Study of In-vehicle Sound Field Creation by Simultaneous Equation Method

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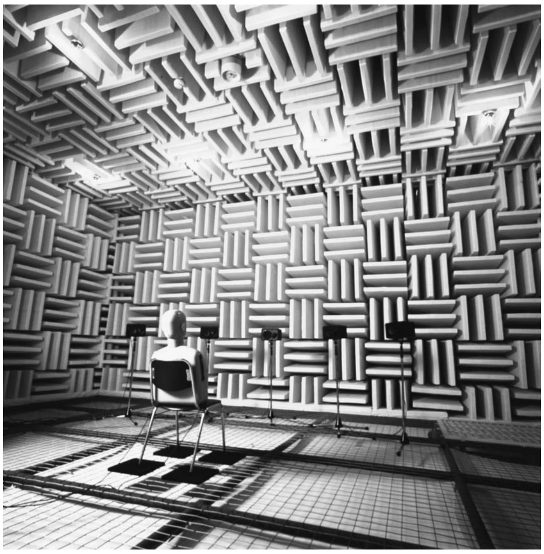


Abstract

FUJITSU TEN Limited has developed "TOYOTA Premium Sound System" using "spatial control technology" for CROWN of TOYOTA Motor Corporation in February 2008, which receives high reputation. We, at FUJITSU TEN Limited, and UNIVERSITY OF HYOGO have been collaborating on research activities of sound field creation technology by a simultaneous equation method through the upgrade of the spatial control technology in order to provide sounds with more natural sense of expanse. Through verifying the principle with a simulation model, we confirmed that it provides appropriate controls depending on listener's moves and creates arbitrary sound field at the periphery of listener's ears. This new technology can provide precise controls depending on listener's moves, and this leads to expansion of the spatial control range whose upper limit used to be 1.5 kHz. We found a clue to providing sounds with more natural sense of expanse.

1 Introduction

A vehicle cabin is one of the precious private spaces for many drivers. Drivers can enjoy music as high quality as at home with many digitized sources. Now, the vehicle cabin is an important space like a living room at home for a driver to enjoy music.

However, looking at the vehicle cabin as a space for enjoying music, it stands under many disadvantageous conditions for replaying music compared to a general living room; for example, with driving noises, limitations of spaces for loudspeaker to be set, sound reflections from vehicle windows and effects occurred by unnecessary vibrations of interior materials. Thus, noise-sensitive automatic volume control [1], compact woofer [2], wide-directional tweeter, equalizer for transmission characteristics correction in a vehicle cabin [3], sound field controller, etc. have been developed and adopted to obtain better sounds under such conditions of a vehicle cabin.

We, at FUJITSU TEN Limited, have developed "TOYOTA premium sound system [4]" in February 2008 for CROWN of TOYOTA, using "spatial control technology." This technology creates a sound field providing an impression as if being in a living room. The technology, by analyzing the sound field in a vehicle cabin precisely, suppresses reflection sounds and unnecessary vibrations that provide the impression of narrow space to a driver and passengers, and adds simulated sound effects that provide the impression of wide space. This system receives high reputation from many users with respect to the sounds with a sense of expanse and open space as never before in a vehicle cabin. We keep developing this system to pursue sounds with more natural sense of expanse.

To obtain the sounds with more natural sense of expanse, the spatial control technology under the specific conditions inside the vehicle cabin described above must be improved. Thus, we adopted the "sound field creation technology using simultaneous equation method [5]." Hereafter, we report our feasibility study where this sound field creation technology can make spatial control.

2 Spatial Control Technology and Task

2.1 Sound Concept

Our sound concept is "creation of impressive sound space." As shown in **Fig.1**, we are pursing the sounds with a sense of expanse instead of a sense of narrow space in a vehicle cabin. Our target wide is approx. 30m^2 for a normal size of a living room where many users listen to music.

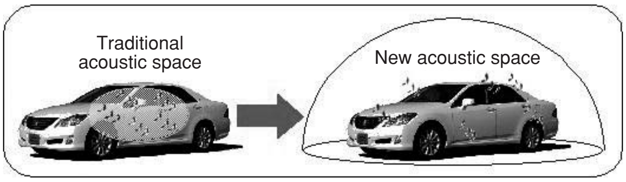


Fig.1 Image of Targeted Acoustic Space

2.2 Spatial Control Technology and Effect

The spatial control technology creates a virtual living room as a sound field inside a vehicle cabin by taking measures to overcome the following restrictions of a vehicle cabin.

