Development of Premium Double Tweeter Sound System for Dealer Option

Toshio NAKAMICHI
Toshimitsu ONBE
Kazuaki SAITO
Yuki NISHIO
Tomoyasu SAKAUE
Kunihiko IRIE

Abstract

Sound of an in-vehicle sound system has been developed in various directions by respective manufacturers, and there are a variety of ways to create sounds depending on types of vehicles. Although the sound specified for its vehicle is created by the premium sound system for maker options, which is set only for some vehicles, the sound system for dealer options is set for almost all vehicles. Therefore, it is necessary to develop components with versatility and to pursue "real sound" which is also a sound concept.

Pursuing the real sound is to reproduce the"accurate sound", and to realize the accuracy of localization of each sound image and the expressive power of musical instruments, vocals, and others at both seats. Joint development with Toyota Motor Corporation was implemented in order to achieve it, which led an approach to double tweeter with two-axis direction, a signal processing technology capable of maximizing its effect, and an improvement in higher sound quality of amplifiers. The contents of approach toward the realization of real sound are described in this article.

1. Introduction

We, DENSO TEN, developed "Premium Double Tweeter Sound System" for dealer options jointly with Toyota Motor Corporation. This system is the one, which was developed to enjoy the real sound at both driver and front passenger seats simultaneously and could be mounted on many vehicles regardless of the vehicle type, leading to achievement of a good sound. This article describes the system development concept and various technologies used to realize the system.

2. Purpose of Development

2.1 Development Concept

We have consistently pursued the "accurate sound" since ECLIPSE home audio was released in 2001. This is for the purpose of delivering artists' thoughts straight to customers and impressing them. Pursuing this "accurate sound" enables to obtain features such as "sense of clarity" as thought you could see vocal mouth movements and players' fingering, "sense of speed" marked by rhythms playing with clear sound, and "spatial reproduction capability" to precisely present location information of recorded sound. The development was carried out with the aim of delivering this "accurate sound" to both the driver and front seat passengers to the fullest extent and of reproducing home audio in a cabin **(Fig. 1)**.

Fig. 1 Sound Image Reproduced in Cabin

2.2 Quality issue of Car Audio

In order to proceed toward the reproduction of "accurate sound," various problems which are caused by a listening environment peculiar to car audio are described below by comparison with the listening environment of home audio.

2.2.1 Sound image localization

First, the most serious problem in car audio listening is the bias of a stereo sound field. People perceive the sense of direction of a sound image based on level and time differences (phase difference) between sounds coming into right and left ears. In addition, the direction is difficult to be specified because the low band has a long wavelength for an interaural distance difference. On the other hand, the mid-high sound has a short wavelength with characteristics of enabling the direction of sound source to be specified easily.

Home audio usually performs listening at the center of right and left speakers. When the same sound (signal of the same phase/sound pressure level) is output from right and left speakers, a listener receives the same loudness of a sound from the right and left speakers at the same time. Thus, the sound image is localized in front of the listener (the center position of right and left speakers). Furthermore, when different sounds are output from the right and left speakers, a sense of sound field with the breadth of back and forth/right and left/up and down can be obtained, enabling the listener to enjoy music with realistic sensation as if a live performance were given in front of them.

Meanwhile, since the right and left speakers are in an asymmetric position for both the driver and front passenger seats which are car audio listening positions, a difference occurs in the sound arrival distance from each speaker to the listener.

when the same sound is output from two speakers having a distance difference, the sound which arrives from the speaker close to an ear becomes larger because the loudness of a sound gradually decreases (distance attenuation) while traveling through the air. Accordingly, the perception of a left-right direction is related to an interaural level difference, which becomes a factor causing the bias of sound image localization, and the mid-high range is particularly susceptible to the effect.

Also, a difference occurs even in the arrival time of sound from the right and left speakers.

As known as the precedence effect, the listener feels that there is a sound source in the direction of a sound which arrives first, resulting in a more biased sound image localization.

