SOUND PHYSICAL PROPERTY MATCHING BETWEEN NON CENTRAL LISTENING POINT AND CENTRAL LISTENING POINT FOR NHK 22.2 SYSTEM REPRODUCTION

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ABSTRACT

NHK has proposed a famous 3D audio system: 22.2 multichannel system, but its loudspeakers are too many and are troublesome to put in home. Ando and Wang has proposed two simplification methods to reduce its channel number, but only 3D sound field at the central listening point can be recovered well by NHK 22.2 system and its simplified systems, the listening experience at a non central listening point is worse than that at the central listening point. In real life, listeners may stay at arbitrary listening point: central or non central point. Conventional pressure matching and particle matching method could be used for non central zone sound field reproduction, but they have some theoretical shortcomings. To address these problems, this paper propose a universal non central listening point sound field reproduction method by matching sound physical property between a non central listening point and the central listening point. Subjective and objective experiments show the effectiveness of the proposed method.

***Index Terms*—** non central listening point, 22.2 multichannel system, simplification, sound field reproduction

1. INTRODUCTION

In recent years, 3D audio and video technology has got great development. There are following 3D audio technologies: Ambisonics [1, 2, 3, 4], Wave Field Synthesis (WFS) [5, 6, 7, 8], Head Related Transfer Function (HRTF) [9, 10, 11], Vector Based Amplitude Panning (VBAP) [12, 13] and so on. Among them, VBAP is very easy and convenient to use. 22.2 multichannel system is a famous 3D audio system proposed by NHK in Japan by making use of VBAP to produce 3D sound image, but 22 loudspeakers is very time-consuming to put in family environment. To address this problem, in 2011 Akio Ando proposed a method which provides physical underpinnings for VBAP, and it can reduce original 22 channel without the two low-frequency effect channels to 10, and 8 channel [14]. But it uses the local optimal solution to form the global solution simply and omits magnitude error of particle velocity. To overcome its problems, in 2015 Wang built a general global model which can solve the global solution and maintain magnitude of particle velocity as much as possible [15]. 22.2 system and its simplification methods in [14, 15] all aim at keeping sound physical property at the center, the best listening point is at the center, but in practical case listener may stay at a non central listening point where they could not get the best listening experience.

As we know, there are some non central zone sound field reconstruction methods. Pressure matching method [16, 17] matches sound pressure in a same zone between original system and reproduced system, we note it as PMSZ. But when the loudspeaker are non-uniformly put or interval between loudspeakers is too big, its performance is worse. To overcome its problems, particle matching method [18] is proposed by matching particle velocity in a same zone between original system and reproduced system, we call it PVMSZ. Though tests are only made in central zone sound reproduction in papers [16, 17, 18], PMSZ and PVMSZ could be used for non central zone sound field reproduction from their theories. But PMSZ and PVMSZ have following theoretical shortcomings: (1) In non central zone sound field reproduction, PMSZ and PVMSZ all match sound physical property in a same zone between original system and reproduced system, so the best case is that a non central zone of original sound field is recovered, whose listening experience is worse than the listening experience in central zone of original system; (2) sound pressure and particle velocity are two main factors to describe sound [19], but PMSZ and PVMSZ just maintain one of them.

To address above problems, this paper takes 22.2 multichannel system reconstruction by 10 channel system as a example and proposes an non central listening point sound field reproduction method basing on sound physical property and

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listening point position which tries to reproduce the sound physical property at a non central listening point the same as the sound physical property at the central listening point.

2. BASIC DEFINITIONS

Sound pressure at the receiving point $\vec{m}=(m_x,m_y,m_z)$ produced by a point source (single loudspeaker could be seen as a point source in fact) locating at $\vec{\xi}=(\xi_x,\xi_y,\xi_z)$ is [14]:

$$p(\vec{m},\omega)=G\frac{e^{-ik|\vec{m}-\vec{\xi}|}}{|\vec{m}-\vec{\xi}|}s(\omega) \tag{1}$$

Particle velocity at the receiving point $\vec{m}=(m_x,m_y,m_z)$ produced by a point source locating at $\vec{\xi}=(\xi_x,\xi_y,\xi_z)$ is [14]:

$$u(\vec{m},\omega)=G(1+\tfrac{1}{ik|\vec{m}-\vec{\xi}|})\tfrac{e^{-ik|\vec{m}-\vec{\xi}|}}{|\vec{m}-\vec{\xi}|^2}\begin{pmatrix} m_x-\xi_x\\ m_y-\xi_y\\ m_z-\xi_z\end{pmatrix}s(\omega) \tag{2}$$

where k is the wave number, G is a proportion coefficient, $k{=}2\pi f/c$, f is sound frequency, c is sound speed in air, $s(\omega)$ is the Fourier transform of the input signal to the loudspeaker.