Task 1: Unnecessary vibration around the periphery of an installed speaker

Solution 1: Technology for suppressing unnecessary vibration

We used damping technology for in-vehicle loudspeakers to suppress the unnecessary vibrations. The damping technology has been developed for Time Domain technology [(1)] for home audio loudspeakers [6].

Task 2: Strong and slightly-delayed reflection sound generated from glass, etc.

Solution 2: Technology for suppressing unnecessary reflection sounds

We developed a new method to negate the unnecessary reflection sounds by using the antiphase sounds emitted from speakers set at the periphery of listener's ears.

Task 3: Only the reflection sounds with the limited incoming directions are received because the ceiling, seat and other materials absorb sounds.

Solution 3: Technology for addition of spatial information

In order to reproduce the reflection sounds in a living room as faithfully as possible, we used special loudspeakers to add spatial information to reproduce reflection sounds simulated by digital signal processing.

Figures 2 to 4 show the effect of the spatial control technology. **Fig.2** is a figure of impulse response [(2)] and directional diffusion diagram [(3)] in the targeted living room. **Figures 3 and 4** are figures of impulse responses and directional diffusion diagrams in a vehicle cabin. Specifically, **Fig.3** is the figure when spatial control processing is off, and **Fig.4** is the figure when the spatial control processing is on.

Looking at the case with the spatial control processing on, the spatial information (reflection sounds) is applied in the impulse responses, and the directional diffusion diagram includes reflection sounds from more various directions. This means the spatial control processing provides characteristics closer to the targeted living room.

＊(1) The technology that emphasizes time-domain characteristics of sounds to reproduce input waveforms precisely
＊(2) Output by System when a temporally infinitesimal, infinite high and very short signal, called impulse, is input
＊(3) Vector diagram showing incoming directions of reflection sounds and their levels

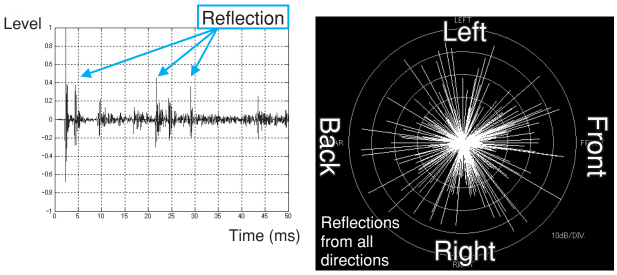


Fig.2 Impulse Response (Left) and Directional Diffusion Diagram of Reflected Sounds (Right) in [Ideal] Living Room

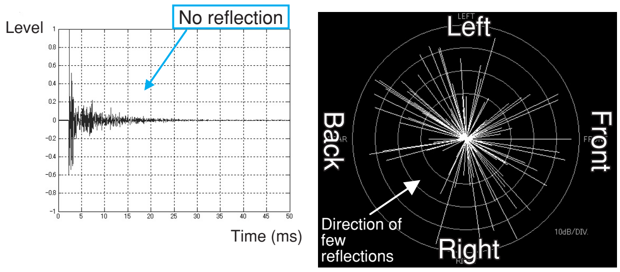


Fig.3 Impulse Response (Left) and Directional Diffusion Diagram of Reflected Sounds (Right) in Vehicle Cabin [with Spatial Control off]

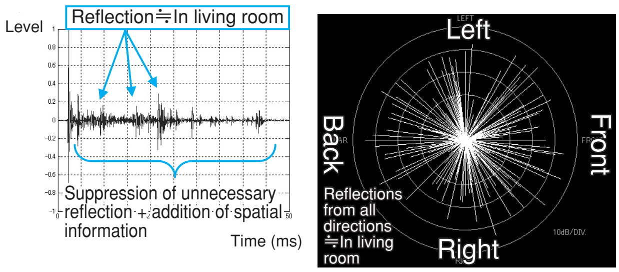


Fig.4 Impulse Response (Left) and Directional Diffusion Diagram of Reflected Sounds (Right) in Vehicle Cabin [with Spatial Control on]

As above, in the spatial control technology, technologies such as vibration suppression of loudspeakers and signal processing are combined with to provide the sounds with a sense of expanse. Specially, the signal processing technology plays an important role in the suppression of unnecessary reflection sounds and the addition of spatial information. We focused on the signal processing technology for this development to provide sounds with more natural sense of expanse.

