

# Development of New Premium Sound System

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## Abstract

The sound of in-vehicle premium sound system is developed with various directional concepts by each manufacture. We, DENSO TEN focus on the delivery of artistic quality of contents to user, and our target is how we accurately reproduce the sound waveform on time axis. In a cabin, there is a problem with many disturbances of the sound waveform that is not generated in normal home audio, such as reflected sound from glass near ears and vibration sound from door panel and body of vehicle. We thought that these disturbances of the sound should be corrected to achieve high quality sound. We have adopted the method that reproduced the sound to cancel the reflected sound by adding the speaker on the shoulder part of the seat in the past. But recently, electric vehicles and hybrid vehicles have increased in automobile market and the need for improving the fuel efficiency increases. Then, we have developed the technology shaping sound waveform by digital signal processing because it is difficult to increase the weight of vehicle.

In this paper, we introduce the efforts of improvement of the sound quality of in-vehicle premium sound system centering on this technology.

## 1. Introduction

“Toyota Premium Sound System” for Crown was developed jointly by Toyota Motor Corporation and DENSO TEN. This system makes “accurate sound,” DENSO TEN target, possible by correcting disturbances of the sound waveform occurred in a cabin when music is reproduced. In this paper, we introduce our development concept of the system and various technologies used to achieve the sound.

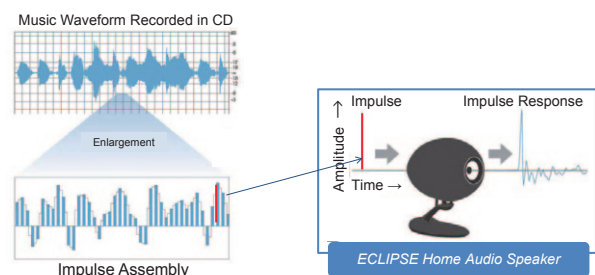
## 2. Purpose of Development

### 2.1 Development Concept

The sound targeted by DENSO TEN is “accurate sound.” In order to deliver artists' thoughts straight to users, the reproduction of the accurate sound in the time domain such as the rising and falling of sounds is considered as important and is being pursued.

Enlargement of the digital signal waveform recorded in CD can be regarded as impulse assembly and an impulse can be thought of as the minimum unit of music signal. Development has been conducted by evaluation with a focus on the impulse response based on our belief the music waveform can be accurately recreated if we accurately reproduce the impulse. (Fig. 1)

“**Accurate Sound** = Deriver Artistic Quality of Content to Users”  
Recreate Every Single Element of Music



**Impulse = the Minimum Unit of Sound**

Fig. 1 Concept for Reproduction of Impulse Response

DENSO TEN ECLIPSE home audio speaker has constantly pursued the reproduction of “accurate sound” since its release in 2001. This has led to achieve the reproduction of “accurate sound” which specialized features such as “sense of clarity” as though you could image vocal mouth movement and players' fingering, “sense of speed” marked by rhythms playing with clear sound, and “spatial reproduction capability” to present location information of recorded sound. This is how we have received good recognition by some of the world's best musicians and recording engineers. (Fig. 2)



Fig. 2 Appearance of ECLIPSE Home Audio Speaker

“Toyota Premium Sound System” for Crown was aimed at creating the accurate sound of ECLIPSE home audio speaker in a cabin.

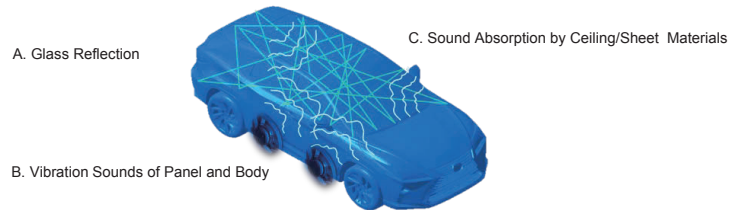
## 2.2 Problems and Countermeasures of Creating Sounds in a Cabin

Two problems are caused principally by the fact that a listening environment is different between vehicle audio and home audio.

