PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Double tetrahedral intensity probes for reducing the spatial bias error of source localization

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ABSTRACT

A compact tetrahedral probe used for measuring the three-dimensional acoustic intensity vector can be used for the source localization. Although such 3D intensimetry is advantageous in miniaturizing the sensing system size, it has not been popularly used due to its large spectral and spatial bias errors, which are additional to the bias errors at low and high frequency ranges. Compensation methods for spectral bias errors are recently proposed, but the spatial bias error, which is related to the probe orientation, is not easy to compensate. In this work, the idea is to adopt two probes together, thus effectively arranging the microphones to reduce the spatial sparseness of sensors and the irregularity in directivity. The number of microphones is minimized by sharing 1 or 3 microphones in the double module probes, while permitting the calculation of two intensity vectors. Two different types of probe configurations are used: twisted double probes, double tetrahedral probe symmetric to a face of the tetrahedron. A numerical simulation is conducted to compare the proposed probe systems with single probe. The result shows that the residual spatial bias error is less than 5.7° for 2.5<kd<4.1 range.

Keywords: 3D Acoustic intensimetry, Source localization, Double tetrahedral intensity probe

1. INTRODUCTION

A compact tetrahedral probe used for measuring the three-dimensional acoustic intensity vector can be used for the source localization. Although such 3D intensimetry is advantageous in miniaturizing the sensing system size compared to the other methods such as TDOA or beamforming, it has not been popularly used due to its inherently large spectral and spatial bias errors, which are additional to the well-known bias errors at low and high frequency ranges (1). Compensation methods for spectral bias errors are recently proposed by using the frequency band averaging or the phase filtering of cross correlation functions (2). However, the spatial bias error, which is related to the probe orientation to the source, is not easy to compensate. In this work, the idea is to adopt two tetrahedral probes together, thus effectively arranging the microphones to reduce the spatial sparseness of sensors and the irregularity in directivity.

2. ESTIMATION OF INTENSITY USING MICROPHONES

The one-dimensional active sound intensity can be estimated by calculating the cross-power spectral density (CPSD) function between adjacent two microphones (3). Similarly, the three-dimensional sound intensity can be estimated by adopting at least four microphones configured in the orthogonal space. To this end, an acoustic intensity probe configured in a tetrahedral microphone layout can be used, in which any set of two microphones keep the same spacing. The intensity vector component calculated in the Cartesian coordinates can be expressed as (4)

$$I_{\mathrm{a}} = \sum_{\mathrm{i=1}}^{\mathrm{m-1}} \sum_{\mathrm{j=i+1}}^{\mathrm{m}} \alpha_{\mathrm{ij}} \,\mathrm{Im}\left(\mathbf{G}_{\mathbf{ij}}\right) \Big/ \left(\rho_0 \omega d\right), \tag{1}$$

where $\mathbf{G}_{\mathbf{ij}}$ means CPSD between the measured pressure data at the i^{th} and j^{th} sensors, α_{ij} is the coefficient of the $\mathbf{G}_{\mathbf{ij}}$, d the spacing between adjacent microphones, ω the circular frequency, ρ_0 the medium density, m the number of microphones. The estimated azimuth and elevation angles denoting

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the source direction can be written as

$$\phi = \tan^{-1}\left\{ I_y(\omega) / I_x(\omega) \right\},\ \theta = \tan^{-1}\left\{ I_z(\omega) \Big/ \sqrt{I_x^{\,2}(\omega) + I_y^{\,2}(\omega)} \right\}. \tag{2}$$

The spectral bias error occurs due to the reflected wave, which can be compensated by the 1/3-octave band averaging or adopting the CPSD filtering method. Also, the spatial sparseness of the sensors makes the non-uniform directivity index (DI) of the probe, which makes the spatial bias error at the high range of Helmholtz number, kd, where k is the wavenumber. It is theoretically possible to compensate the spatial bias error by using the pre-calculated spatial error database for a single probe, but the compensation is not easy in practical problems.