2.3 Residual Task

In the traditional technology for the suppression of unnecessary reflection sounds, the available range of a control filter is 1.5 kHz or less. If the range is expanded over 1.5 kHz, the sounds will provide more natural sense due to the unnecessary reflection sounds suppressed in a wider range.

However, in the expanded control range as in **Fig.5** (traditional method), there are some cases of insufficient cancellation effect against high frequency (short-wavelength) sounds depending on a listener's move. Thus, we have been developing a new technology by setting our tasks to expand the control range and to avoid the depression of the control effect depending on the listener's move. We pursue the condition of the sound field as if in a living room as shown in **Fig.5** (Sound field creation technology) that is kept at the periphery of listener's ears without the depression of the control effect under the expanded range of control even when a listener moves.

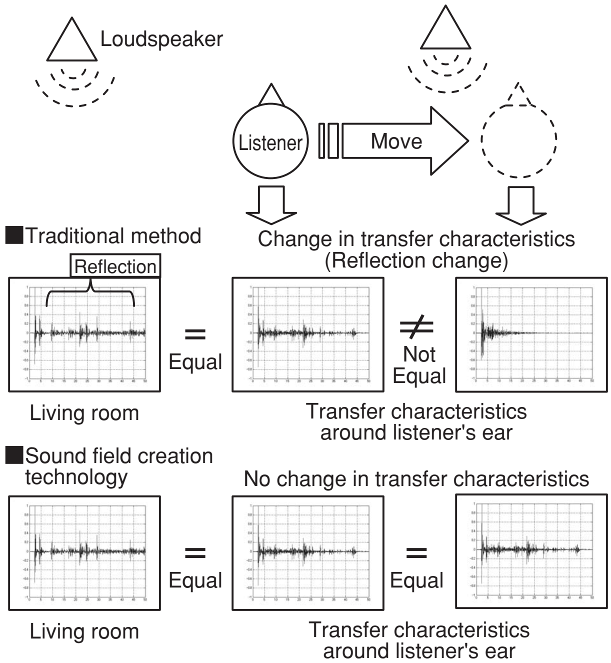


Fig.5 Control Effect Image

3 Sound Field Creation Technology

To deal with the tasks, we took an adaptive control technology to control the unnecessary reflection sounds depending on the listener's move. A simultaneous equation method is specifically adaptive to the listener's move among the adaptive control technologies. This method keeps detecting the listener's move and controls the unnecessary reflection sounds depending on the move.

Further, it is possible to set the transfer characteristics at the periphery of listener's ears to any characteristics and to control the addition of the spatial information.

This section introduces the outline of sound field creation technology and its principle.

3.1 Outline of Sound Field Creation Technology

Fig.6 shows the control flowchart of the traditional method and the sound field creation technology. The traditional method does not follow the listener's move since the coefficient of the control filter is to be set for the first thing and not to be changed afterward. On the other hand, the sound field creation technology, first, keeps obtaining the differences between the transfer characteristics at the periphery of listener's ears and the target characteristics such as of the ones in a living room (hereinafter referred to as target sound field). Then, the technology updates the control filter so that the target sound field is created at the periphery of listener's ears based on the differences. Once the difference is disappeared, the technology stops the update of the control filter, which means that the sound characteristics at the periphery of listener's ears are equal to the ones in the target sound field.

The technology that keeps obtaining the differences detects the listener's move and keeps the transfer characteristics in a vehicle cabin by adjusting them based on the detected differences.

This technology is called sound field creation technology since it creates a sound field as above.

