, it is possible to calculate the 3D sound intensity at center of array O.

I_{03}, I_{12}, I_{13} and I_{23} are measured by the 4-ch microphone array in the direction of all six pairs of the four microphones. We calculated 3D sound intensity from the six sound intensities. Each element of 3D sound intensity $\vec{I} = (I_x, I_y, I_z)$ is

$$I_x = \frac{I_{01} - I_{02} - 2I_{12} - I_{13} + I_{23}}{4}, \tag{2}$$

$$I_y = \frac{I_{01} + I_{02} + I_{03}}{\sqrt{6}}, \tag{3}$$

$$I_z = \frac{-I_{01} - I_{02} + 2I_{03} + 3I_{13} + 3I_{23}}{4\sqrt{3}}. \tag{4}$$

The sound intensity level is

$$L_i = 10 \log_{10} \frac{|\vec{I}|}{I_0}, \tag{5}$$

where $I_0 = 10^{-12}\mathrm{W/m^2}$ is a reference intensity. Finally, the 3DCG cone object is positioned at each measurement point by combining the transmitted 3D sound intensity data and its positional information in OSTHMD as shown in Fig. 3. The direction of the cone shows that of $\vec{I}$, and the color of the cone shows L_i.

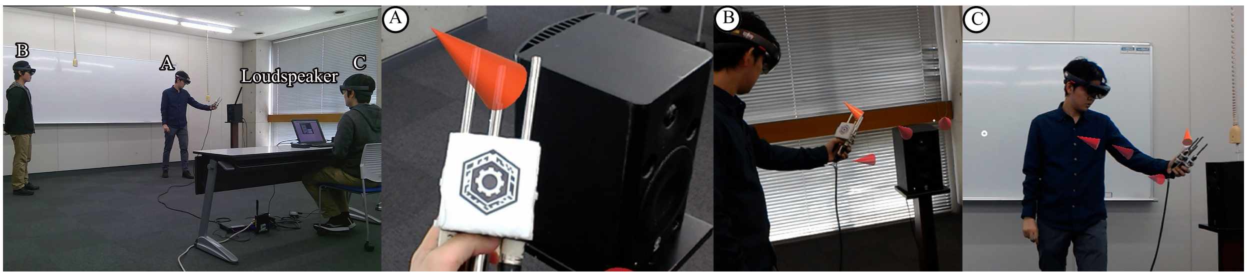

Figure 3. The state of measurement. The cone object of sound intensity is plotted by scanning the sound field with the microphone array.

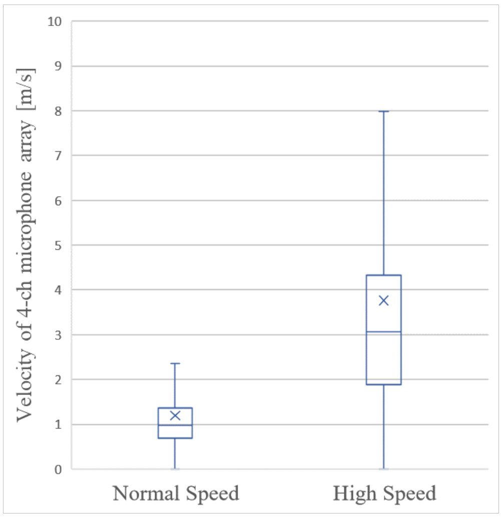

Figure 4. The velocity of 4-ch microphone array when movement is at normal (Normal speed) and quick (High speed).

2.2 Velocity of 4-ch microphone array

To investigate the influence of the Doppler shift by the movement of microphone array, the velocity of microphone array in our visualization system was measured. The position of the microphone array is detected with a AR marker by OSTHMD at 60 fps. Assuming that the movement path of the microphone array is line in 1/60 s frame interval, the velocity between two points is calculated from positional information. In experiment, the distribution of velocity was confirmed by acquiring 12000 samples each for the normal and quick movement. As shown in Fig. 4, the averages of velocity at the normal and quick movement are 1.12 m/s and 3.77 m/s, respectively. The maximum velocity at the quick movement is 7.98 m/s.

