Estimating 3D-Position of A Stationary Random Acoustic Source Using Bispectral Analysis of 4-Point Detected Signals

Katsumi Hirata

Abstract—To develop the useful acoustic environmental recognition system, the method of estimating 3D-position of a stationary random acoustic source using bispectral analysis of 4-point detected signals is proposed. The method uses information about amplitude attenuation and propagation delay extracted from amplitude ratios and angles of auto- and cross-bispectra of the detected signals. It is expected that using bispectral analysis affects less influence of Gaussian noises than using conventional power spectral one. In this paper, the basic principle of the method is mentioned first, and its validity and features are considered from results of the fundamental experiments assumed ideal circumstances.

Keywords—4-point detection, a stationary random acoustic source, auto- and cross-bispectra, estimation of 3D-position.

I. INTRODUCTION

TO develop the useful acoustic environmental recognition system, it is the problem to be solved to localize the acoustic sources. We, human beings have the ability to localize acoustic sources using information about propagation delay and/or amplitude attenuation. In this study, we will realize the function of acoustic localization with simpler engineering way.

For such kind of problem, various methods are being developed [1]–[3], but most of those target the deterministic signal such as the voice with little consideration to influences of the observation noise. On the other hand, we propose localization methods which are applied to the random signal. Our conventional methods are based on the power (second order) spectral analysis and assumed that mutually uncorrelational noises are added to the detected signals. However, If the noise sources locate spatially, same or mutually correlated noises are added at detectors, and there is a possibility that the power spectral methods are difficult to be applied [4].

Then, we propose a method to estimate the 3D-position of a stationary random acoustic source using bispectral (third order spectral) analysis. We think that the bispectral method makes the localization under the circumstance with correlated Gaussian noises possible because the bispectrum of Gaussian signal vanishes [5].

In this paper, the basic principle of the proposed method is explained, then results of fundamental experiments under the ideal circumstance without acoustic reflections are presented,

K. Hirata is with the Department of Innovative Electrical and Electronic Engineering, Oyama National College of Technology, Oyama-shi, Tochigi, 323-0806 Japan (e-mail: hirata@oyama-ct.ac.jp).
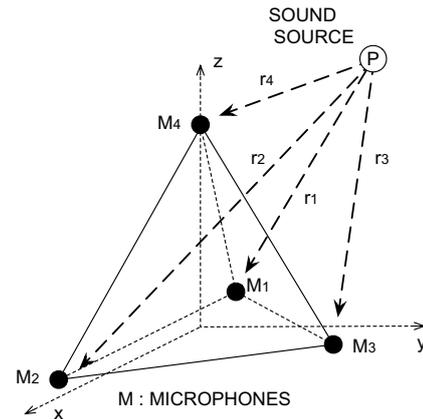
Fig. 1 The geometrical arrangement of a source and 4 microphones, where 'P', 'M's and 'r's denote a source, microphones and distances between the source and each microphone, respectively

and the validity and features of the localization method are made clear.

II. PRINCIPLE OF THE PROPOSED METHOD

A. Arrangement of Detectors and Detected Signals

This method is to estimate the 3D-position of a stationary random acoustic source using auto- and cross-bispectral analysis of signals detected at 4 spatially fixed microphones, where the signals are radiated from the source. The geometrical arrangement of a source and 4 microphones is illustrated in Fig.1. In the figure, P is a source, M_1, M_2, M_3 and M_4 are microphones, and r_1, r_2, r_3 and r_4 denote distances between the source and each microphone respectively. The origin of the coordinate axes is located at the centroid of a regular tetrahedron which has microphones at its apexes. The detected signals $x_i(t)$ at the microphones M_i are

$$x_i(t) = \frac{1}{r_i} s\left(t - \frac{r_i}{c}\right) + n_i(t), \quad i = 1, 2, 3, 4, \qquad (1)$$

where $s(t)$ is a stationary random signal radiated from a source, n_i is Gaussian noise added at the microphone, and c is the speed of sound. Therefore, the auto-bispectra $\Phi_{x_i x_i x_i}(f_1, f_2)$ of $x_i(t)$ are

$$\Phi_{x_i x_i x_i}(f_1, f_2) = \frac{1}{r_i^3} \Phi_{sss}(f_1, f_2), \quad i = 1, 2, 3, 4, \qquad (2)$$