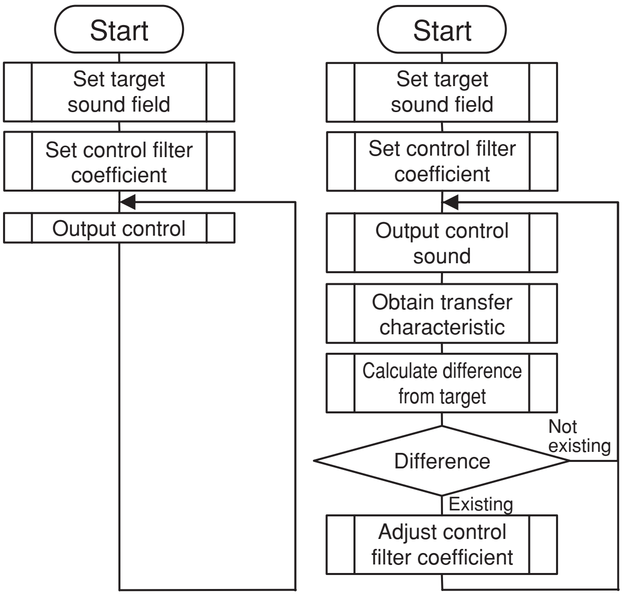


Fig.6 Overview Control Flowchart
(Left: Traditional Method, Right: Sound Field Creation Technology)

3.2 Principle

3.2.1 Configuration

Fig.7 shows a system configuration of the sound field creation technology. First, a microphone near a listener catches acoustic signals that were output from a loudspeaker and passed through acoustic space. Then, an arithmetic processor analyzes the signals obtained and calculates the control filter to create the target sound field around the listener.

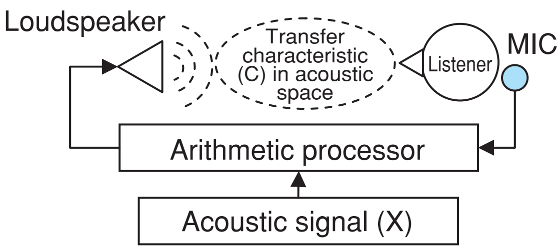


Fig.7 System Configuration

Here, the processing inside the arithmetic processor is described.

First, the general adaptive control technology in **Fig.8** that does not use a simultaneous equation method is described, and then, its problem is described.

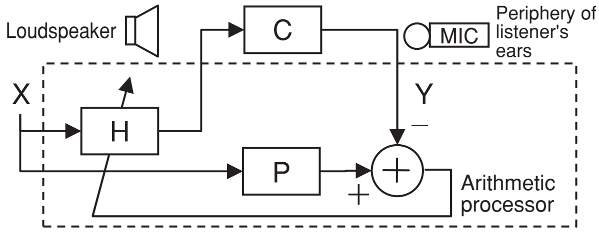


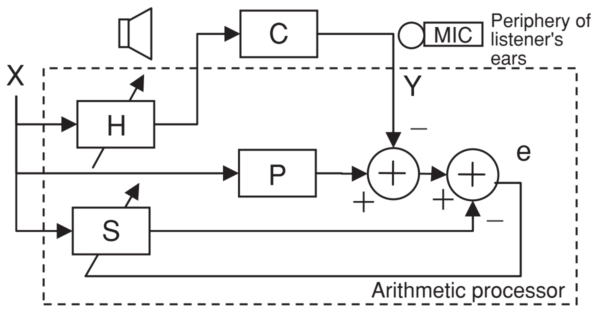
Fig.8 Block Diagram of Arithmetic Processor
(General Adaptive Control Technology)

The letter *P* expresses a target sound field filer, in which we can set arbitrary characteristics such as the ones in a living room.

The letter *C* expresses a transfer characteristic of the acoustic space between a listener and a loudspeaker, which is unknown value since it varies depending on listener's move.

The letter *H* expresses a control filter to be adjusted based on the difference between the output of the target sound field (*P*) and the signal (*Y*) at the periphery of listener's ears in order to create the target sound field (*P*).

The length of memory of the control filter (*H*) shall be set long enough to cover a longer reverberation time of transfer characteristic of acoustic space (*C*), which varies depending on listener's moves or other reasons. This makes it possible for the control filter to provide proper control depending on the listener's move. However, when the transfer characteristic of acoustic space (*C*) changes more than expected, the length memory of the control filter (*H*) becomes insufficient or excess. The excess length of memory takes time to make calculation, and the insufficient length of memory makes it difficult to provide proper control.



