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서라운드시스템을 위한 가상 음상정위 알고리즘

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Virtual Sound Localization algorithm for Surround Sound Systems

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Abstract

In this paper, we propose a virtual sound localization algorithm which improves the sound localization accuracy and sound color preservation for two channel and multi-channel surround speaker layouts. In conventional CPP laws, the sound direction is different from the panning angle and the sound color is different from real sound source especially when the speakers are spread out widely. To overcome this drawback, we design a virtual sound localization algorithm using directional psychoacoustic criteria (DPC) and sound color compensator (SCC). The analysis results show that in the case of the proposed system, the sound direction is the same as the panning angle in the audible frequency range and the sound color is less deviated from a real sound source than the conventional CPP law. In addition, its performance is verified by means of subjective tests using a real sound source.

Index Terms — CPP law, DPC, enhanced CPP law.

I. INTRODUCTION

In audio systems, the use of a parametric potentiometer (pan-pot) is essential to sound recording and reproduction. Recently, many pan-pot algorithms, namely panning laws, have been proposed for phantom sound localization using multiple loudspeakers. These panning laws can be classified into two categories. The first one is the frequency panning method that makes use of head related transfer function (HRTF) data according to the panning angle, but this technique is not widely used, because it results in the degradation of sound quality [1]. The second is the intensity panning method in which the gain function of the loudspeakers is adjusted according to the panning angle. The CPP law, which belongs to the second category, is the most commonly used method, because of its simplicity.

In loudspeaker systems which make use of the CPP law, there is a tendency, called the detent effect, for the sound image to be pulled closer to the nearest loudspeaker [2]. Since stereo sound systems have a narrow spreading angle of the loudspeaker, the detent effect is not a serious problem. In a 5.1 channel loudspeaker layout, however, the spreading angle of the rear speakers (speakers LS and RS) is increased to 140°. This increases the detent effect significantly.

To eliminate this detent effect, we derived an enhanced CPP law which allows for the panning angle to be equal to the direction of the sound source in the audible frequencies. In order to implement the pan-pot, this enhanced CPP law is applied to a hybrid system model.

Through the subjective sound localization test of the CPP law, we found that the enhanced CPP law can significantly reduce the sound localization error.

II. ANALYSIS OF CPP LAW

A. Directional Psychoacoustic Criteria

Although the DPC cannot describe the models of human localization accurately, it standardizes for the design of pan pots. The velocity vector direction, θ_V, and energy vector direction, θ_E, have been extensively used to define optimum panning laws, and those algorithms that are optimized using these criteria are the ones that best conform to the design criteria for surround sound systems and pan-pots [3]. The velocity vector direction, θ_V, and the energy vector direction, θ_E, are expressed as follows:

$$\theta_V = \tan^{-1}\left(\frac{\sum_{i=1}^{n} g_i \sin\theta_i}{\sum_{i=1}^{n} g_i \cos\theta_i}\right), \tag{1}$$

$$\theta_E = \tan^{-1}\left(\frac{\sum_{i=1}^{n} g_i^2 \sin\theta_i}{\sum_{i=1}^{n} g_i^2 \cos\theta_i}\right). \tag{2}$$

Here, g_i and θ_i are the gain and the angular position of the i-th speaker, respectively. The velocity vector direction, θ_V, is the apparent sound direction according to low-frequency (particularly below 700 Hz) inter-aural phase localization theories, when the listener faces the apparent sound source [4]. The energy vector direction, θ_E, determines the apparent sound direction for listeners facing the apparent sound source in the frequency range from 700 Hz to 3.5 kHz. Because this frequency region is the most significant frequency region for human perception, θ_E is a more useful criterion than θ_V for the estimation of the angular position of the apparent sound source, in both the central listening and phase-incoherent cases (for example, off-center listening, etc.) [4]. Since θ_V is equal to θ_E in the case of real sound sources, this equality between θ_V and θ_E should hold up for all panning angles.