3. SOUND PHYSICAL PROPERTY AND LISTENING POINT POSITION BASED ERROR MINIMUM METHOD

First, we solve the distribution coefficients of q loudspeakers when they replace a point source. In cartesian coordinates, assume a point source and q loudspeakers are on a same sphere, whose center is O ($\vec{o}=(0,0,0)$), and radius is R, the point source locates at $\vec{\xi}=(\xi_x,\xi_y,\xi_z)$, q loudspeakers locate at $\vec{\xi}^{(j)}=(\xi_x^{(j)},\xi_y^{(j)},\xi_z^{(j)})$, $j=1,2,\cdots,q$, the arbitrary listening point is M whose coordinate is $\vec{m}=(m_x,m_y,m_z)$, $|\vec{m}|\le R$.

Assume that the sound pressure at O produced by a point source is the same as the sound pressure at M produced by q loudspeakers, we can get:

$$G\sum_{j=1}^{q}\frac{e^{-ik|\vec{m}-\vec{\xi}^{(j)}|}}{|\vec{m}-\vec{\xi}^{(j)}|}s_j(\omega)=G\frac{e^{-ik|\vec{o}-\vec{\xi}|}}{|\vec{o}-\vec{\xi}|}s(\omega) \tag{3}$$

where $s_j(\omega)=d_js(\omega)$. Let real part and image part on both sides of the equation (3) be equal, we can get:

$$\begin{pmatrix}\tilde{b}_{11} & \tilde{b}_{12} & \cdots & \tilde{b}_{1q}\\ \tilde{b}_{21} & \tilde{b}_{22} & \cdots & \tilde{b}_{2q}\end{pmatrix}D=\begin{pmatrix}b_1\\ b_2\end{pmatrix} \tag{4}$$

where

$$\begin{cases}\tilde{b}_{1,j}=\frac{\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{|\vec{m}-\vec{\xi}^{(j)}|}, & b_1=\frac{\cos\left(k|\vec{\xi}|\right)}{|\vec{\xi}|}\\ \tilde{b}_{2,j}=\frac{\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{|\vec{m}-\vec{\xi}^{(j)}|}, & b_2=\frac{\sin\left(k|\vec{\xi}|\right)}{|\vec{\xi}|}\\ D=(d_1,d_2,\cdots,d_q)^T, & j=1,2,\cdots,q\end{cases}$$

Assume that the particle velocity at O produced by a point source is the same as the particle velocity at M produced by q loudspeakers, we can get:

$$\begin{aligned}&G\textstyle\sum_{j=1}^{q}(1+\frac{1}{ik|\vec{m}-\vec{\xi}^{(j)}|})\frac{e^{-ik|\vec{m}-\vec{\xi}^{(j)}|}}{|\vec{m}-\vec{\xi}^{(j)}|^2}\begin{pmatrix} m_x-\xi_x^{(j)}\\ m_y-\xi_y^{(j)}\\ m_z-\xi_z^{(j)}\end{pmatrix}s_j(\omega)\\ &=G(1+\tfrac{1}{ik|\vec{o}-\vec{\xi}|})\tfrac{e^{-ik|\vec{o}-\vec{\xi}|}}{|\vec{o}-\vec{\xi}|^2}\begin{pmatrix} 0-\xi_x\\ 0-\xi_y\\ 0-\xi_z\end{pmatrix}s(\omega)\end{aligned} \tag{5}$$

Let real part and image part on both sides of the equation (5) be equal, we can get:

$$\begin{pmatrix}\tilde{b}_{31} & \tilde{b}_{32} & \cdots & \tilde{b}_{3q}\\ \tilde{b}_{41} & \tilde{b}_{42} & \cdots & \tilde{b}_{4q}\\ \tilde{b}_{51} & \tilde{b}_{52} & \cdots & \tilde{b}_{5q}\\ \tilde{b}_{61} & \tilde{b}_{62} & \cdots & \tilde{b}_{6q}\\ \tilde{b}_{71} & \tilde{b}_{72} & \cdots & \tilde{b}_{7q}\\ \tilde{b}_{81} & \tilde{b}_{82} & \cdots & \tilde{b}_{8q}\end{pmatrix}D=\begin{pmatrix}b_3\\ b_4\\ b_5\\ b_6\\ b_7\\ b_8\end{pmatrix} \tag{6}$$