※Adjust control filter based on coefficient of auxiliary-filter (S)

Fig.9 Block Diagram of Arithmetic Processor
(Adaptive Control Technology by Simultaneous Equation Method)

Next, an adaptive control technology (sound field creation technology) by a simultaneous equation method shown in **Fig.9** is described. This technology adjusts the control filter (*H*) automatically depending on the listener's move.

The new technology uses an auxiliary filter (*S*), unlike the general technology. The auxiliary filter (*S*) shows the difference between the characteristics at the periphery of listener's ears (*CH*) and the target sound field (*P*), and is adjusted so that the difference (*e*) between the characteristics of the auxiliary filter (*S*) and the target sound field characteristics is eliminated. The auxiliary filter (*S*) includes information about the changes in transfer characteristic of acoustic space (C) and shortage /excess of the control filter (H). Here, through the calculation of the control filter (H) from the value of the auxiliary filter (S), the control filter (H) can be updated appropriately to the transfer characteristic of acoustic space (C).

It can be said that this simultaneous equation method is the appropriate adaptive control technology since it can effectively cover various transfer characteristics of acoustic space (C).

The next section describes adjustment method of the control filter by the simultaneous equation method.

3.2.2 Adjustment Method of Control Filter

The procedure for adjusting the control filter is as follows; first, obtaining the difference between the target sound field and the transfer characteristic at the periphery of listener's ears, second, estimating the transfer characteristic up to the listener's ears, and lastly, adjusting the control filter. Here, the procedure is described in order. As in **Fig.9**, a listener listens the observed signal (Y) coming through the control filter (H) and the transfer characteristic of acoustic space (C). Here, the signal at the listener's position is as follows:

$$Y = CHX$$

Signal at listener's position

The final purpose is to make this characteristic equal to the acoustic signal (PX) coming through the target sound field filter (P). Here, the control filter (H) is as follows:

$$PX = CHX$$
$$\Rightarrow H = \frac{P}{C}$$

Optimized solution of control filter (H)

This is the optimized solution relating to the transfer characteristic of acoustic space (C). However, the optimized solution can not be obtained due to the unknown transfer characteristic of acoustic space (C). Here, the auxiliary filter (S) is set as follows:

$$S = P - CH$$

Auxiliary filter (S) definition equation

$$\Rightarrow SX = PX - CHX$$
$$\Leftrightarrow SX = PX - Y$$

Formula for auxiliary filter (S)

In **Fig.9**, the auxiliary filter (S) is adjusted so that the difference (e) between the auxiliary filter (S) and the target sound field is eliminated. At this time, the right side of the auxiliary filter (S) definition equation above is obtained.

Then, the difference between the target sound field (P) and the characteristics at the periphery of listener's ears (CH) is obtained

Next, when the auxiliary filter (S) is completely estimated, the value of the transfer characteristic of acoustic space (C) is estimated as approximation C' from the auxiliary filter definition equation using the known values (P, H and S).

$$C' = \frac{P - S}{H}$$

Formula for transfer characteristic of acoustic space (C)

Expressing the control filter (H) using this C', the control filter (H) update equation is expressed with the auxiliary filter (S).

$$H = \frac{P}{C'} = \frac{P}{P - S} H$$

Control filter (H) update equation

As in this equation, the control filter (H) can be obtained using the difference without the measurement of the transfer characteristic of acoustic space (C).

3.2.3 System Operation Example

This section describes the example of the system operation using the auxiliary filter (S) and the control filter (H) when the transfer characteristic of acoustic space (C) is changed.

■When System is Operating

First, when the system is operating, the auxiliary filter (S) is estimated by the auxiliary filter definition equation.

Next, the control filter (H) is calculated using the control filter update equation. Here, an optimized solution of the control filter (H) can be calculated using the auxiliary filter (S) coefficient without the measurement of the transfer characteristic of acoustic space (C).

The indexes in the following equations express the number of updates. Here, "0" is a default value.