B. Analysis of CPP law

The mathematical form of the CPP law is given by the trigonometric identity

$$\sin^2\theta + \cos^2\theta = 1 \tag{3}$$

where θ denotes the angular position of the phantom sound. Then, the gain, g_i, of the loudspeaker is expressed with both the angular position, θ_i, of the i-th loudspeaker and the panning angle, θ_{pan}

$$g_1 = \cos\theta_m,\; g_2 = \sin\theta_m \tag{4}$$

where $\theta_m = 90^\circ \times (\theta_{pan} - \theta_1)/(\theta_2 - \theta_1)$ for $\theta_1 \le \theta_{pan} \le \theta_2$.

The analysis results of the CPP law for θ_V and θ_E are presented in Fig. 1, where the vertical arrow denotes the angular position of the loudspeakers. θ_V and θ_E are obtained through (1) and (2), respectively. As the panning angle approaches the rear direction, which has a large spreading angle, the detent effect is intensified, as shown in Fig. 1. This figure also shows that θ_E is a more efficient criterion than θ_V in describing the detent effect.

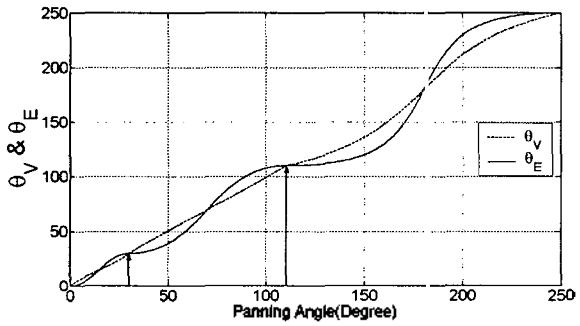

Fig. 1. Analysis of a CPP law using DPC.

III. ENHANCED CPP LAW

To overcome the sound localization error of the CPP law, we derived an enhanced CPP law which can eliminate the detent effect. The two requirements of the DPC in the design of an enhanced CPP law are as follows:

- The total power should be independent of the panning angle.
- θ_V and θ_E should be equal to the panning angle, θ_{pan}.

The first requirement can be satisfied by using the CPP law based on (3) and (4), and the second requirement can also be satisfied as follows.

Substituting (3) and (4) into (1) gives

$$\theta_V = \tan^{-1}\frac{\cos\theta_m \sin\theta_1 + \sin\theta_m \sin\theta_2}{\cos\theta_m \cos\theta_1 + \sin\theta_m \cos\theta_2}. \tag{5}$$

Rearranging (5) in order to obtain the value of θ_m by using the property of trigonometric functions gives the following equation:

$$\theta_m = \tan^{-1}\frac{\tan\theta_V \cos\theta_2 - \sin\theta_2}{\sin\theta_1 + \tan\theta_V \cos\theta_1} \tag{6}$$

where $\cos\theta_m \neq 0$. Replacing θ_{pan} with θ_V^{target} in (6) and rearranging it give

$$\theta_V^{target} = \frac{1}{90^0}(\theta_2 - \theta_1)\tan^{-1}\frac{\tan\theta_V \cos\theta_2 - \sin\theta_2}{\sin\theta_1 + \tan\theta_V \cos\theta_1} + \theta_1. \tag{7}$$

To satisfy the requirement that θ_V should be equal to θ_{pan}, we substitute θ_{pan} for θ_V in (7)

$$\theta_V^{target} = \frac{1}{90^0}(\theta_2 - \theta_1)\tan^{-1}\frac{\tan\theta_{pan} \cos\theta_2 - \sin\theta_2}{\sin\theta_1 + \tan\theta_{pan} \cos\theta_1} + \theta_1. \tag{8}$$

Equation (8) shows that the speaker gains should be modified using θ_V^{target} instead of θ_{pan}, in order to position the apparent sound source at the angle, θ_{pan}.