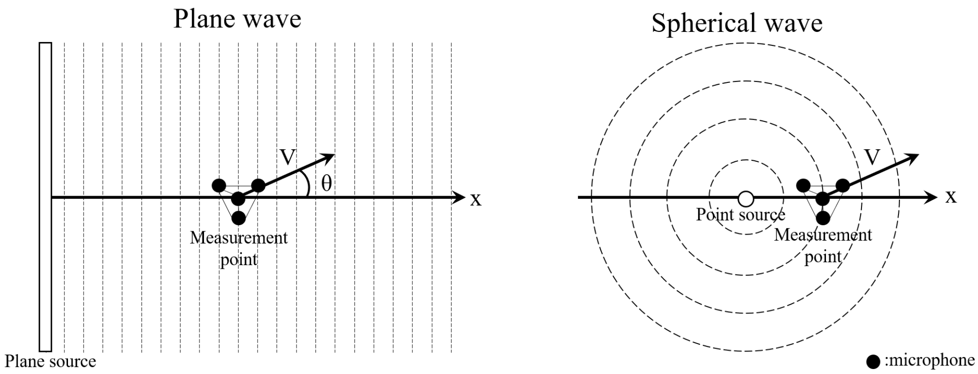

Figure 5. Arrangement of microphones and sound fields of plane wave and spherical wave. 4-ch microphone array is located on x-axis. It moves to the direction V.

3 THEORY

3.1 The effect of moving microphone in a plane wave

The medium is assumed to be stationary. A plane wave travels in the positive direction of x-axis with the speed of sound C. A 4-ch microphone array moved with velocity V. Then, the angle between the direction of propagation and the direction of V is described by θ as shown in Fig. 5.

The Doppler frequency shift f' in the plane wave field is as follows,

$$f' = \frac{C - V\cos\theta}{C} f, \tag{6}$$

where f is frequency of a sound source [16]. Using Eq. (6), the sound obtained by the moving microphone S_{moved} is represented as,

$$S_{\text{moved}} = e^{(ikr - 2\pi f' t)} = e^{\frac{2i\pi V \cos\theta f t}{C}} S_{\text{fixed}}, \tag{7}$$

where $i = \sqrt{-1}$, k is a wave number vector, r is a position of the microphone and S_{fixed} is the sound obtain the fixed microphone [17]:

$$S_{\text{fixed}} = e^{i(\vec{k}\vec{r} - 2\pi f t)}. \tag{8}$$

Thus, the sound affected by the Doppler shift can be described by the sound of the fixed microphone. By using the cross-spectrum G obtained from these four sound waves S_{moved}, the sound intensity obtained by the moving microphones can be calculated from the Eq. (1).

3.2 The effect in a spherical wave

When the microphone moves in sound field of a spherical wave, it is necessary to consider the reduction due to the distance from the sound source. Assuming that the sound source is placed at the origin, the distance between the source and the initial measurement point in the x-axis is r. The microphone array travels at velocity V. The sound measured at a distance r is defined as [17]:

$$S_{\text{fixed}} = \frac{e^{i(kr - 2\pi f t)}}{4\pi r}. \tag{9}$$

The distance between the measurement point and the source is sequentially changed as $r' = |r + vt|$. Then, the sound obtained by the moving microphone S_{moved} can be represented as follows,

$$S_{\text{moved}} = \frac{e^{i(kr - 2\pi f' t)}}{4\pi r'} = \frac{r e^{\frac{2i\pi(r' - r) f t}{C}}}{r'} S_{\text{fixed}}. \tag{10}$$

Thus, it is necessary to multiply signal of each microphone with a coefficient which changes with the distance. The 3D sound intensity obtained by the moving microphone array in the spherical wave can be calculated by using the cross-spectrum method from the obtained sound wave S_{moved} as well as the plane wave condition.

