"Toyota Premium Sound System" for CROWN Using Acoustical Space Control Technology

Hisao TAKAHASHI
Junji TABAYASHI
Shinichi NAKAISHI
Yuji TOMITA
Tadashi IMAMURA
Masayoshi KAGEYAMA
Shinichi YAMASAKI

Abstract

FUJITSU TEN LIMITED developed "Toyota premium sound system" for CROWN jointly with TOYOTA MOTOR CORPORATION. in February 2008. By making full use of "Acoustical Space Control Technology" (hereinafter refereed to as "Spatial Control Technology"): newly and originally developed by FUJITSU TEN LIMITED, this system has achieved the acoustical space with a sense of expanse and open space, as if being in a living room of approx. 30m^2 when listening to not only 5.1ch DVD but also normal 2ch music CD. This report explains about; 1) development background, 2) development concept, 3) technology to realize the concept - spatial control technology (suppression of unnecessary vibration, suppression of unnecessary reflected sound, addition of spatial information) and technology for sound quality improvement of speakers / amplifiers.

1 Introduction

In TOYOTA MOTOR CORPORATION, the first full-fledged premium sound system was named as "super live sound system" and installed in 1989. These days, premium sound systems jointly developed with the brand makers are widely used. Although these systems were developed under the pure sound conscious concept (wide band, powerful and seeking texture feeling), TOYOTA MOTOR CORPORATION requested developing a new premium sound system to be installed in this new sound system for CROWN with another directional concept added.

Looking at music media transition in order to propose the new concept, home theater has become popular together with DVD media in recent years. The "surrounded sense" and "sense of expanse" are becoming popular in the sound concept. The questionnaire conducted by Fujitsu Ten among users who have the premium sound system in a vehicle resulted in that "the sound with a sense of expanse" is preferred (**Fig. 1**).

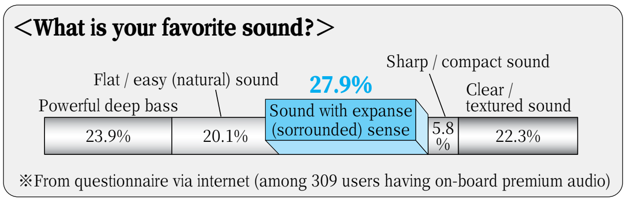


Fig.1 Results from Questionnaire on Sound Preferences among Premium Audio Users

As the conventional technologies to give a sense of expanse, there were surround technology with 5.1ch and acoustical space control technology with DSP (digital signal processing). However, since they were not originally considered to suit the environment of a vehicle cabin, there was enough room for improvement.

So, we started to develop the new technology to control sound field to give an impression of broad acoustical space in a vehicle cabin.

2 Development Objective

2.1 Sound Concept

Taking account of the background mentioned above, we set the targeted sound concept as "Free from the cage of narrow vehicle cabin."

The targeted wide space was set to the living room of approx. 30m^2 with which many users are familiar from listening at home, not to the acoustical space such as "concert hall" or "stadium," which we have targeted previously. It is possible to produce the impression of wider acoustical space technically, but we deemed that such a wider space impression when being in a vehicle cabin might be strange on the contrary. **Fig. 2** shows the image of targeted acoustical space.

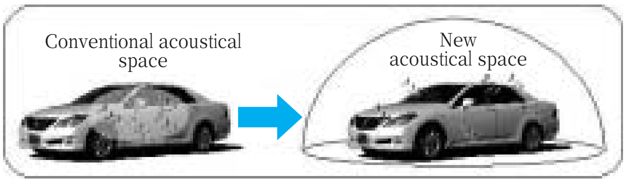


Fig.2 Image of Targeted Acoustic Space

2.2 Current Problems (Vehicle Cabin Space) and Solution (Action to Realize Concept)

To realize the target sound, we focused upon the difference of sound attenuation in time domain, as well as the conventional issues of expanding frequency band and flattening characteristics. **Fig. 3** shows the difference between conventional sound and desired sound.