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:8, No:6, 2014

where $\Phi_{sss}(f_1, f_2)$ is the auto-bispectrum of the radiated signal $s(t)$. The bispectrum is a third order spectrum. On the other hand, the cross-bispectra $\Phi_{x_i x_i x_4}(f_1, f_2)$ between $x_i(t)$ and $x_4(t)$ are

$$\Phi_{x_i x_i x_4}(f_1, f_2)$$
$$= \frac{1}{r_i^2 r_4} \Phi_{sss}(f_1, f_2) e^{-j2\pi(f_1+f_2)(r_4-r_1)/c}, \qquad (3)$$
$$i = 1, 2, 3.$$

There is no term including noise in the auto- and cross-bispectra because the third order statistics of Gaussian vanish.

B. Estimation of 3D Position of A Source

Equations (2) and (3) denote that the auto- and cross-bispectra of detected signals are inversely proportional to the cubic (or third-order) of the distances r_i, and the cross-bispectra have the phase term proportional to the differences of the distances $r_4 - r_i$. The following information is extracted from the ratio of amplitude and phase of the bispectra.

$$A_i(f_1, f_2) := \frac{|\Phi_{x_i x_i x_4}(f_1, f_2)|}{|\Phi_{x_i x_i x_i}(f_1, f_2)|} = \frac{r_i}{r_4}, \quad i = 1, 2, 3, \quad (4)$$

$$d_i(f_1, f_2) := \frac{c}{2\pi(f_1 + f_2)} \arg\left[\frac{\Phi_{x_i x_i x_4}(f_1, f_2)}{\Phi_{x_i x_i x_i}(f_1, f_2)}\right]$$
$$(5)$$
$$= r_4 - r_i, \qquad\qquad i = 1, 2, 3.$$

Equations (4) and (5) denote that $A_i(f_1, f_2)$ and $d_i(f_1, f_2)$ are the ratios and the differences of the distances r_i, respectively. The distances r_i are derived by solving these simultaneous equations, and then the 3D-position of the source is calculated with the microphones coordinates. This is the principle to estimating the source position by the method.

If the auto-bispectra of radiating signal is spread over the analyzing band, $A_i(f_1, f_2)$ and $d_i(f_1, f_2)$ must be constant irrespective of the frequencies f_1 and f_2. It is thought that the information is extracted accurately by averaging them over the analyzing band B_H,

$$\hat{A}_i = \frac{1}{B_H^2} \iint_{B_H} A_i(f_1, f_2) df_1 df_2, \qquad i = 1, 2, 3, \quad (6)$$

$$\hat{d}_i = \frac{1}{B_H^2} \iint_{B_H} d_i(f_1, f_2) df_1 df_2, \qquad i = 1, 2, 3. \quad (7)$$

III. FUNDAMENTAL EXPERIMENTS

A. Conditions

Fundamental experiments were conducted to make clear the validity and features of the proposed method. In the experiments, estimations of the 3D-position were carried out many times for four kinds of positions under noiseless or noisy environments, and the statistics of estimates are evaluated. The detected signals were made from abnormal sound radiated from a small fan of 50 mm in a diameter with amplitude attenuation and time delay which depend on each position of the source. The main experimental conditions are shown in Table I.

TABLE I
THE EXPERIMENTAL CONDITIONS

Position of source	A: (0.50, 0.25, 1.10) m
	B: (1.10, 0.54, 2.00) m
	C: (0.00, 0.00, 1.50) m
	D: (0.00, 0.00, 2.00) m
S/N of detected signal	∞, 20, 15, 10 and 5 dB
Radiated signal	abnormal sound of a fan (50mmϕ)
Intervals of microphones	1 m
Sampling frequency	44.1 kHz
Length of analyzed signal	0.046 s
Estimation of bispectra	nonparametric indirect method [6]
Smoothing window of bispectra	Parzen window
Analyzing band	$\leq$ 14.7 kHz