where

$$\begin{cases}\tilde{b}_{3,j}=\frac{\left(\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)-\frac{\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_x-\xi_x^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ \tilde{b}_{4,j}=\frac{\left(\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)-\frac{\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_y-\xi_y^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ \tilde{b}_{5,j}=\frac{\left(\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)-\frac{\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_z-\xi_z^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ \tilde{b}_{6,j}=\frac{\left(\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)+\frac{\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_x-\xi_x^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ \tilde{b}_{7,j}=\frac{\left(\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)+\frac{\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_y-\xi_y^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ \tilde{b}_{8,j}=\frac{\left(\sin\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)+\frac{\cos\left(k|\vec{m}-\vec{\xi}^{(j)}|\right)}{k|\vec{m}-\vec{\xi}^{(j)}|}\right)\left(m_z-\xi_z^{(j)}\right)}{|\vec{m}-\vec{\xi}^{(j)}|^2}\\ b_3=\frac{\left(\cos\left(k|\vec{\xi}|\right)-\frac{\sin\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_x)}{|\vec{\xi}|^2}\\ b_4=\frac{\left(\cos\left(k|\vec{\xi}|\right)-\frac{\sin\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_y)}{|\vec{\xi}|^2}\\ b_5=\frac{\left(\cos\left(k|\vec{\xi}|\right)-\frac{\sin\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_z)}{|\vec{\xi}|^2}\\ b_6=\frac{\left(\sin\left(k|\vec{\xi}|\right)+\frac{\cos\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_x)}{|\vec{\xi}|^2}\\ b_7=\frac{\left(\sin\left(k|\vec{\xi}|\right)+\frac{\cos\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_y)}{|\vec{\xi}|^2}\\ b_8=\frac{\left(\sin\left(k|\vec{\xi}|\right)+\frac{\cos\left(k|\vec{\xi}|\right)}{k|\vec{\xi}|}\right)(-\xi_z)}{|\vec{\xi}|^2}\end{cases}$$

Construct a simultaneous equation by equation (4) and (6):

$$\tilde{B}D=\hat{B} \tag{7}$$

where $\tilde{B} = (\tilde{b}_{h,j})_{8\times q}$, $\hat{B} = (b_h)_{h\times 1}$, $h = 1, 2, \cdots, 8$.

Then we get the following model:

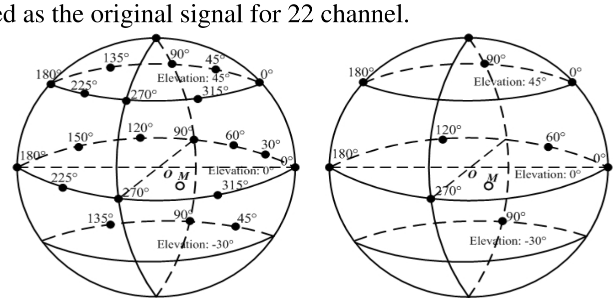
$$\begin{array}{l} \min\limits_{D} \frac{1}{2}\|\tilde{B}D - \hat{B}\|_2^2 \\ s.t.\ \ D \geq 0 \end{array} \tag{8}$$

It is a least squares problems with inequality constraints and could be worked out by many existing algorithms.

Second, if q loudspeakers replace multiple point sources, the final distribution coefficients of q loudspeakers can be got by adding up corresponding loudspeaker's distribution coefficients in every replacement process respectively. We call the proposed method sound pressure, particle velocity and listening point position based error minimum method (PPVLPP).

4. EXPERIMENTS

The performance of PMSZ, PVMSZ and PPVLPP are measured in non central zone sound field reconstruction. NHK 22.2 system arrangement without LFE channels is reproduced by 10 channel arrangement as in Fig. 1, which is designed by NHK researchers [14]. The center of the loudspeaker array is O, the non central listening point is at $M(0.5, -0.8, 0)$. We assume sound speed c is 340 m/s, the radius of human head is about 0.085 m. Single frequency signals of 1000Hz is selected as the original signal for 22 channel.



(a) (b)

Fig. 1. Loudspeakers arrangement. • denotes loudspeakers, ○ denotes listening point. (a): 22 loudspeakers arrangement; (b): 10 loudspeakers arrangement.