For the reasons stated above, correcting the difference in time/level of sound reproduced from the right and left speakers is necessary to eliminate the bias of sound image localization

2.2.2 Sense of Clarity for Sound

The next problem is a lack of sense of clarity for sound. For home audio, listening is performed with the speaker in the state of facing directly (or close to the opposite) and also a sufficiently large listening room can be secured. Compared with the "direct sound" which is an output sound from the speaker and directly delivered to the listener, the loudness of "reflected sound" which is the sound reflected by a floor or wall and then delivered to the listener is relatively small and has an appropriate time difference, enabling the listener to enjoy music with the reverb according to listening room environments (size, shape, interior materials).

On the other hand, the listening space of car audio is extremely narrow and strongly influenced by the reflected sound. As the sound source (speaker) and the reflecting surface (glass, door, or the like) are closer to the listener, the reflected sound with a loudness level close to that of the direct sound arrives in a short time. If the reflected sound is large and the time is short compared with the direct sound, the sound image gives the impression of being blurred with less sense of clarity.

Furthermore, for car audio, a high band reproduction speaker (tweeter) is embedded upward in an instrument panel in many cases. Although this is because the unity of interior design is emphasized, under such conditions, a high band with high straightness is efficiently delivered to the listener by using the reflection of the windshield, which is a mounting method improving spatiality of a space in a narrow cabin. However, there is a lack of sense of clarity because the proportion of direct sound which is delivered to the listener is reduced.

From the above, delivering the direct sound to the listener as much as possible is important to obtain the sound quality with the high sense of clarity.

2.3 Approach to Issue

Contents of approaching the sound system for dealer options in response to the car audio quality issues which were described in Chapter 2.2. are described in this chapter.

2.3.1 Premium Double Tweeter System

As described in chapter 2.2.1, the time/level difference of sound from the right and left speakers to the listener occurs in car audio and the bias of sound image becomes a problem. In order to solve its problem, adjustments have been made to align the sound level and its arrival timing (time alignment) for a specific listening point by the conventional method. For example, in the case of optimizing the arrival timing of sound in the driver's seat, it is as shown in **Fig. 2**.

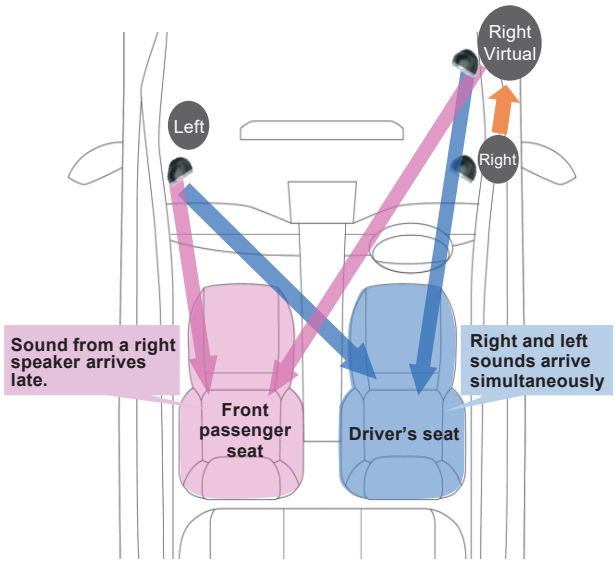


Fig. 2 Correction Method for Conventional Arrival Timing (time alignment)

By delaying the output timing of the right speaker close to the driver's seat, the right speaker is virtually moved away to match the sound arrival timing from the left speaker. As a result, a passenger in the driver's seat can feel the spatiality of sound as if he or she were listening to the sound in the middle of right and left speakers. Instead of that, the right speaker on the far side for a passenger in the front passenger seat is virtually moved further away, resulting in a more biased sound image localization. In other words, the passengers in both seats could not obtain the ideal sound image localization simultaneously by the conventional method.