TABLE II
ERRORS OF POSITION ESTIMATES

(a) Bias errors [m]

Position	S/N				
	∞	20 dB	15 dB	10 dB	5dB
A	0.01	0.01	0.01	0.01	0.07
B	0.01	0.01	0.09	0.15	0.32
C	0.00	0.00	0.02	0.02	0.05
D	0.02	0.00	0.02	0.15	0.02

(b) RMS errors [m]

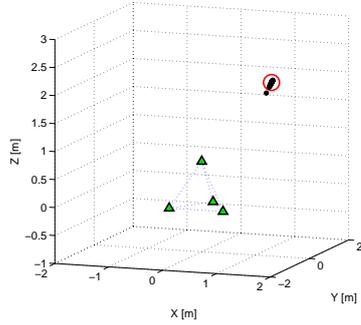| Position	S/N				
	∞	20 dB	15 dB	10 dB	5dB
A	0.01	0.06	0.09	0.13	0.25
B	0.03	0.13	0.33	0.51	0.70
C	0.00	0.06	0.16	0.40	0.64
D	0.02	0.11	0.14	1.24	0.63

B. Results

The distributions of the estimated positions from 50 independent estimations are shown in Fig. 2, 3 and 4, where red circles, black dots and green triangles indicate true positions, estimated positions of sources and microphones respectively. Fig. 2 show the estimates under the noiseless environment (S/N is ∞), and (a) - (d) are for the position A - D, respectively. For any positions, it is found that the estimates are very good with small errors because 50 dots are placed at the circle. Therefore, The source positions are able to be estimated by the method using bispectral analyses of detected signals.
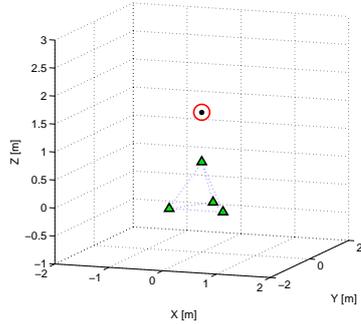
Next, Fig. 3 show the estimates under the noisy environment for the position A, where the Gaussian noises are added to the detected signals, and the S/N's are (a) 20 dB, (b)15dB, (c)10dB and (d) 5 dB. It is found that the variances of estimates are larger as the S/N is lower. But the estimates distribute around the true positions (the red circles). Though the 5dB-S/N is the very ill condition with loud noise, it is indicated the possibility of localization to a certain degree of accuracy with our method. Table II shows (a) bias and (b) RMS errors of estimates of positions in meters under each S/N, though the figures of the distributions of estimates for the position B, C and D are omitted for lack of space. The bias error is the norm of the 3D-vectors obtained by subtracting the true position from the mean of 50 estimated positions. The RMS error is the root of squared sum of the bias and the variance, and the error means the averaged magnitude of the error of the estimated positions. For noiseless estimation (S/N=$-\infty$), the bias and RMS errors are very small, and it is found that
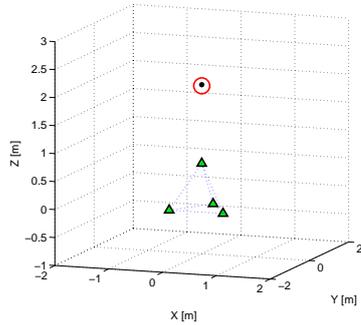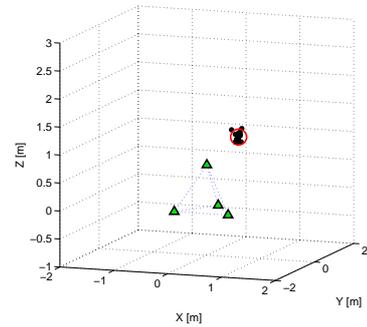
World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:8, No:6, 2014
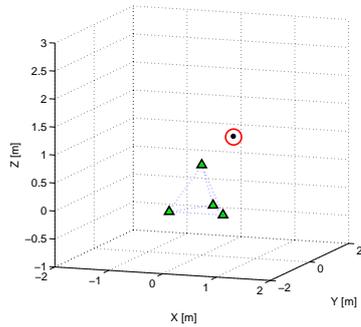
(a) Position A