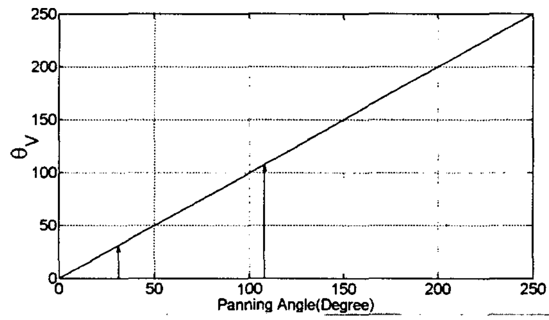

Fig. 2. Analysis of an enhanced CPP law optimized in terms of θ_V^{target} using DPC.

Secondly, the intermediate angle, θ_E^{target}, for the energy vector direction is obtained through the same procedure as that used to determine θ_V^{target}, except that the speaker gain, g_i, is replaced with g_i^2.

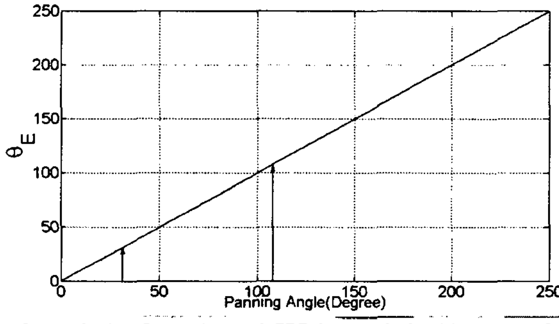

Fig. 3. Analysis of an enhanced CPP law optimized in terms of θ_E^{target} using DPC.

Consequently, θ_E^{target} is expressed as follows

$$\theta_E^{target} = \frac{1}{90^0}(\theta_2 - \theta_1)\tan^{-1}\sqrt{\frac{\tan\theta_{pan} \cos\theta_2 - \sin\theta_2}{\sin\theta_1 + \tan\theta_{pan} \cos\theta_1}} + \theta_1. \tag{9}$$

The analysis results of the enhanced CPP law are presented in Figs. 2 and 3, where θ_V and θ_E are equal to the respective panning angle, θ_{pan}.

IV. Implementation

In order for the velocity and energy vector directions to be equal to the panning angle in the audible frequency range, we propose a hybrid system model, as shown in Fig. 4, in which different panning laws are adhered to depending on the frequency region (low or high frequency region) [5]. Once the mono-input signal being has been divided into two bands (above and below 700Hz), the speaker gain g_i is distributed according to (8) in the low frequency band and (9) in the high frequency band.

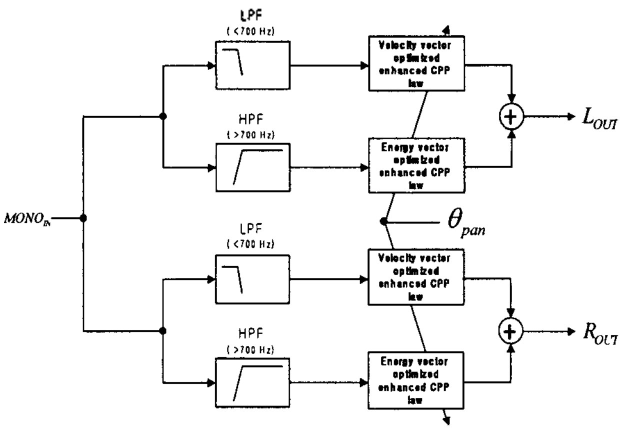

Fig. 4. Hybrid system model.

V. Subjective Tests

As shown in Fig. 5, we developed a computer program to evaluate the CPP law. By using this program, a subjective sound localization test was carried out.