Problem① : significant disturbance of the impulse response

Since there are many disturbances of the sound such as reflected sound from glass and vibration sound from door panel and vehicle body in a cabin, they cause significant disturbance in the impulse response. (Fig. 3)

### ● Harsh Environment in a Cabin as Acoustic Space



### ● Impulse Response in a Cabin

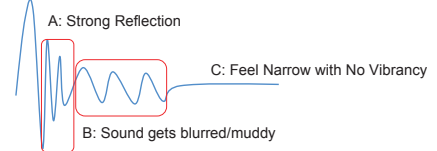
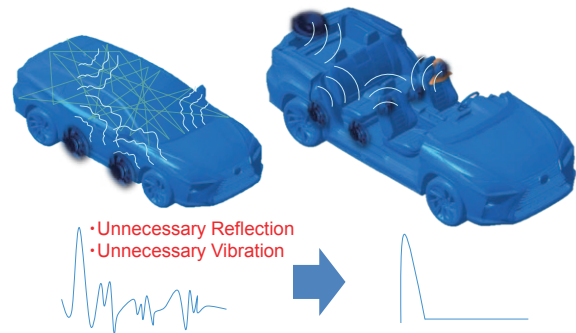


Fig. 3 Disturbances of Impulse Response in a Cabin

These disturbances of the impulse response should be corrected to achieve accurate sound in a cabin. (Fig. 4)



### Eliminate Unnecessary Reflection/Vibration

Fig. 4 Correct Disturbances of Impulse Response

Previously, we adopted the method to correct the disturbances of the impulse response by reproducing the antiphase sound with the speaker on the shoulder part of the seat close to ears. But on the other hand, number of speakers and the weight increased. Therefore, we adopted a technology of shaping the impulse response with digital signal processing without adding a speaker this time. That is called “Impulse response rectification technology.” The content is described in chapter 3.

Problem② : Sound is biased toward the side of speaker close to ear (Fig. 5)



Fig. 5 Localization Bias (image)

The problem specific to car audio is the “localization bias” that the sound<sup>(1)</sup> supposed to be heard properly from the front of you tends to be biased toward either left or right depending on your listening position. To solve this, we have used our own localization correction technology. The content is described in chapter 4.

This sound system takes astonishing attention to the power amplifier circuit and performance of the speaker itself, and thus “accurate sound” has been achieved with the entire system. The content is described in chapter 5.

### 3. Impulse Response Rectification Technology

#### 3.1 Introduction to Impulse Response Rectification Technology

This is a technology to improve a sense of clarity, speed, and spatial reproduction for the sound by shaping the disturbances of the impulse response caused by in-cabin environment at the listening position.

Reproduction of the impulse response waveform at the listening position is achieved by performing the correction filter processing to the sound source by DSP (Digital Signal Processor) in the amplifiers beforehand. The procedure of designing correction filter is to correct the extracted “disturbances of the impulse response” by measuring the impulse response from the input to ears including a speaker

\* <sup>(1)</sup> Monaural components. They are included in various music such as vocal and bass drum.

and utilizing our own evaluation technology acquired through development of ECLIPSE home audio speaker. (Fig. 6)

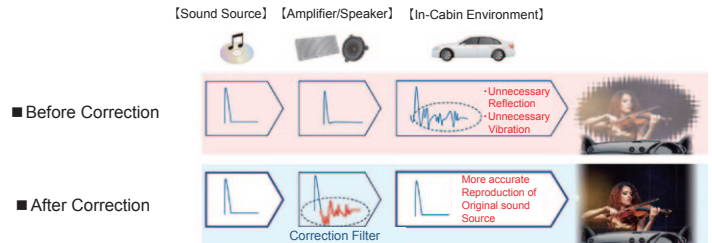


Fig. 6 Image of Rectification Technology of Impulse Response

### 3.2 Issues and Measures

There are following two issues for applying the technology to on-vehicle application.