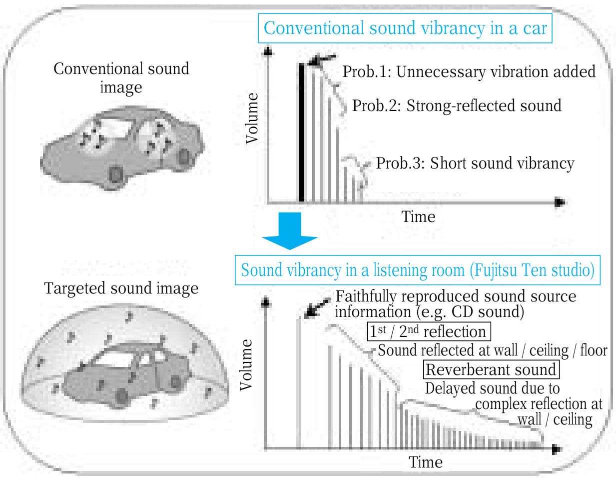


Fig.3 Difference between Conventional Sound and Desired Sound

There are three problems as follows in the conventional acoustical space in a vehicle cabin.

Problem 1):
Unnecessary vibration around the speaker installed in the vehicle body is added to the sound from the speaker.

→The vibration from the speaker transmits to the body while reproducing sound, and then becomes unnecessary vibration. It causes blurred sound image.

Problem 2):
Strong reflected sound is generated from glass / instrument panel.

→The sound emitted from a speaker is reflected at the glass / instrument panel, and the reflected sound makes listeners feel as though they are close to a wall and the acoustical space becomes narrow in the result.

Problem 3):
The reverberant period is shortened because the reverberant sound is absorbed in the ceiling and seat.

→Since the space is surrounded by soft and absorbent surface such as seat and ceiling materials, the reverberant period is extremely shortened. It makes listeners feel the acoustical space is narrow.

FUJITSU TEN LIMITED took the following concrete actions to solve these problems.

Solution 1):

Suppression of unnecessary vibration by damping technology

We used the speaker damping technology, developed by Fujitsu Ten. This technology for on-board speakers was applied from the TD technology (1) developed for home audio speakers by Fujitsu Ten.

Solution 2):

Suppression of unnecessary reflected sound by using antiphase sound

We developed a new method to negate the unnecessary reflected sound by using the antiphase sound emitted from the speakers that were set close to the listener's ears.

Solution 3):

Addition of spatial information from a special speaker

Based on the method reproducing the reflected sound to be generated as if being in the listening room from the different position of the direct sound emitted, special speakers were set to add spatial information.

Fujitsu Ten named these combined technologies as next generation "spatial control technology."

3 Spatial Control Technology

Here are the three technologies comprising of spatial control technology: 1) suppression of unnecessary vibration, 2) suppression of unnecessary reflected sound, 3) addition of spatial information.

3.1 Suppression of Unnecessary Vibration

For the first action of spatial control, it is essential to improve the quality of the sound itself emitted from a speaker. As mentioned in Section 2, by taking the damping technology developed and cultivated for home audio into the speakers, we addressed occurrence prevention of the unnecessary vibration that became the cause of blurred sound image. **Fig. 4** shows the waveforms before and after suppressing the unnecessary vibration. With the conventional speakers, unnecessary vibrations were generated after the direct sound and became the cause of the blurred sound image.

However, the new speaker with TD structure enables reproducing original sound precisely by emitting only the direct sound to listeners.

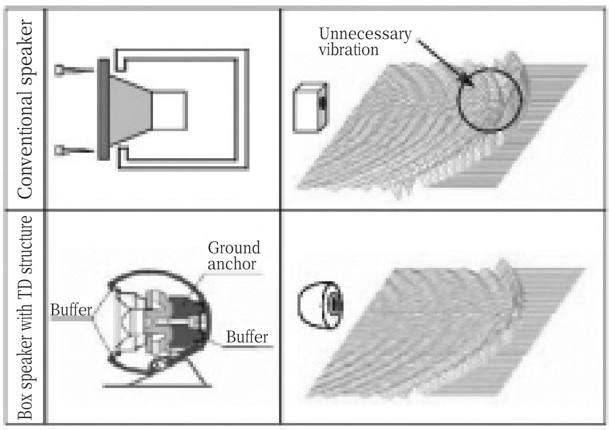


Fig.4 Suppression of Unnecessary Vibration

3.2 Suppression of Unnecessary Reflected Sound

Once the direct sound even with high fidelity is emitted, it becomes lower with unnecessary sound attached, by receiving reflected sounds from all around the vehicle cabin. It is known that the cause of the reflected sound is window glass, but it is impossible to remove the window glass.