3. DOUBLE TETRAHEDRAL INTENSITY PROBE

In this study, two probes are adopted as one module, thus effectively arranging the microphones to reduce the spatial sparseness of sensors and the irregularity in directivity. To this end, two different types of probe configurations are adopted: twisted double module, face-symmetric double module. Figure 1 shows the shape of single and double-tetrahedral probe modules and estimated DI and the spatial bias error for kd=2.5. The number of microphones is minimized by sharing 1 or 3 microphones in the double module probes, while permitting the calculation of two intensity vectors. One can find that the DI variation of the double tetrahedral modules is less than 0.8 dB, which is smaller than the single module case that bears the variation less than 1.0 dB. In case of the single module, the spatially averaged bias error is 4.1°, which is about two times larger than that of the double modules. Also, the spatial error variation of a single module is far larger than that of the double modules. One can figure out that the pattern of spatial bias error appears differently for each module, and the pattern is proportional to the gradient of DI as shown in Fig. 2. In Figures 1(e-f) and 2(b-c), the twisted and the face-symmetric double tetrahedral modules show that the error is maximum in the direction around z- and y-axis. Although such spatially non-uniform error occurs in the pole region of the double modules, one can find that the localization accuracy is better than the single module.

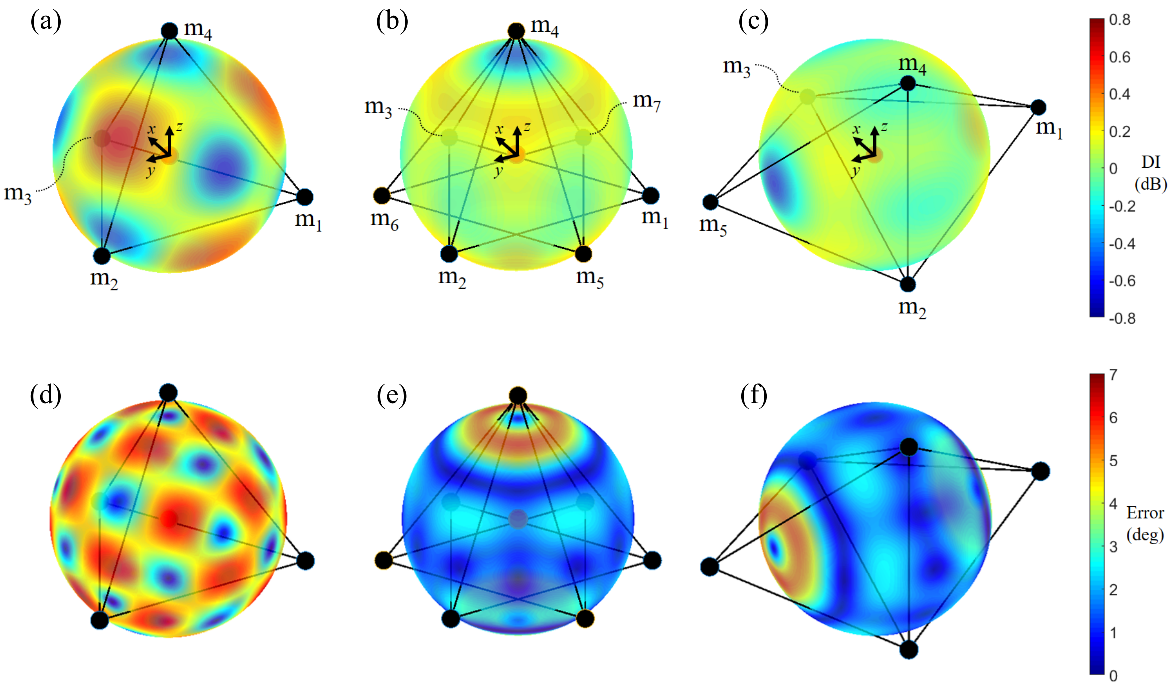

Figure 1. The shape of the single and double-tetrahedron intensity probes and the estimated DI and DoA error for kd=2.5: (a)(b)(c) DI of the probes, (d)(e)(f) the spatial bias error. (a)(d) Single-tetrahedron intensity module, (b)(e) twisted double module, (c)(f) face-symmetric double module.