The relative mean square error (RMSE) is defined as:

$$\varepsilon(k\alpha) = \frac{\iiint\limits_{V} |P_r(\vec{m}+\vec{r},\omega) - P_d(\vec{r},\omega)|^2 dV}{\iiint\limits_{V} |P_d(\vec{r},\omega)|^2 dV} \tag{9}$$

where the integration zone V is a spherical ball of radius α and center O, $\vec{r} = (r_x, r_y, r_z)$ is arbitrary point in V, V' is different spherical ball with radius α and center $\vec{m}$, $\vec{m}+\vec{r} \in V'$, $P_d(\vec{r},\omega)$ and $P_r(\vec{m}+\vec{r},\omega)$ are the original and reproduced sound pressure respectively. RMSE is compared in Fig. 2. When $\alpha = 0.085$, RSME of PMSZ, PVMSZ and PPVLPP are respectively 97.13%, 85.19% and 14.91%. The RMSE by PPVLPP is 82.22% lower than that by PMSZ, 70.28% lower than that by PVMSZ in a human head zone. But when α grows bigger, the RMSE of PPVLPP increases much faster.

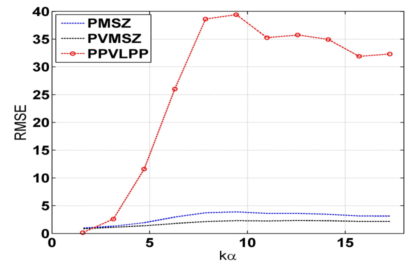


Fig. 2. The relative mean square error comparison.

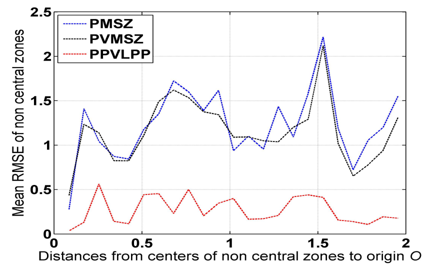


Fig. 3. The mean relative mean square error comparison.

Mean RMSE (MRMSE) is the average of all non central zones' RMSE, when the centers of these non central zones are a constant distance from the center O. MRMSE is used to measure the influence of non central zone's location on non central zones' RMSE. Suppose these non central zones are all 3D spherical region with radius 0.085m. The MRMSE comparison is shown in Fig. 3. The distances variation range from centers of these non central zones to O is in [0, 2] m, the MRMSE variation range is in [27.15%, 221.74%] by PMSZ, in [42.94%, 211.98%] by PVMSZ, in [3.41%, 56.29%] by PPVLPP for 10 channel layout. The MRMSE by PPVLPP is much lower than that by PMSZ and PVMSZ and the change trend of MRMSE by PPVLPP is more gentle than the change trend of MRMSE by PMSZ and PVMSZ. It means that the influence of non central zone's location on RMSE by PPVLPP is less than that by PMSZ and PVMSZ.

The particle velocity direction could be obtained by normalization:

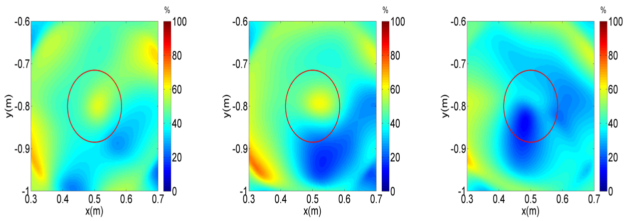
$$\vec{u}_{oI}(\vec{r},\omega) = \frac{\vec{u}_{ori}(\vec{r},\omega)}{|\vec{u}_{ori}(\vec{r},\omega)|}, \vec{u}_{rI}(\vec{m}+\vec{r},\omega) = \frac{\vec{u}_{rep}(\vec{m}+\vec{r},\omega)}{|\vec{u}_{rep}(\vec{m}+\vec{r},\omega)|} \tag{10}$$

where $\vec{u}_{ori}$, $\vec{u}_{rep}$ are particle velocity of original system and reproduced system respectively. Then the particle velocity direction error is:

$$\eta(\vec{r},\vec{m},\omega) = \frac{cos^{-1}\left(\vec{u}_{oI}(\vec{r},\omega)\cdot\vec{u}_{rI}(\vec{m}+\vec{r},\omega)\right)}{\pi} \times 100\% \tag{11}$$

The particle velocity direction error in plain $z = 0$ are compared in Fig. 4. The radius of the red circle is 0.085m. It shows that the particle velocity direction error by PPVLPP method is less than that by PMSZ and PVMSZ in a human head zone around M.