This time, tweeter with two axes with which the sound image can be localized at both seats for the driver and front seat passengers at the same time **(Fig. 3)** was developed jointly with Toyota Motor Corporation.

Fig. 3 Double Tweeter (left channel)

And then, two tweeters with different roles were integrated, which enabled the sound of two axes to be freely adjust (time/level). **Fig. 4** and **Fig. 5** show the role of each tweeter and the concept of sound creation. First, one tweeter adopted "direct tweeter" which outputs a delayed sound to a nearby passenger, the other tweeter adopted "horn tweeter" having a horn-type structure with narrow directivity, which is directed toward the faraway passenger on the diagonal line to prevent sound from leaking to the front passenger as much as possible.

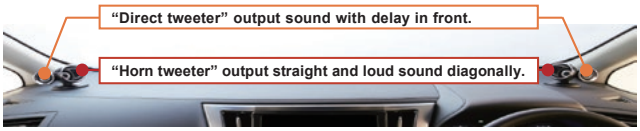


Fig. 4 Role of Each Tweeter

In addition, the direct tweeter and the horn tweeter can deliver to both the driver and front passenger seats simultaneously by setting the delay time of direct tweeter according to the timing when the sound of horn tweeter arrives.

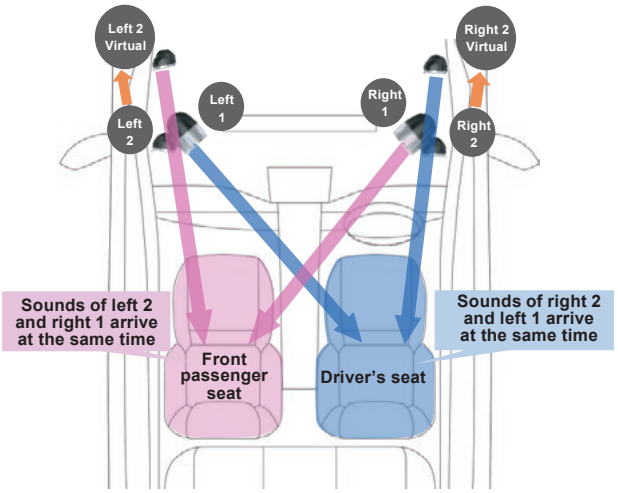


Fig. 5 Correction Method of This Arrival Timing (time alignment)

As a result, the sound image which had been biased until now appeared clearly in front of their eyes, which led to achievement of the realization of the sound image localization similar to the home audio.

Furthermore, the double tweeter is arranged on both sides of the instrument panel and the sound axis of the speaker is directed to each listener, which allowed the sound of components with a lot of direct sounds to be delivered. Accordingly, Reproduction of high-level stereo space which had not been achieved with the previous car audio systems could be realized simultaneously in the driver and front passenger seats while ensuring a sense of clarity for sound.

3. System Structure

The system structure is described in this chapter. The double tweeters which characterize the sound system are arranged on both sides of the instrument panel.

Also, front door speakers have been changed from conventional full range types to woofer types specialized in low band range.

Furthermore, a high-quality sound power amplifier with 8-channel output has been adopted so that these speaker performances can be delivered to the fullest extent. Sound system structure diagram is shown **(Fig. 6)**.