The first issue is a problem of “differences in sound quality depending on the listening position.” The effect of the impulse response rectifier fluctuates with changes in the user's ears or seat position in different listening. Because the control was vulnerable to fluctuations of the listening position in a limited range capable of obtaining the effect of correction filter. As a countermeasure against that, the vehicle interior is divided into plural areas and then we measure the impulse responses at every area. Correction characteristics are determined by extracting common feature points based on our accumulated knowledge and experience from each data. This enables us to reduce differences in sound quality depending on the listening position and have expanded listening areas. (Fig. 7)

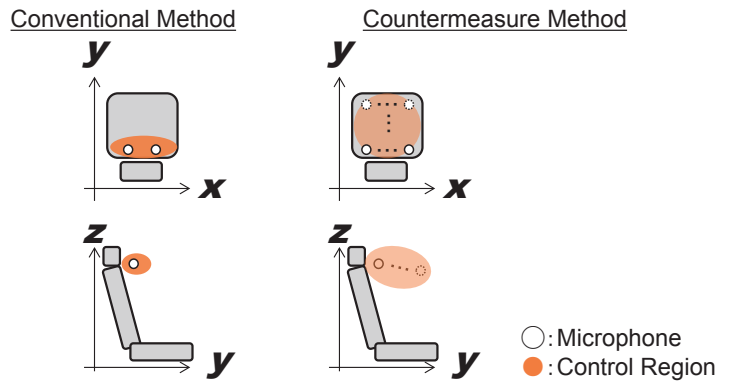


Fig. 7 Countermeasure for Differences in Sound Quality by the Listening Position

Another issue is “measures for multiple speaker system.” Multiple speakers are used to expand reproduction frequency band and improve broadening sense for the premium system. The challenge was how to implement the impulse response rectification for such a system.

Previously, reproduction frequency band was divided and the sound was created with a focus on a frequency response shared by plural speakers that reproduce respective specialized frequency band such as woofer, squawker, and tweeter. In the concept of the impulse response rectification, we constituted a unique coupling filter which enables a speaker for high frequency band and a speaker for low frequency band to be virtually treated as one speaker due to the occurrence of frequency band constraint on the independent processing for each speaker, and then performed the impulse response rectification for each virtual speaker. (Fig. 8)

Thus, the optimal impulse response rectification has been performed while taking advantage of the characteristics of each speaker. Furthermore, the idea of the virtual speaker has led to reduce the number of speakers to be tuned and efficiently perform acoustic design.

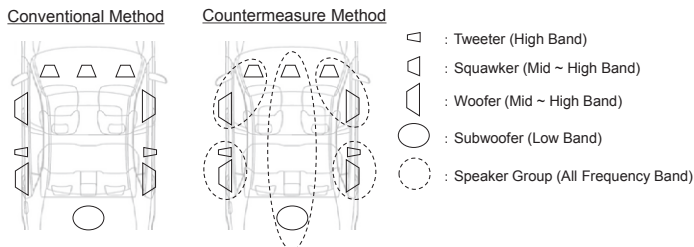


Fig. 8 Example of Coupling Filter

Finally, the measurement results of the impulse response waveform before and after the impulse response rectification correction technology is shown. (Fig. 9) the well-shaped peak of the rising part of impulse response is confirmed after the disturbance was corrected.

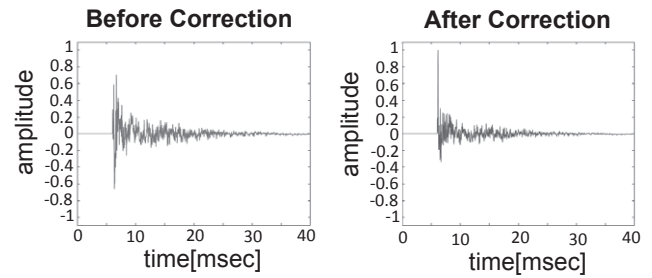


Fig. 9. Impulse Response Waveform Before and After Correction

## 4. Localization Correction Technology

### 4.1 The Factor Causing Localization Bias

Since speakers for stereo reproduction are asymmetrical with respect to the listening position in a cabin, the bias of a sound stage will occur. Especially, the sound image to be localized at the center is biased toward a near-side speaker. That is because the sound from the near-side speaker arrives at the listener slightly before the sound from the other side. The bias can be improved by performing delay processing. However, it causes the reverse effect on the opposite side to the left and right seat, respectively.

### 4.2 Issues on Conventional Localization Correction Technology

Accordingly, with conventional technology, the process to match the band phase contributing to a sense of localization is considered by focusing on a binaural phase frequency response and using an all-pass filter because the left and right localization of sound images at the center are improved simultaneously. However, the process using all-pass filter causes response waveform disturbances from the point of view of the impulse response. Therefore, the improvement of a sense of the sound image localization and the sound clarity is a trade-off relation.