Two subjective tests are also made. Comparison Mean



(a) PMSZ (b) PVMSZ (c) PPVLPP

Fig. 4. The particle velocity direction error comparison in plain $z = 0$.

Opinion Score (CMOS) is used to test PMSZ, PVMSZ and PPVLPP. The test material consists of Ref/A/B, in which Ref is the original sound source signal, A is signal generated by proposed method, and B is signal generated by PMSZ in test 1 and by PVMSZ in test 2. But listener dose not know which method produces A or B. Ref is played back by 22 loudspeakers of original 22.2 multichannel system, when listener listens Ref, his head is at the center O. A and B are played back by 10 loudspeakers of reproduced multichannel system, when listener listens A or B, his head is at non center point M. We compare the sound image of A and B which is closer to Ref. The score has 7 levels, which are listed in Table 1. 10 listeners performed the listening test. All of them actively work in the audio field. The test results consist of an average score and a 95% confidence interval. A white noise is used as original test sequence whose sample rate is 48kHz, bit depth is 16bits , intensity is 12dB , and length is 10s. The test results for test 1 and test 2 are given in Figure 5. We can see that our method is statistically comparable to PMSZ and PVMSZ method in a 95% confidence interval sense. The average scores of proposed method are 2.05 in test 1 and 1.5 in test 2, which means that the location accuracy of our method is better than other methods when 22 channel is reproduced by 10 channel and are in accordance with above objective test results.

Table 1. Levels comparison standard

Comparison of the Stimuli	Score
Sound image of A is much closer to Ref than B	+3
Sound image of A is closer to Ref than B	+2
Sound image of A is slightly closer to Ref than B	+1
Sound image of A to Ref is the same as B	0
Sound image of A is slightly further to Ref than B	-1
Sound image of A is further to Ref than B	-2
Sound image of A is much further to Ref than B	-3

5. RELATION TO PRIOR WORK

22.2 multichannel system and its simplified system [14, 15] are aiming at the sound field recovery at the center listening point. The effect of reproduced non central listening point sound field is worse than that of central listening point sound field. Existing non central zone sound field reproduction methods: PMSZ [16, 17] and PVMSZ [18] all maintain sound physical property in a same zone between original system and reproduction system, in non central zone sound field reproduction they recover sound field in a non central zone of original system whose listening effect is worse than that of the central zone of original system. But PPVLPP aims at reproducing the sound physical properties at a non central listening point the same as the sound physical properties at the central listening point, makes listener at a non central listening point could have the same listening effect as he is at the central listening point. Sound is mainly described by sound pressure and particle velocity, so in sound field reproduction, sound pressure and particle velocity should be recovered well. But PMSZ just maintains sound pressure, PVMSZ just maintains particle velocity. PPVLPP maintains both sound pressure and particle velocity. Due to above reasons, the proposed method is better than PMSZ and PVMSZ in non central zone sound field reproduction.

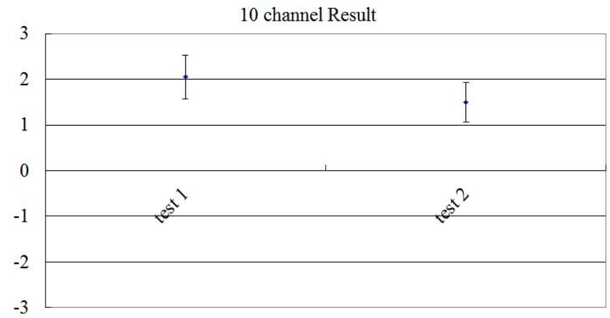


Fig. 5. CMOS scores for white noise signal. test 1: PMSZ *vs* PPVLPP, test 2: PVMSZ *vs* PPVLPP.

6. CONCLUSIONS

To make listener at a non central listening point could get better listening experience for multichannel system, this paper proposes a non central listening point sound field reproduction method basing on sound pressure, particle velocity and listening point position (PPVLPP), it tries to reproduce the sound physical property at a non central listening point the same as the sound physical property at the central listening point. Subjective and objective experiments are made for 22.2 multichannel system being reproduced by 10 channel system, test results indicate that the proposed method has lower relative mean square error, mean relative mean square error and particle velocity direction error in a human head zone than conventional methods. The location of non central zone has less influence on relative mean square error by PPVLPP than that by conventional methods. PPVLPP is conducive to the popularization and application of 22.2 multichannel system with less channel. Also, it is a universal method and could be used for other multichannel systems in non central point or non central zone sound field reconstruction.

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