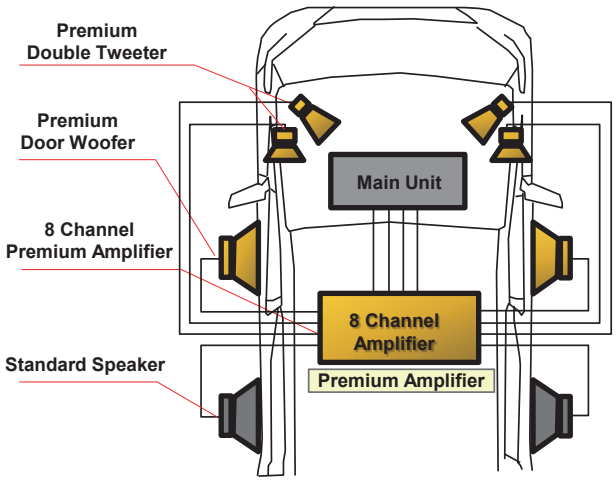


Fig. 6 Sound System Configuration Diagram

3.1 Speaker Technology

An approach to improving the high-quality sound has been implemented even for a speaker itself. Accordingly, technology for reproducing the "accurate sound" which is cultivated in ECLIPSE home audio is incorporated especially into the premium double tweeter.

Double Tweeter

The structure is shown in **Fig. 7**, and each role is described in this chapter.

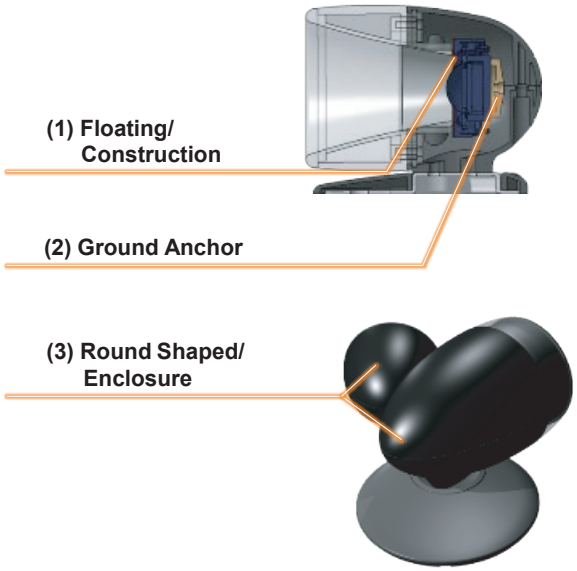


Fig. 7 Double Tweeter

(1) Floating Construction

A floating structure which avoids a direct contact between the speaker unit and the speaker box was adopted. Unnecessary vibrations other than the sound to be played are suppressed.

(2) Ground Anchor

The conversion efficiency from an electrical signal to sound, which will become an issue, is improved by the floating structure provided with a scaffolding called a ground anchor (spindle).

(3) Round-Shaped Enclosure

A unique curved form is adopted for the enclosure to suppress the turbulence of a radiated sound wave caused by the outer diameter, which allowed the sound waveform to be played more accurately.

In addition, these speakers were devised to be made versatile (possible to be mounted on various types of vehicles) even in terms of overall size and leg shape.

Premium Door Woofer

We developed a premium door woofer with improved power linearity characteristics, focusing on sound tracking **(Fig. 8)**. In particular, the support system was strengthened (shape, materials, and the like) and a large damper was adopted for a damper. Also, urethane with good linearity was used for the edge. As a result, the resonance point (f0) of low frequency band has not been changed substantially and low-band reproduction with less distortion has been achieved even in large input **(Fig. 9)**.

Furthermore, since the linearity is good, the sound quality which has the tracking capability for a wide range of sound changes from small signals to large signals and has a sense of speed could be also ensured.

Fig. 8 Premium Door Woofer

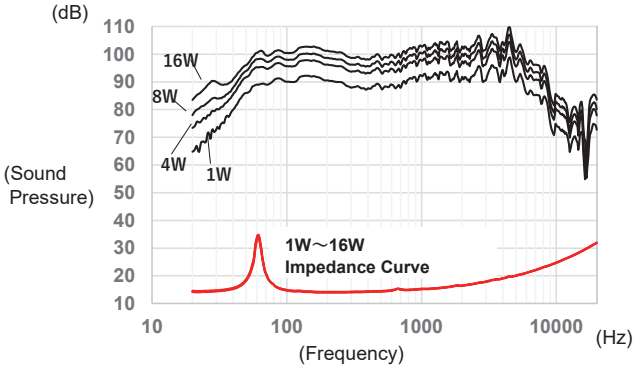


Fig. 9 Power Linearity Characteristics (1W~16W)

4. Signal Processing Technology

An in-vehicle amplifier is generally equipped with DSP (Digital Signal Processor) so that the acoustic characteristics in a cabin can be corrected. Even for this product, the time alignment and sound pressure frequency characteristics can be corrected for each channel, contributing to the reproduction of the "accurate sound." In addition, the thickness of vocal is also important in order to enjoy music more with the double tweeter system.