\* <sup>(2)</sup> All-pass Filter: Filter circuit changing only phase characteristic while the amplitude characteristic remains unchanged.

### 4.3 Development of New Localization Correction Technology

Thereby, in this system, a new localization correction technology improving a sense of the sound image localization at the center was developed by proactively utilizing the center speaker, combining well the sound level that arrives at the listener from each speaker and the timing in space, and adjusting it. The IACC (Inter Aural Cross-Correlation) is used for evaluation method of a sense of localization. Each frequency range from 100Hz to 1kHz, which comes to the problem particularly of the disturbance largely on acoustic feeling in a cabin, is measured, graphed, and evaluated though IACC is the measurement of the correlation of signal waveform applying to both ears. (Fig. 10)

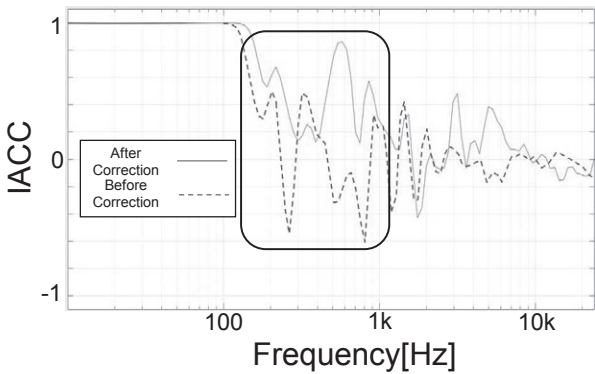
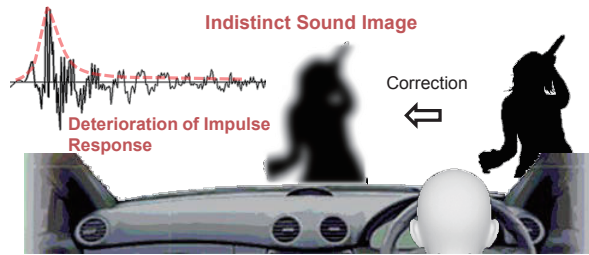


Fig. 10 IACC Graph Before and After Correction

By this localization technology, a sense of localization has been acquired without damaging the clear sound image obtained with the impulse rectification technology. The results of the conventional and new localization correction technologies are shown. (Fig. 11)

### Conventional Localization Correction Technology



### New Localization Correction Technology

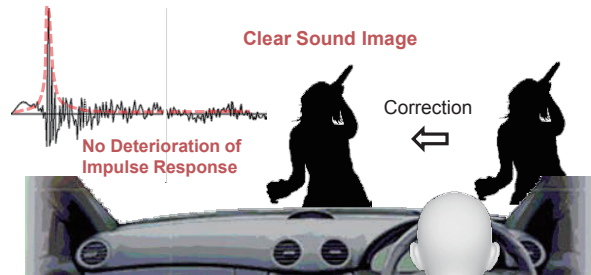
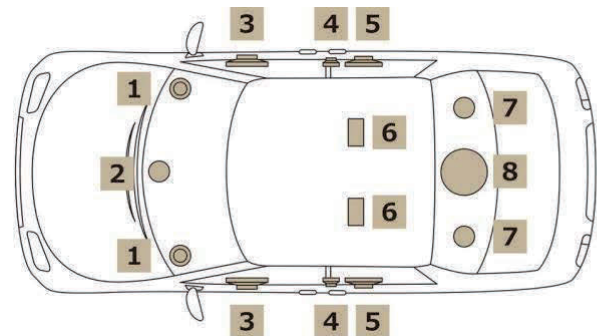


Fig. 11 Results by Conventional and New Localization Correction Technologies (The impulse response and sound quality image)

## 5. System Configuration

The system configuration is described in this section. This is the speaker arrangement taking into consideration of both listeners for front and rear seats. (Fig. 12)



- 1 9cm/2.5cm Front Side Speaker ×2
- 2 9cm Center Speaker
- 3 18cm Front Door Woofer ×2
- 4 2.5cm Rear Door Tweeter ×2
- 5 16cm Rear Door Speaker ×2
- 6 Thin Type Ceiling Speaker ×2
- 7 9cm Rear Satellite Speaker ×2
- 8 20cm Rear Tray Subwoofer

Fig. 12 Speaker Arrangement



This section describes each speaker technology

## 5.1 Speaker Technology

The speaker unit itself is also aimed to achieve “accurate sound” and equipped with technology to enhance the reproduction of the impulse response.