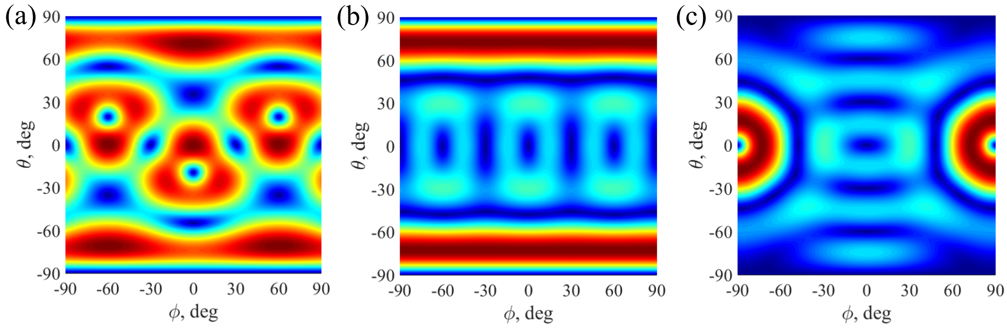

Figure 2. The gradient of DI of the single and double-tetrahedron intensity probes for *kd*=2.5: (a) single-tetrahedron intensity module, (b) twisted double module, (c) face-symmetric double module.

4. LOCALIZATION TEST

A numerical simulation is conducted to compare the localization performance of the proposed double module probes and a single module probe. A band-limited white noise for 0.5-1.6 kHz with 20 dB signal-to-noise ratio is used as the source signal, and the noise is incident from 543 directions, which are uniformly distributed in 3D space, on the acoustic center of each module. The spacing between adjacent microphones is varied for 85-140 mm, that corresponds to $2.5<kd<4.1$. Figure 3 shows the band-averaged spatial bias error of each module displayed in $-\pi/2<\phi<\pi/2$ and $-\pi/2<\theta<\pi/2$ for *kd*=2.5, 3.5, 4.1, respectively. The test result for $kd<2.5$ is omitted because the spatially averaged