However, when listening to the sound of a door-mounted speaker at an asymmetric stereo listening position such as the driver and front passenger seats in a cabin, a dip occurs in a specific frequency band due to phase interference caused by a difference in distance from the right and left speakers to the listening point.

The band where the dip (around 200Hz to 400 Hz) is generated is an important band as the thickness of the vocal, and the thickness of the vocal cannot be obtained even if it is simply corrected by using an equalizer. Therefore, an all-pass filter is used to eliminate the phase difference as much as possible, and then the equalizer processing is performed **(Fig. 10** and **Fig. 11)**.

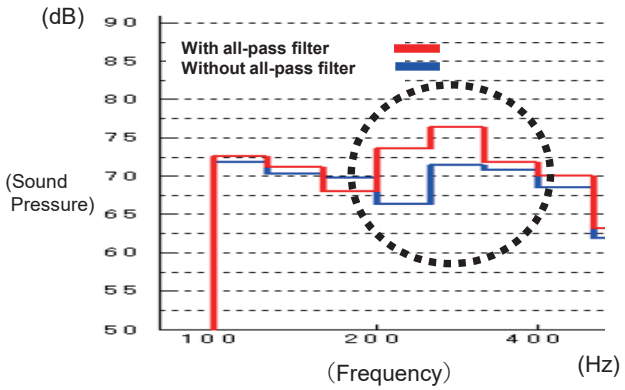


Fig. 10　Sound Pressure Frequency Characteristics in Cabin (diver's seat)

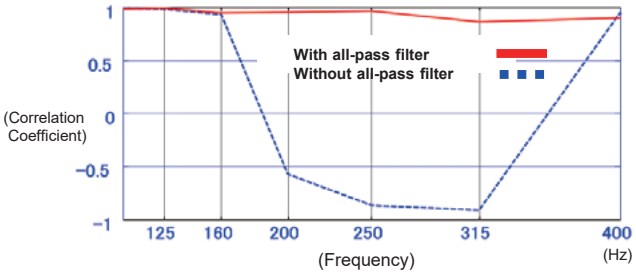
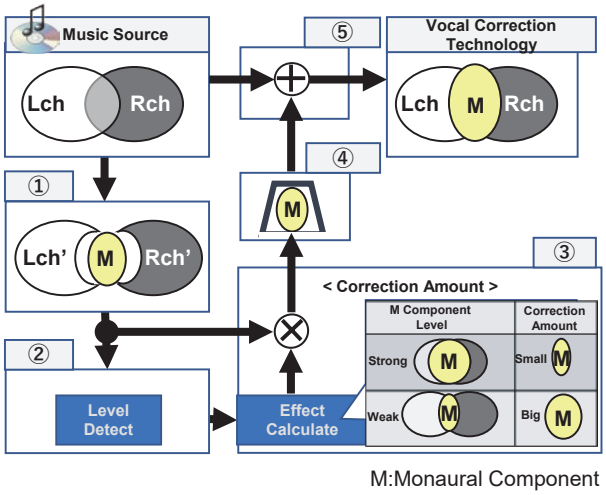


Fig. 11　Binaural Correlation Coefficient Characteristics (driver's seat)

Furthermore, a correction technology with a general equalizer which corrects a certain amount of sound may not be optimally corrected on acoustic feeling because the level of recorded mid-low band is different depending on the source. This time, the new correction technology has been established, which is described in detail below.