### (1) 1 9cm/2.5cm Front Side Speaker (Fig. 13)

Clear sound with little disturbance of waveform has been achieved by adopting a coaxial type where 9cm reproducing middle frequency band and 2.5cm reproducing high frequency band are coaxially arranged.

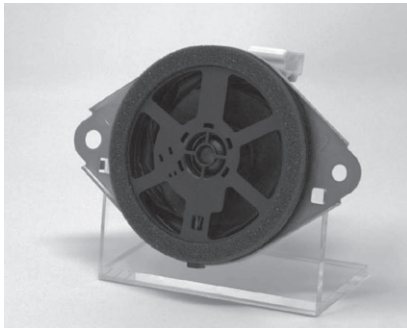


Fig. 13 Front Side Speaker

#### • 9cm Speaker Part

The sound quality rising the sound quickly without excessive incidental sound has been achieved by adopting a double-layer diaphragm for the diaphragm. Although diaphragm property values with a high propagation velocity (=a high stiffness) and high loss (less specific resonance) is considered ideal, it was difficult to achieve them with a single material due to contradictory characteristics. To work on the issue, the compatibility has been achieved by arranging two materials with different characteristics in two layers.

#### • 2.5cm Tweeter Part

Natural sound quality with less inherent sounds was aimed by adopting a soft dome diaphragm for the tweeter part.

### (2) 2 9cm Center Speaker

#### 7 9cm Rear Satellite Speaker (Fig. 14)

By adopting double-layer diaphragm for a diaphragm, the sound quality with the sound rising

faster without any excessive incidental sound has been achieved.

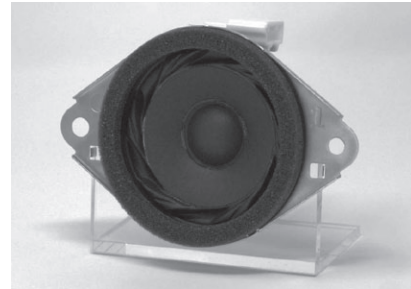


Fig. 14 Center Speaker/Rear Satellite Speaker

### (3) 3 18cm Front Door Woofer (Fig. 15)

#### 5 16cm Rear Door Speaker (Fig. 16)

The high stiffness requested in woofer has been ensured by adopting HR (HYPERBOLIC PARABOLOIDAL ROTATION) shaped double-layer diaphragm and being formed into HR shape. Furthermore, natural tone without any inherent sound has been achieved by resonance dispersion effect.



Fig. 15 Front Door Woofer



Fig. 16 Rear Door Speaker

### (4) 4 2.5cm Rear Door Tweeter (Fig. 17)

Natural sound quality with less inherent sounds was aimed by adopting a soft dome diaphragm.

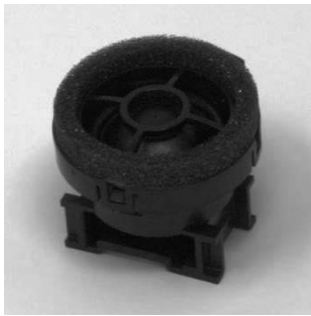


Fig. 17 Rear Door Tweeter

(5) **6** Thin Type Ceiling Speaker (Fig. 18)

It has been mounted at a slightly rear ceiling from front seats, adopted for adding space information, made the sound image wider, and achieved the spatial reproduction.



Fig. 18 Thin Type Ceiling Speaker

(6) **8** 20cm Rear Tray Subwoofer (Fig. 19)

Even more stiffness has been ensured. Low-sound reproduction without distortion has been achieved even in large input by adopting HR shaped non-press diaphragm, and further increasing the thickness in addition to HR shape.