- **Auxiliary filter definition equation**

$$S_1 = P - CH_0 = P - C \qquad H_0 = 1$$

- **Control filter update equation**

$$H_1 = \frac{P}{P - S_1} H_0 = \frac{P}{P - (P - C)} = \frac{P}{C}$$

Under an ideal environment with no change in transfer characteristic of acoustic space (C), the optimized solution of the control filter (H) is obtained after updating once. At the next updating, the value of the auxiliary filter (S) becomes "0", which means the difference with the target sound field becomes "0". Thus, the control filter (H) is not updated.

- **Auxiliary filter definition equation**

$$S_2 = P - CH_1 = P - C\frac{P}{C} = 0$$

- **Control filter update equation**

$$H_2 = \frac{P}{P - S_2} H_1 = \frac{P}{P} H_1 = \frac{P}{C}$$

■When transfer characteristic of acoustic space (C) changes

When the transfer characteristic of acoustic space (C) changes ($C \Rightarrow C + \Delta$) depending on listener's move, the auxiliary filter (S) is not "0" anymore and the control filter

(H) is to be updated. After updating, the optimized solution of the control filter (H) corresponding to the changed transfer characteristic of acoustic space ($C+\Delta$) is calculated.

- **Auxiliary filter definition equation**

$$S_3 = P-(C+\Delta)H_2 = P-(C+\Delta)\frac{P}{C} = -\frac{P}{C}\Delta$$

- **Control filter update equation**

$$H_3 = \frac{P}{P-S_3}H_2 = \frac{P}{P+\frac{P}{C}\Delta}\,\frac{P}{C} = \frac{P}{C+\Delta}$$

When the optimized solution of the control filter (H) was obtained, the auxiliary filter (S) becomes "0"at the next updating and the control filter (H) is not to be updated.

- **Auxiliary filter definition equation**

$$S_4 = P-(C+\Delta)H_3 = P-(C+\Delta)\frac{P}{C+\Delta} = 0$$

- **Control filter update equation**

$$H_4 = \frac{P}{P-S_4}H_3 = \frac{P}{P}\,\frac{P}{C+\Delta} = \frac{P}{C+\Delta}$$

In this method, the control filter (H) is to be updated appropriately whenever the transfer characteristic of acoustic space (C) changes depending on the listener's move. As above, even in the expanded control range, this method provides sounds with more natural sense of expanse and avoids the reduction of effects caused by the listener's move.

4 Outcome of Principle Verification

4.1 Simulation

Next, we verified the principle of the sound field creation technology. **Fig.10** shows a simulation model. Here, we set as follows: a simulated characteristic for the default value of transfer characteristic of acoustic space (C); the characteristic as in **Fig.12** for the target sound field filter (P), "0" for the auxiliary filter (S); and "1" for the control filter (H). Here, the following matters shall be confirmed.

- **Is the sound field characteristic at the periphery of a listener equal to the target sound field?**
- **Is the sound field characteristic equal to the target sound field even after the change in the transfer characteristic of acoustic space?**

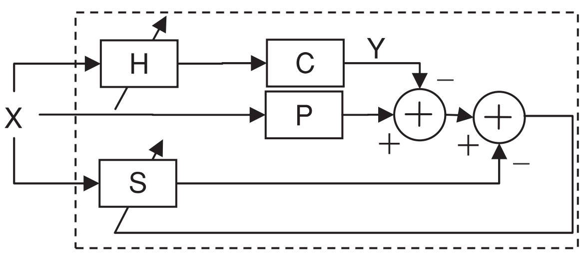


Fig.10 Simulation Model

A white noise was used as an acoustic signal (X) in order to assure the precise target sound field.

The estimation error (E), prescribed as follows, is used as an indicator for estimation. When the target sound field filter (P) is equal to the sound field characteristics at the periphery of listener's ears (CH), this is expressed in the forms as follows.

$P=CH$ and $E=0$

Here, the smaller the estimation error is, the closer the sound field characteristic at the periphery of listener's ears (CH) becomes to the target sound field filter (P).

$$E = 10\log_{10}\left[\frac{(P-CH)^2}{P^2}\right]$$

Estimation error definition equation

E: Estimation error, P: Target sound field filter,
CH: Sound field characteristic at periphery of listener

4.2 Simulation Outcome

Fig.11 shows the transition of the estimation errors. In this figure, the horizontal axis expresses the number of updates of the control filter and the vertical axis expresses the estimation error.