This technology for correcting the depth of sound (vocal band thickness) is a technology for detecting the level of a monaural signal included in a music source and optimizing an equalizer correction amount according to the detection results. An overview of the correction technology is shown in **Fig. 12**.



① Extraction Part of Monaural Component:
Extract monaural component included in music source
② Detection Part of Level:
Detect monaural signal level in real time
③ Calculation Part of Correction Amount:
Calculate correction amount according to monaural signal level
④ Band Pass Filter (BPF) Part:
Extract vocal (mid-low range) from monaural signal
⑤ Mix Processing Part:
Add vocal to music source

Fig. 12　Outline of Vocal Correction Technology

This technology enables the depth of sound to be actively corrected in real time, allowing a uniform sense of vocal thickness to be created constantly even for music sources of various recording levels which could not be achieved with the conventional equalizer correction.

The results of correction technology with the conventional equalizer and the new vocal correction technology are shown **(Fig. 13)**.

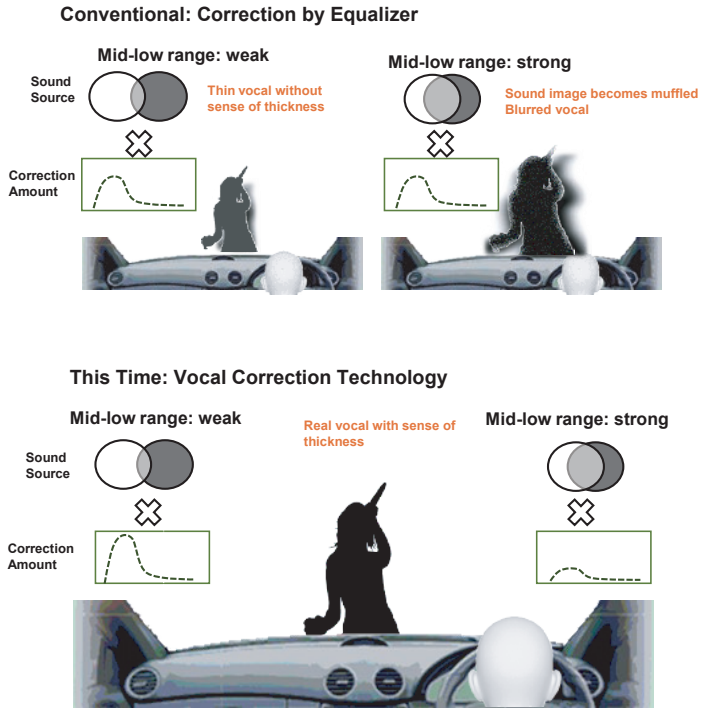


Fig. 13 Vocal Correction Technology

In this system, a door woofer covers frequency band of 2kHz or less. It is said the longer wavelength is, namely the lower frequency (about 150 Hz or less) is, the less the influence on the sound image localization is, the asymmetry of a mounting position often has influence in any higher frequency band. Therefore, this system was tuned in consideration of the balance with sound from a tweeter while confirming the characteristics of interaural correction coefficient for these frequencies toward the realization of more accurate sound localization.

5. Premium Power Amplifier

The sound quality correction in a cabin is mainly performed by signal processing. However, a raw sound (pure sound of hardware itself) cannot be corrected by the signal processing.

This time, in order to achieve the target "accurate sound," it is indispensable to develop an amplifier having a high sense of clarity and a sense of sound depth/speed, and also having realized a high level of accurate sound localization even in the original sound evaluation at a listening room. Approach to its development is described in this chapter.

Although there are various approaches to improving the original sound, we focused on the phase noise performance which was the base performance of sound creation this time.

The phase noise performance is a performance indicating the purity of a digital clock signal. In the case where a noise is superimposed on a clock signal from a power supply line or signal line, a temporal fluctuation (jitter) occurs in the signal waveform, resulting in an unintended minute deviation at the time of converting from digital to analog, which adversely affects in sound quality. For example, a lack of sense of clarity has an adverse effect on the overall sound quality, such as a reduction in a sense of sound depth/speed and inability to determine the sound image localization.