So, we took another approach to suppress the generated reflected sound.

This method uses the principle that a sound signal can be cancelled by emitting its antiphase signal, shown as **Fig. 5**.

In this system, the cancellation is especially for the sounds from the center speaker and the speakers set in the instrument panel, which receive particularly strong effects from reflected sound among the on-board speakers."

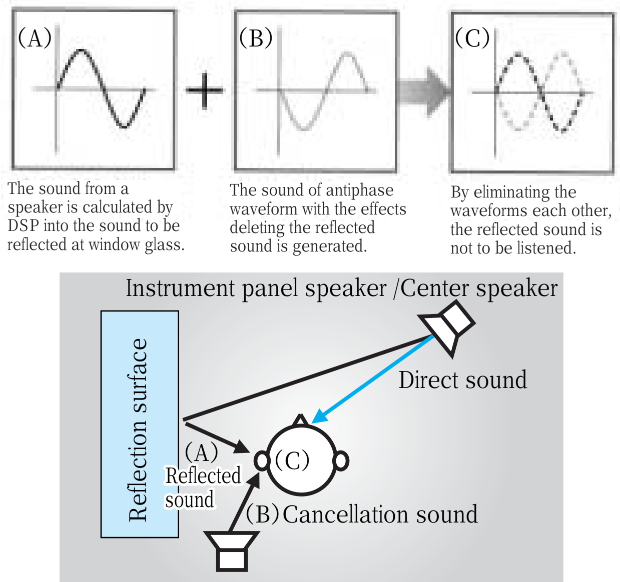


Fig.5 Cancellation of Unnecessary Reflected Sound by Antiphase Signal

The cancellation signal is produced by DSP: digital signal processing. First, the transfer characteristics from each speaker to a listener's ear position were measured, and then the filter factor for canceling only the reflected sound part was calculated with the results. In this system, to cover the reflected sounds generated in a vehicle cabin, the sounds that reach in 40ms at maximum after the direct sound are to be controlled.

*(1) TD technology: Time Domain technology
This refers to the technology that enables replaying the input waveform as precisely as possible, based on the time domain characteristics.

The frequency band of the cancellation signal is set 1.5kHz maximum. It is difficult to ensure the cancellation effects to the sounds in short wavelength band (high frequency waves) in the case such as listening point misalignment. Further, the excessive control may generate a new extra sound, and lead to sound degradation. For this reason, the control was implemented to the sounds only in the band with the big cancellation effect, which resulted in achieving a good balance between cancellation effects and stability. At the same time, it enabled reducing the number of the sampling frequencies to be operated through canceling filter, and DSP throughput drastically to approx. one-tenth.

The speaker providing the cancellation signal is set on shoulder area of the seat as shown in **Fig. 6**. The speaker close to listener's ear position enables not only controlling effectively but also directing the center of sound to the listener's ear. It prevents the new reflected sound that is generated when the cancellation signal is reflected by the surrounding window glass etc., and it improves the sound quality.

Since the acoustical performance is under the influence of human body size, we have found the best installation angle and speaker directional characteristics after implementing a number of studies.

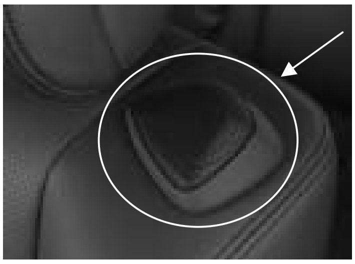


Fig.6 Seat Speaker

Fig. 7 shows the example data of comparison on the frequency response of reflected sounds before and after cancellation at the listening point.

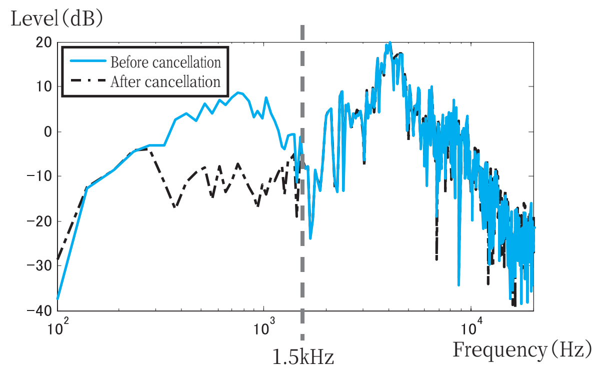


Fig.7 Frequency Response of Reflected Sound

3.3 Addition of Spatial Information

The last action for the spatial control is to add spatial information in order to reproduce the targeted acoustical space with a sense of expanse.