4 NUMERICAL SIMULATION

In this numerical simulation, the initial position of the source was located at (0 m, 0 m, 0 m), and the initial center position of the 4-ch microphone array r_0 was located at (5 m , 0 m , 0 m). The sound signals were measured with 44.10 kHz of sampling frequency and 4096 sample of analysis length. The frequency band used for the cross-spectrum method was an octave band of 1 kHz.

4.1 Plane wave simulation

First of all, we confirmed that the formula of the moving microphone array could be proved by theory when the source information was known. Figure 6 shows comparison of the sound intensities measured by moving

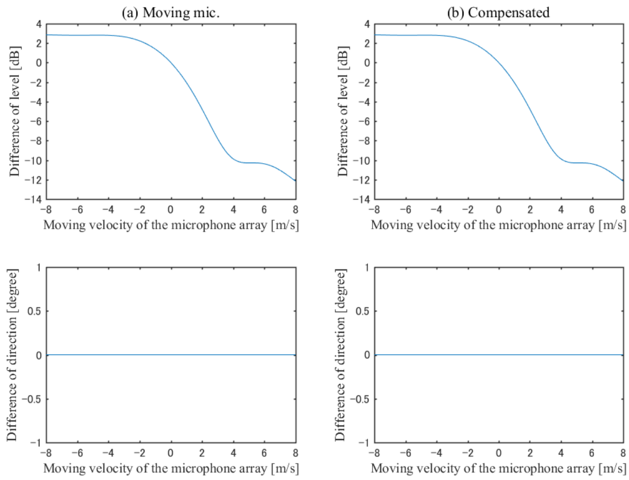

Figure 6. Sound intensities of plane wave at different velocities of the 4-ch microphone array along x-axis. The Right side was calculated by moving the microphone array, and the left side was calculated from the fixed microphone array by using an estimation method.

the microphone array in x-axis and the sound intensity compensated by a coefficient based on Eq.10. A plane wave of a single frequency 707 Hz is used as the sound source. The difference of sound intensities was defined as $10 \log 10(|I_{\mathrm{moved}}|/|I_{\mathrm{fixed}}|)$, where I_{moved} is the 3D sound intensity by moving microphone array and I_{fixed} is the fixed 3D sound intensity. The results showed that the fixed microphone and the actual moving microphone can accurately reproduce the direction and level difference regardless of the velocity.

From this result, it was found that when the velocity of microphone was positive, the frequency of the sound source was shifted downward. Then, the sound intensity was out of the range of frequency band due to the Doppler shift. Thus, about 10 dB of the difference of intensity level occurred compared to the fixed microphone. Thus, it was considered that the Doppler shift affects the intensity calculation result at the start and end of the frequency band [707 Hz 1414 Hz]. Then, by changing the frequency of the sound source near the start point of the band pass, the difference in the intensity level caused by the moving speed of the microphone in x-axis was confirmed. Figure 7 shows a result that the Doppler shift affected the sound intensity level by changing a frequency of sound source. [688 Hz 710 Hz] at 8 m/s of moving microphone array velocity, and [704 Hz 718 Hz] at 8 m/s were more than 10 dB of the difference in sound intensity. Therefore, we will need to take into account that the effect on intensity if the sound source have a frequency band near the edge of the intensity frequency band in a measurement. On the other hand, even when measuring at a normal speed of 2.5 m/s, it was confirmed that the influence of 7 dB at the maximum was received.

4.2 Spherical wave simulation

Figure 6 showed that the plane wave does not affect the direction of intensity. When the sound source is a spherical wave, the direction of sound intensity is affected. Then, the influence on the 3D sound intensity caused by the direction of the microphone movement is simulated in Fig. 8. When the microphone moves perpendicular to the propagation direction of the sound wave, the influence of the sound intensity level is small. However, the difference between the direction of intensities of the fixed and moving microphones had a difference of about four degrees in high speed condition. In this paper, although the movement direction of the microphone is limited to movement only along the axis in order to simplify the problem, rotations of the microphone and movement specific to handy microphone array are occurred.