Fig. 19 Rear Tray Subwoofer

A High-quality sound power amplifier of 12 channel outputs has been developed to fulfill those speaker performances to the fullest extent. Sound

reproduction of 12 channel using 16 speakers has enabled elaborate tuning to be suited to the characteristics of speakers. (Fig. 20)

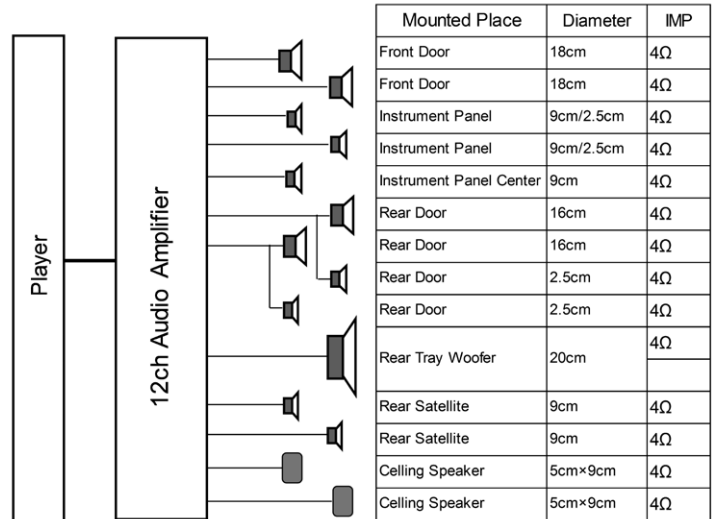


Fig. 20 System Configuration

## 5.2 Amplifier Technology

This section describes amplifier technology.

### 5.2.1 Sound Creation for Time Base Domain

We have attached great importance to the following contents when we try to improve the impulse response performance.

- Phase/group delay characteristics is flat
- Dynamic range is large

In addition to this content, we have focused on removals of waveform distortion components and noise components which are difficult to express only by the impulse response performance.

Distortion/noise components are caused primarily by electronic circuit operation in the amplifier. This is contained in the impulse response waveform on an extremely small level. According to actual comparison and evaluation of the sound quality with or without noise, the result has been found that the case without noise is much more faithful to original sound. (Fig. 21)

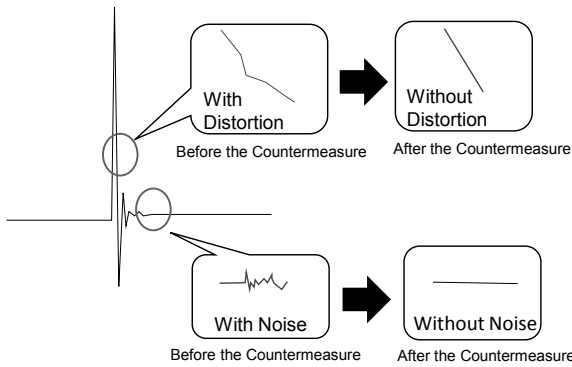


Fig. 21 Noise Contained in the Impulse Response Waveform

We placed great importance on the impulse response performance with excellent waveform and sound quality and worked on it, though spending enormous amount of time could be predicted by the work of removing distortion/noise.

### 5.2.2 Efficiency Enhancement by Utilizing Simulations

This time, a circuit board simulation was introduced in order to work for removing distortion/noise efficiently.

This simulation is utilized for

- Calculating a path and influence range of distortion current/noise current
- Calculating necessary board circuit characteristics to reduce distortion/noise (Fig. 22)

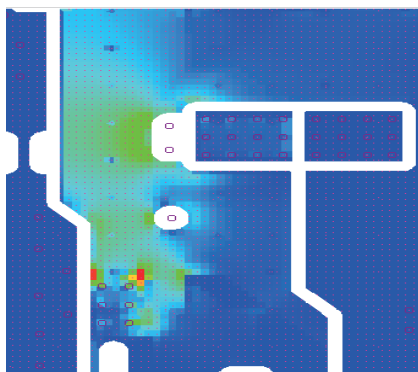


Fig. 22 Example of Circuit Board Simulation Result (Calculation for a Path and Influence Range of Distortion Current/Noise Current)

Many simulations in the case of taking measures in various patterns have been conducted before an actual listening evaluation is performed. (① on Fig. 23) The sequence of verification is conducted by the

listening evaluation for the effective items in the simulations. (② on Fig. 23)