People perceive a spatial width with the direct sound from a sound source and its reflected sounds from surrounding objects. This reflected sound is called spatial information. If the spatial information of an intended room is reproduced precisely, it is deemed possible to give an impression as if being in the room.

The structure of reflected sound is expressed by the level mainly with two angles: one is "time axes", the other is "incoming direction". First, to reproduce the reflected sound of an intended space, we applied the filter capable of reproducing reverb waveforms precisely by sampling time, differing from reverb by conventional acoustical control. However, reproducing the time axes is not sufficient to give the impression of expanse to all directions. It is necessary to reproduce the incoming directions of reflected sound without fail. So, in this system, each speaker is undertaking a role: the speaker for sound effect in the instrument panel emits the reflected sound from the front, the seat speaker emits the sound from the side, and the ceiling speaker emits the sound from above and back. This enables reproducing the spatial information with both time axes and incoming direction, similar to the real acoustical space.

Fig. 8 and **Fig. 9** show the incoming directions of reflected sound in a listening room and under this system.

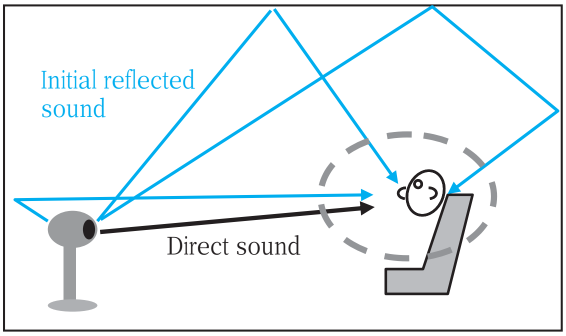


Fig.8 Incoming Direction of Reflected Sound in Listening Room

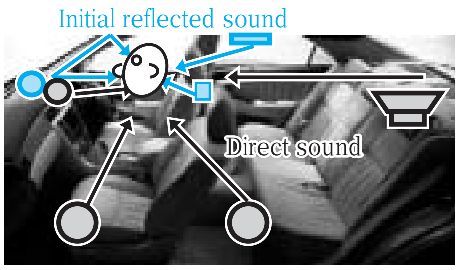


Fig.9 Incoming Direction of Reflected Sound by Toyota Premium Sound System

4 System Configuration

Here is the system configuration. To realize the spatial control technology mentioned in the above section, speakers are set as shown in **Fig. 10**.

With dividing speakers into "for direct sound" and "for correction of acoustical space", the speakers for direct sound were set at the conventional positions (Figure 10, letters in blue), and the speakers for correction of acoustical space (for spatial control: **Fig. 10**, letters in red) were added.

The speaker for correction of acoustical space takes a role to suppress the unnecessary reflected sound and add the spatial information. This layout features the speaker for suppressing the unnecessary reflected sound set on the seat shoulder part and speakers for adding the spatial information set on the instrument panel, the ceiling, and the rear tray. (The seat speaker is also used for adding the spatial information) For the speaker to be set to the ceiling, TPDS (Ten Planar Dynamic Speaker): ultra-slim high quality sound / high performance speaker was newly developed.

Through the speakers for correction of acoustical space set, it is possible to provide the spatial information with the sense as if being surrounded by sounds from the rear / front, above / below, right / left directions.

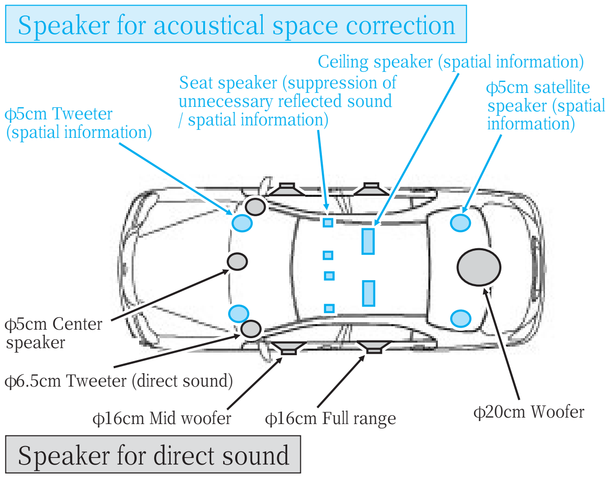


Fig.10 Speaker Layout

Here are the explanations of speaker specifications and appearances.