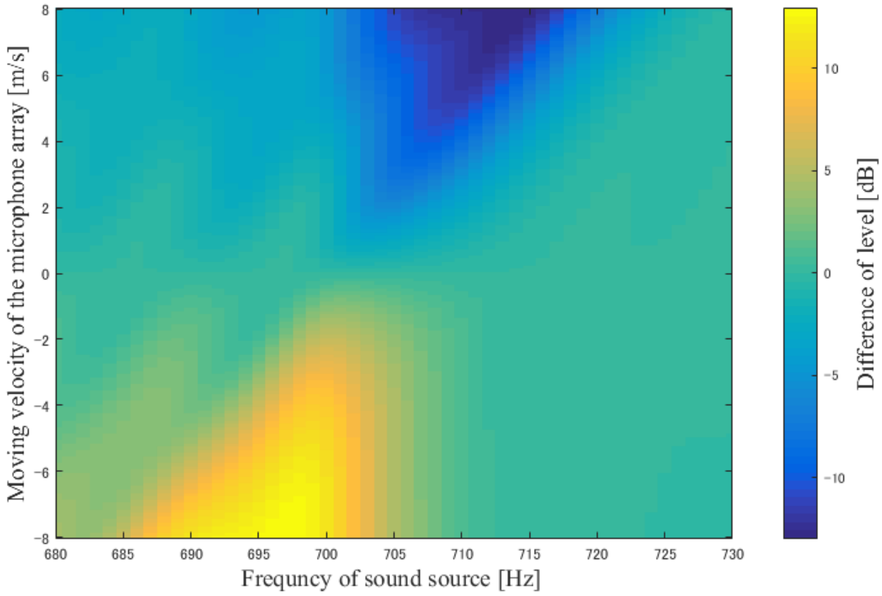

Figure 7. Sound intensity level difference between fixed and moving microphone caused by change of frequency of sound source. Specific frequencies affected the frequency band for calculating cross-spectrum method by Doppler shift.

5 CONCLUSIONS

In this paper, we investigated the effect caused by scanning the handy 4-ch microphone array of a real-time measurement and visualization system using OSTHMD. The velocity distribution of the handy 4-ch microphone array moved at normal speed and high speed was measured in our system. By multiplying the sound signals acquired from the fixed microphones by coefficients, When the source information is known, the 3D sound intensity obtained by the moving microphone array can be compensated. In numerical simulation, the difference of 3D sound intensity level was over 10 dB due to only the Doppler shift in a plane wave. The directional effect of the 3D sound intensity reaches 4 degrees when the microphone array moves at high speed perpendicularly to the propagation direction of spherical wave. Thus, it is necessary to remove the effect of 3D sound intensity when measuring at high speed. Although the simulation was performed in the moving direction along the axis

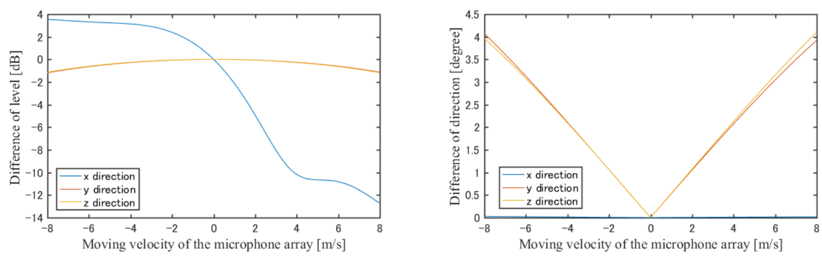

Figure 8. Relationship between the direction of moving microphone array and difference of sound intensity in a spherical wave. Unlike the plane wave, the direction of intensity was affected by moving microphone.

to simplify the conditions in this paper, the effect of 3D sound intensity with the other specific trajectory of handy microphone will be considered.

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