Thus, reducing the noise factors is necessary to improve the phase noise performance. Since the noise is caused mainly by internal electronic circuit operation, a review is necessary to be implemented in a much deeper area for detailed design such as power supply performance, component performance, communication waveform, and patterning of each IC. In this area, even if there is a slight improvement in performance, a great change on acoustic feeling is likely to occur.

Therefore, the following efforts were made to achieve the target "accurate sound" by repeating careful performance studies and hearing evaluations.

5.1 Development of High-quality Sound Electrolytic Capacitors

A high-quality sound electrolytic capacitor is being jointly developed with component manufactures in order to pursue more "accurate sound" than conventional models', and this high-quality sound electrolytic capacitor is a component used in a power supply line of a power amplifier IC for driving a speaker.

Moreover, the power supply of power amplifier IC requires to have a performance for supplying electric power quickly and sufficiently, which is necessary for driving a large number of speakers.

Even in the past, the electrolytic capacitors which were used for this power supply had been examined for sound quality performance while repeating trial listening, in addition to creating the necessary electrical performance. This time, we reviewed the constituent materials of electrolytic capacitor to meet the "accurate

sound" pursued by the double tweeter and vocal correction technology **(Fig. 14)**.

First, a joint trial listening was performed at our listening room with a capacitor manufacture, and we decided on the details of contents to improve the sound quality, starting from firmly grasping each other's listening point and way of feeling.

Occasionally, by making multiple samples at once, we evaluated which electrical characteristic has the most effect on the sound quality improvement, and also evaluated even sleeve colors, printed colors, or the like which did not appear in the electrical characteristics, accumulating the improvement of sound quality while adding fine adjustment **(Fig. 15)**.

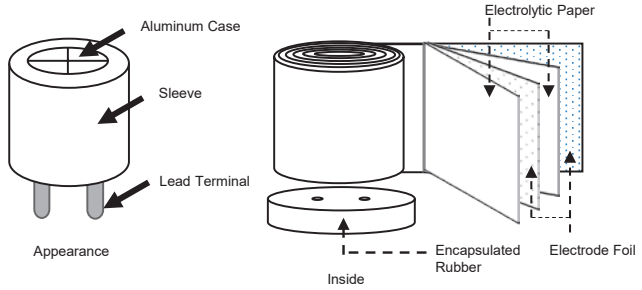


Fig. 14 Electrolytic Capacitor (structure)

Fig. 15 Electrolytic Capacitor
(a part of component under consideration)

The examination results show that adjusting the ESR (Equative Series Resistance) value is the most effective way for the "accurate sound" as electrical characteristics of electrolytic capacitor.

And furthermore, the ESR value was finely adjusted and the trial listening was repeated, which finally enabled the sound quality to be created. As a result, the ESR value has been reduced by 15% from the conventional product's **(Fig. 16)**.

Fig. 16 Adopted Electrolytic Capacitor

5.2 Overall Sound Quality Adjustment

As described in the previous chapter, most of the phase noise performance degradation is caused by the operation of an electronic circuit. Thus, we focused on the power supply line and communication line of the circuit having the greatest influence, and then implemented a review of improvement for the phase noise performance **(Fig. 17)**.

Moreover, just like the high-quality sound electrolytic capacitor described in chapter 5.1, reselection of component and patterning studies were repeated on the entire circuit while confirming the correlation between desktop simulation and audibility evaluation, resulting in the reduction of noise factors affecting the phase noise performance.