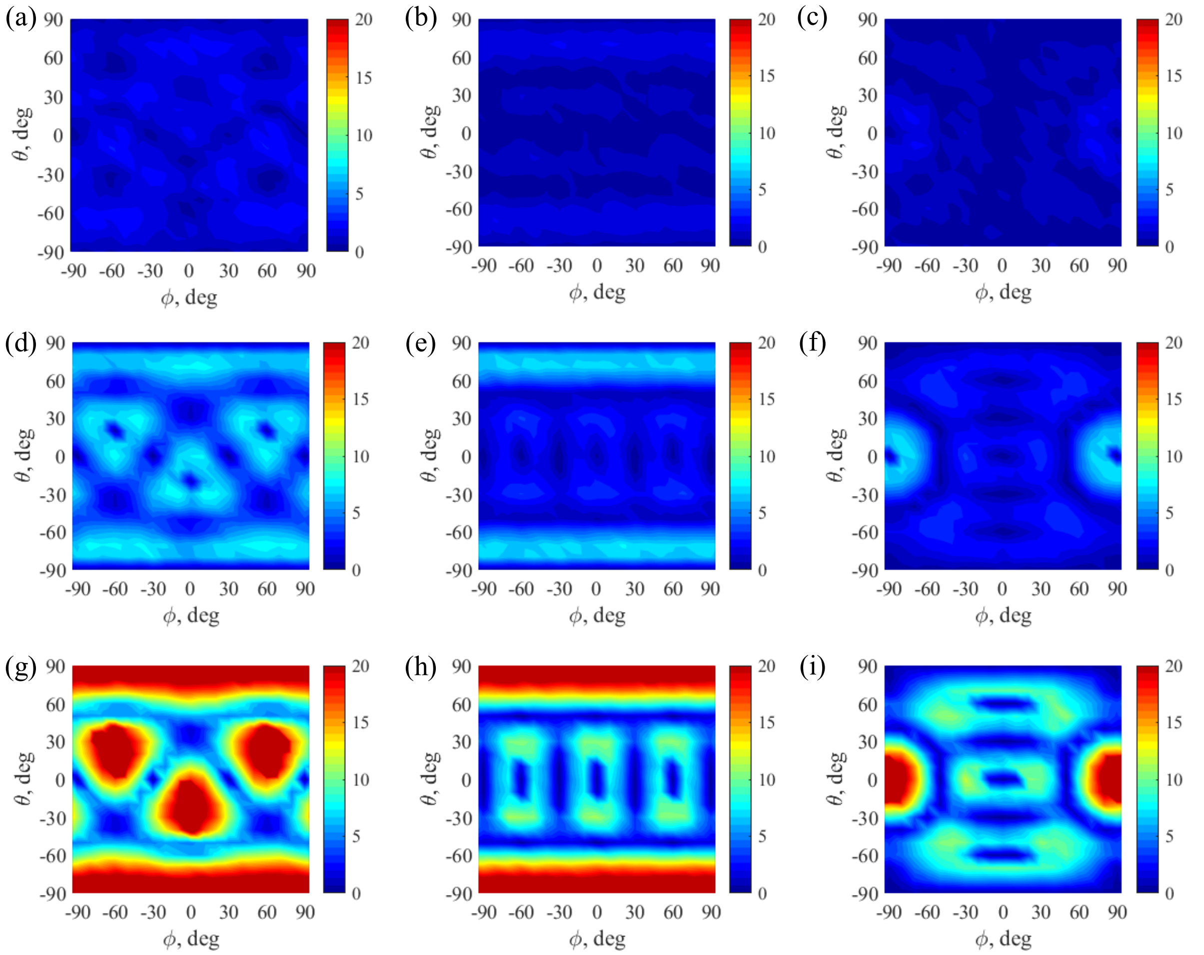

Figure 3. A comparison of single and double tetrahedral intensity probes in localization error for $2.5<kd<4.1$: (a)(b)(c) *kd*=2.5, (d)(e)(f) *kd*=3.5, (g)(h)(i) *kd*=4.1. (a)(d)(g) Single-tetrahedron intensity module, (b)(e)(h) twisted double module, (c)(f)(i) face-symmetric double module.

bias error of a single module is less than 1.4° and it is not significantly different for single and double modules. One can find that the difference of the error between the modules becomes large for *kd*>2.5 as presented in Figure 3. At *kd*=4.1, the averaged spatial bias error of twisted double module and face-symmetric double module is 4.8°, 5.7°, respectively, which is far smaller than the single module case that bears the error as much as 10.7°. The gradient of the DI forms a spatial bias error pattern of each module. By considering the pattern of the double modules, the twisted double module has robustness in azimuth angle, and the face-symmetric module is robust to the elevation angle in the source localization.

5. CONCLUSIONS

The spatial bias error in the 3D intensity vector measurement is compensated by using two types of double tetrahedral probes. The double modules have a residual error in the pole region, however, the spatially averaged bias error is much smaller than of the single tetrahedral module so the double module can conduct more accurate source localization in the high frequencies. The residual error in the direction of arrival becomes less than 5.7° for 2.5<*kd*<4.1. The twisted and face-symmetric modules are robust to the azimuth angle and elevation angle, respectively.

ACKNOWLEDGEMENTS

This work was partially supported by BK21-Plus Project, NRF grants (No. 2017R1A2B4007133 and 2016K2A9A2A12003779).

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