(b) Position B

(c) Position C

(d) Position D

Fig. 2 The distributions of estimated positions from 50 independent estimations under the noiseless environment, where red circles, black dots and green triangles indicate true positions, estimated positions of sources and microphones respectively
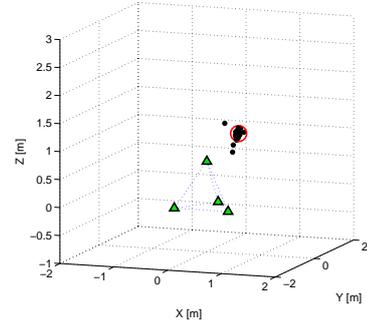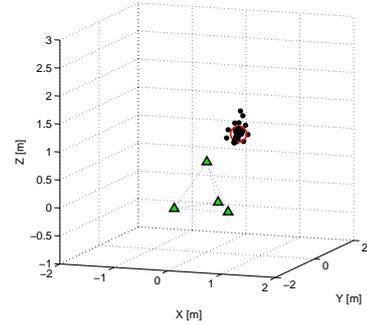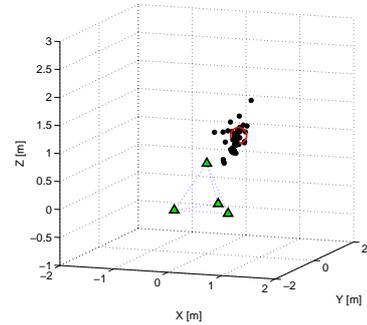

(a) S/N 20 dB

(b) S/N 15 dB

(c) S/N 10 dB

(d) S/N 5dB

Fig. 3 The distributions of estimated positions from 50 independent estimations under the noisy environment for the position A, where red circles, black dots and green triangles indicate true positions, estimated positions and microphones respectively

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:8, No:6, 2014

the estimations are implemented in errors of about 3 cm at maximum. Especially, the errors of estimates for the position A and C are nearly zero because the positions are closer from the microphones than others. The lower S/N cause increasing the RMS errors. The increases of bias errors are not as much as the RMS. Therefore, for examples, it is thought that the error can be suppressed by meaning multiple estimates for a estimation.

IV. Simplified Bispectral Analysis

The bispectrum is the 2-dimensional information with 2 parameters of frequencies f_1 and f_2. Therefore bispectral analysis takes time for calculation, and a memory is consumed. Then we introduce the simplified bispectral analysis to estimate a source position. In this section, the result of estimating using auto- and cross-bispectra only at $f_1 = f_2$ is reported as an example. The simplified auto- and cross-bispectra $B_{x_i x_i x_i}(f)$, $B_{x_i x_i x_4}(f)$ are described following equations.

$$B_{x_i x_i x_i}(f) = \frac{1}{r_i^3} B_{sss}(f), \quad i = 1, 2, 3, 4, \qquad (8)$$

where $B_{sss}(f)$ is the simplified auto-bispectrum of radiated signal $s(t)$, and

$$B_{x_i x_i x_4}(f) = \frac{1}{r_i^2 r_4} B_{sss}(f) e^{-j2\pi(2f)(r_4 - r_1)/c},$$
$$i = 1, 2, 3. \quad (9)$$

Fig. 4 shows examples of (a) the conventional auto-bispectra and (b) the simplified one of the signal detected at the microphone M_4, where a white broken line indicates $f_1 = f_2$. It is found that most of the components of the signal are on and near the line.

Table III shows (a) bias and (b) RMS errors of estimates of positions under each S/N. With a very few exceptions, the errors of estimates using simplified bispectra are as small as using conventional ones. It is thought that the information about the ratios and the differences of the distances from the microphones to the source is extracted efficiently because the most of the information is concentrated on the $f_1 = f_2$. Therefore, for the source signal having such a bispectral density, the method using simplified bispectra brings the efficient and effective estimation.