The outcome shows the repeated updates of the control filter reduce the estimation errors. The estimation error converges at approx. 1/100 (-40 dB) level after a few updates, which is equal to the target sound field.

At the sixth update, the transfer characteristic of acoustic space (C) is changed to simulate a listener's move. Thus, the estimation error goes up and far from the target sound field drastically. However, the estimation error goes down shortly to the level approx. -40 dB, which is equal to the target sound field.

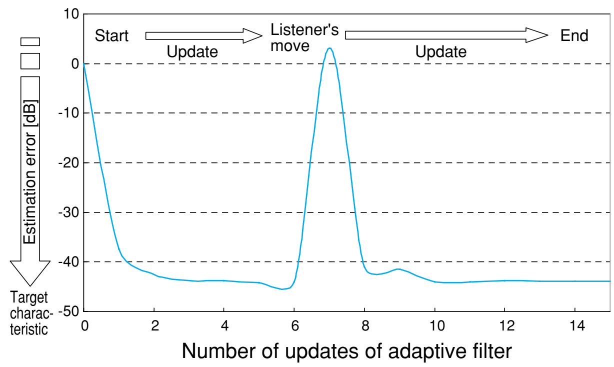


Fig.11 Transition of estimation errors

Fig.12 shows the impulse response of the target sound field filter (P). **Fig.13** shows the impulse response expressing the characteristic of the sound field around the controlled point (CH), where the control filter (H) with the estimation error of approx. -40 dB is used. As shown in the two figures, the characteristics of the sound field at the periphery of the listener equal to the target sound field sufficiently.

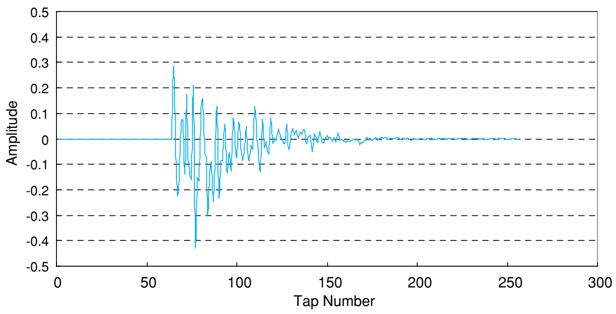


Fig.12 Impulse Response in Targeted Sound Field

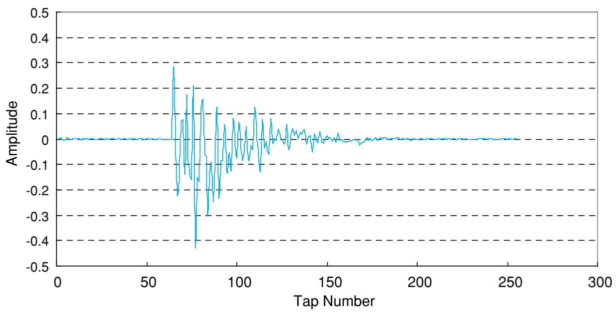


Fig.13 Impulse Response in Sound Field around Listener

Through the verification above, we confirmed the following matters; the characteristic of the sound field at the periphery of the listener (*CH*) is equal to the target sound field filter (*P*), and the characteristic of the sound field at the periphery of the listener (*CH*) is back to the target sound field even after the transfer characteristic of acoustic space (*C*) is changed depending on a listener's move.

5 Conclusion

This paper introduced the sound field creation technology by simultaneous equation method and its principle verification. This technology succeeds in avoiding the reduction of effects caused by listener's move in an expanded control range by updating the control filter appropriately whenever a listener moves.

We found a clue to providing sounds with more natural sense of expanse regardless of a listener's position.

This simulation uses white noises instead of music signals in order to assure the accuracy. However, for the practical use, we have to assure the accuracy using music signals. This will be our next task.

Further, we will pursue the measurement method of this simultaneous equation method to adjust sound field in a vehicle, and promote new products applying this technology.

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