Also, the accuracy of effect/prediction of measures had been accumulated by applying the result to simulations and we could efficiently proceed with the examination. (③ on Fig. 23)

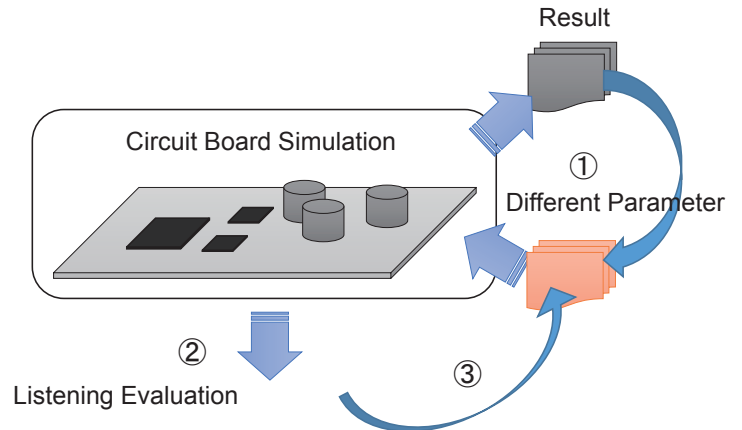


Fig. 23 Simulation and the Sequence of Actual Device Verification

As its effect, the sound quality of the newly developed audio amplifier leads to the sound that can nicely reproduce the portion where subtle sound of the like of fine rhythms and tone such as hi-hats, etc. are changed. We strongly hope that many people experience this sound. The appearance of the newly developed product (audio amplifier) is shown in Fig. 24.

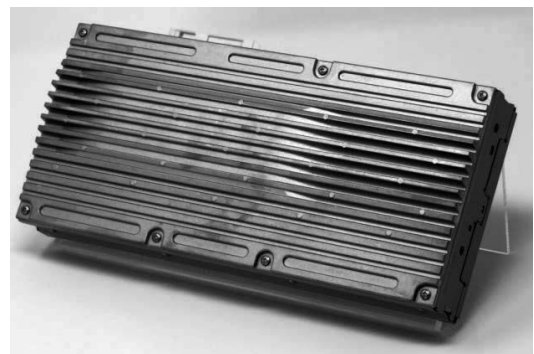


Fig. 24 The Newly Developed Audio Amplifier

## 6. Conclusion

In this article, we described the sound creation of “Toyota Premium Sound System” mounted on the 2018 new Crown while mixing in the introduction to development background and technology.



A Comparison result of sound quality compared with a general premium system is shown in the radar chart. (Fig. 25) The textures of “distortion,” “low band,” “middle band,” and “high band” have also surpassed the general premium system by each sound quality improvement technology of amplifier and speaker along with a substantial improvement of “sense of clarity,” “sense of speed,” “spatial reproduction,” and “sense of localization” by the impulse response rectification and new localization correction technologies. That enables us to provide it with confidence in the finish. Therefore, we'd like everyone to listen.

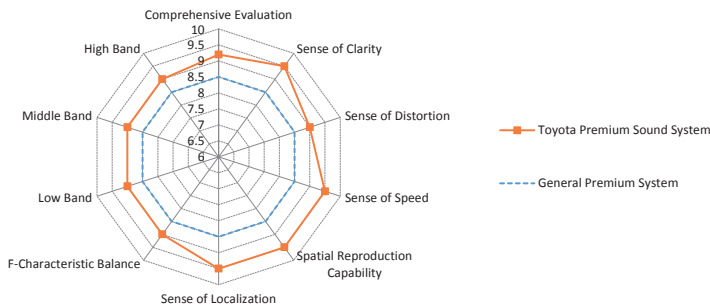


Fig. 25 Sound Quality Comparison Radar Chart

In addition, we would like to make the “Impulse response rectification technology” developed towards much more types of cars by further enhancing it along with passing down the know-how cultivated in this “Toyota premium sound system” to the future sound creation.

**Acknowledgments**

We would like to take this opportunity to express our deepest appreciation to TOYOTA Motor Corporation for the cooperation of this development.

- CROWN is a registered trademark of Toyota Motor Corporation.
- ECLIPSE is a registered trademark of DENSO TEN Limited.

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