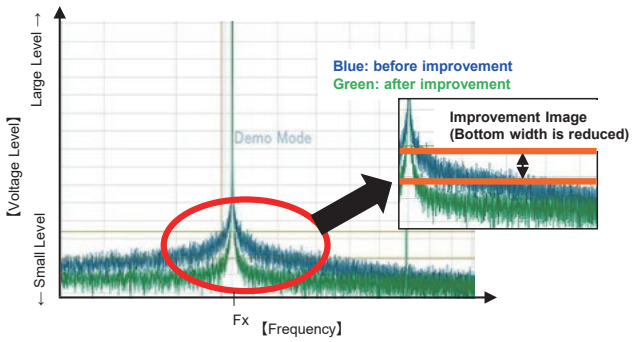


Fig. 17 Image of Effect by Phase Noise Reduction
(Amplifier Output Part)

The sound quality of a newly developed audio amplifier enabled a sense of clarity to be given so that particle profiles of each sound are clearly audible. Furthermore, a sense of sound depth, the rising of sounds, and the sound image localization were improved by increasing a sense of clarity, which led to the achievement of the raw sound suitable for the "accurate sound" targeted by us.

6. Conclusion

As explained above, the sound creation of premium double tweeter sound system for dealer options was described with development history and technical introduction.

The result of sound quality comparison with a general audio system (standard grade) is shown as a radar chart **(Fig. 18)**. This sound quality evaluation results were obtained by several sound designers, and the sound quality of total points which are eight or more points is considered to be suitable for premium sound.

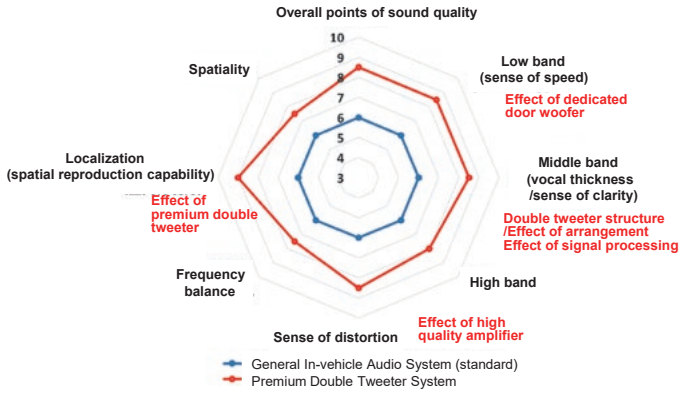


Fig. 18 Radar Chart of Sound Quality Comparison

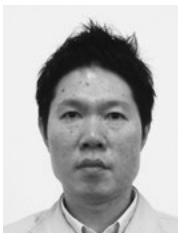
"Spatial reproduction" which accurately drew even position information of the recorded sound for both the driver and front passenger seats were realized by the double tweeter. Also, for the installation, "sense of clarity" was greatly improved by adopting the speaker structure and arrangement which could deliver sound directly as though you could see vocal mouth movement and players' fingering. In addition, for signal processing technology, the vividness of sound could be expressed by naturally emphasizing the thickness of vocals in any source. Furthermore, for the door woofer, even a fine signal was reproduced from the rising to the falling of sounds, and "sense of speed" marked by rhythms with clear sound could be realized. It makes us feel like we are listening to home audio in a cabin.

That enables us to prove this system with confidence in the finish. Therefore, we'd like to everyone to listen.

Acknowledgements

We would like to take this opportunity to express our deepest appreciation to Toyota Motor Corporation for their great cooperation in the development of this system, and to Nichicon Corporation and Nichicon (Ohno) Corporation for their cooperation in the provision of many samples and audio quality audition for the development of high-quality electrolytic capacitors.

Profiles of Writers



Toshio
NAKAMICHI

CI Business Group
Acoustic
Engineering Div.

Toshimitsu
ONBE

DENSO TEN
TECHNOLOGY
Limited

Kazuaki
SAITO

DENSO TEN
TECHNOLOGY
Limited

Yuki
NISHIO

DENSO TEN
TECHNOLOGY
Limited

Tomoyasu
SAKAUE

TOYOTA MOTOR
CORPORATION

Kunihiko
IRIE

CI Business Group
Acoustic
Engineering Div.