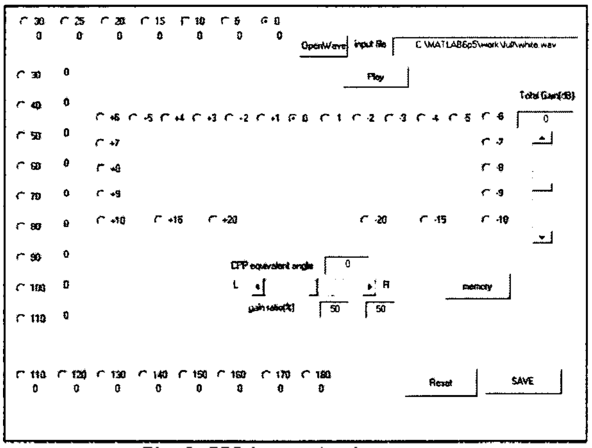

Fig. 5. CPP law evaluation program.

The first test signal was presented by the real loudspeaker, and then the same signal was presented by the virtual loudspeaker after being calculated using the CPP law. Each listener adjusts the panning angle by pressing the button or moving the slide bar until the angular position of the phantom sound appears to be equal to that of the real speaker. This test was done every 5°s for the frontal angle and every 10°s for the side and rear angles. Assuming that the listening environment is symmetric, the tests were conducted for only half of the possible angles. A white noise signal having duration of one second was used in the test, and the subjects were 10 men aged in their twenties.

The results of the subjective tests are shown in Fig. 6, in which the dot and the vertical bar denote the mean and variance of the responses of the 10 subjects, respectively. The vertical axis indicates the gain of one loudspeaker. For most panning angles, the speaker gain obtained from the subjective tests is closer to the result of the enhanced CPP law than that of the CPP law.

Through the subjective test, we verified that the enhanced CPP law is a more appropriate panning algorithm than the CPP law for surround sound systems.

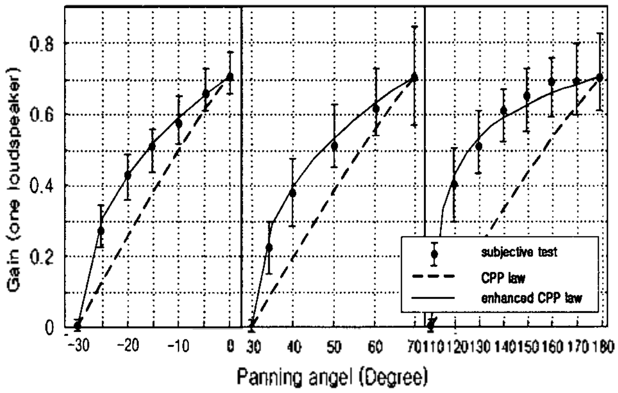

Fig. 6. Subjective sound localization test.

VI. Conclusion

By using both DPC analysis and a subjective sound localization test, we confirm that the CPP law is not an appropriate panning algorithm for surround sound systems, because of the sound localization error in the side and rear angles. To solve this problem, we derive an enhanced CPP law and apply it to a hybrid system model, in which the velocity and energy vector directions are equal to the panning angle in the audible frequencies. Through the subjective sound localization test, we confirmed that the proposed model can significantly reduce the sound localization error. Therefore, the hybrid system model using the enhanced CPP law can be used for several kinds of audio systems, e.g. mixing consoles, sound reproduction systems and sound field processors, etc. Further research needs to be done for off-central listening environments.

References

[1] West J. R, "Five-channel panning laws: an analytic and experimental comparison", Master's Thesis, Music Engineering, University of Miami, 1998.

[2] H. D. Harwood, "Stereophonic image sharpness," *Wireless World*, vol. 74, pp. 207-211, 1968.

[3] Michael A. Gerzon, "General metatheory of auditory localization", *92nd Convention of the Audio Engineering Society, J. Audio Eng. Soc.*, preprint 3306, May, 1992.

[4] Michael A. Gerzon, "Panpot laws for multispeaker stereo", *92nd Convention of the Audio Engineering Society, J. Audio Eng. Soc.*, preprint 3309, May. 1992.
[5] Michael A. Gerzon, "Psychoacoustic decoders for multispeaker stereo and surround sound", *93rd Convention of the Audio Engineering Society. J. Audio Eng. Soc.*, preprint 3406, Oct. 1992.