V. Conclusion

To develop the useful method of 3D-localization of an acoustic source, the method applicable to a stationary random acoustic source using the bispectral analysis of 4-point detected signals is proposed, and the validity and the features were made clear through the evaluations of the fundamental experimental results. As a result, first, the validity of the method was confirmed under the ideal and noiseless condition. Next, it was found that it is a task to heighten accuracy of the bispectra estimation and the information extraction. Moreover, we found that the estimates by the simplified bispectral analysis is as accurate as the conventional bispectral one but depending on the spectral density of the source signal.
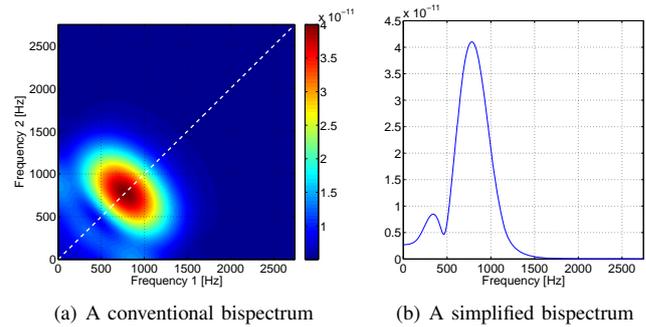

(a) A conventional bispectrum　　(b) A simplified bispectrum

Fig. 4　Examples of bispectra of the signal detected at M_4, where the white broken line indicates $f_1 = f_2$ in (a)

TABLE III
Errors of Position Estimates (Simplified Bispectral Analysis)

(a) Bias errors [m]

Position	S/N				
	∞	20 dB	15 dB	10 dB	5dB
A	0.01	0.01	0.01	0.03	0.05
B	0.01	0.03	0.13	0.07	0.11
C	0.00	0.00	0.01	0.28	0.03
D	0.02	0.04	0.02	0.02	0.07

(b) RMS errors [m]

Position	S/N				
	∞	20 dB	15 dB	10 dB	5dB
A	0.01	0.03	0.06	0.13	0.22
B	0.05	0.15	0.37	0.46	0.84
C	0.00	0.05	0.12	1.69	0.21
D	0.02	0.11	0.18	0.40	0.51

In addition, It is thought that it is necessary to consider applying to multiple sources or echoic environment.

References

[1] M. Shen and H. Liu, "A Modified Cross Power-Spectrum Phase Method Based on Microphone Array for Acoustic Source Localization," *Proceedings of the 2009 IEEE International Conference on Systems, Man, Cybernetics*, 2009, pp.1286-1291.
[2] H. Umezu and K. Suyama, "Multiple Sound Source Localization based on Local Existence Property of Speech Signal," *World Academy of Science, Engineering and Technology*, Vol.60, 2011, pp.491-494.
[3] A. Kumar and M. Pal, "Acoustic Source Localisation System using Microphone Arrays," *International Journal of Advanced Research in Computer Science and Software Engineering*, Vol.2, 2012, pp.82-88.
[4] K. Hirata and K. Sasaki, "3D-Localization Method of A Stationary Random Acoustic Source in Near-Field by Multi-Point Detectors and Its Experimental Evaluation," *Transaction of SICE of Japan*, Vol. 36, No. 6, 2000, pp. 467-472.
[5] T. Sato, K. Sasaki, and M. Taketani, "Bispectral Passive Velocimeter of A Moving Noisy Machine," *Journal of the Acoustical Society of America*, Vol.68, No.6, 1980, pp.1729-1735.
[6] C. L. Nikias and A. P. Petropulu, *Higher-Order Spectra Analysis: A nonlinear Signal Processing Framework*, Prentice Hall, 1993, pp.124-132.

Katsumi Hirata was born in Osaka, Japan, in 1975. He received the Ph.D. degree in engineering from University of Tsukuba in 2002. He is currently an assistant professor at Oyama National College of Technology, Japan.
Dr. Hirata is a member of the IEEE, the Institute of Electronics, Informations and Communication Engineers of Japan and the Society of Instrument and Control Engineers of Japan.