(1) Seat speaker (ϕ4cm BOX type)

Fig. 11 shows the appearance. The speakers, with right and left ones made in one set, are installed on the both front seats of each shoulder part, and used for suppressing the unnecessary reflected sound and adding spatial information as mentioned above. With passenger's / driver's sitting positions considered, the directional characteristics were added to the speakers, and the sound axis direction was optimized.

The speaker is installed into the seat with its body implanted so as to protect a driver / a passenger in case of crash. To ensure the band capable of replaying bass sounds in a compact size of speaker, bass reflex structure is applied.

(2) Ceiling Speaker (TPDS)

Fig. 12 shows the appearance. The speaker is installed on the ceiling slightly backward of the front seat, used for adding spatial information.

Development of the speaker capable of playing sounds with broadband, low distortion rate and high fidelity in the size of 8.5mm height and 61g weight, minimized the restriction, and made the ideal speaker layout possible.

(3) Side Speaker in Instrument Panel (ϕ5cm+ϕ6.5cm)

Fig. 13 shows the appearance. A ϕ5cm speaker for adding spatial information and a ϕ6.5cm speaker for replaying direct sound are made in a pair and set at the both sides of instrument panel. The faithful reproduction of the original sound was achieved by applying a floating structure to fix a speaker unit with clipping by bracket / bezel, and suppressing the speaker vibration transmitting to a vehicle.

In order to reproduce clearer sound, titanium as the material of the diaphragm (cap), as well as microfiber cone diaphragm, was applied.

(4) Center Speaker in Instrument Panel (ϕ5cm)

Fig. 14 shows the appearance. As with the side speaker in instrument panel, in order to reproduce clearer sound, titanium for the material of diaphragm (cap) was applied.

(5) Front Door Speaker (ϕ16cm)

Fig. 15 and **Fig. 16** show the appearances. The 550g-ground anchor newly added to the magnetic circuit part receives the counteracting force generated by amplitude of diaphragm, and makes sound-rise improved.

(6) Rear Door Speaker (ϕ16cm)

Fig. 17 and **Fig. 18** show the appearances.

In order to make the sound quality clearer by improving over features, the outside magnet structure with neodymium magnet used in the magnet circuit was applied.

(7) Satellite Speaker on Rear Tray (ϕ5cm)

Fig. 19 shows the appearance. The speaker is used for adding spatial information set on both sides of the rear tray. Titanium was applied for the material of diaphragm (cap) in order to reproduce clearer sound.

(8) Woofer in Rear Tray (ϕ20cm)

Fig. 20 shows the appearance. This woofer reproduces sharp bass sound of 70Hz or less by using pulp diaphragm, set at the position of the center of rear tray.

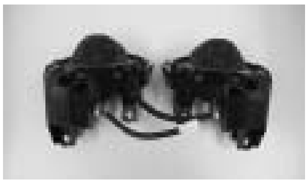


Fig.11 Seat Speaker

Fig.12 Ceiling Speaker

Fig.13 Side Speaker in Instrument Panel

Fig.14 Center Speaker in Instrument Panel

Fig.15 Front Door Speaker

Fig.16 Front Door Speaker

Fig.17 Rear Door Speaker

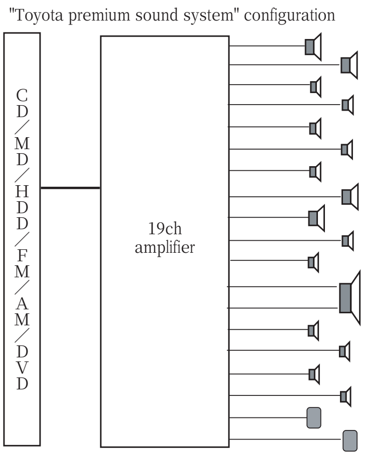
Fig.18 Rear Door Speaker

Fig.19 Satellite Speaker in Rear Tray

Fig.20 Woofer in Rear Tray

In order to make full use of these speakers' effects, a high fidelity sound power amplifier with 19 ch output was developed. The amplifier is capable of driving all the speakers with respective channels and tuning speakers to the fine conditions in accordance with their respective characteristics (**Fig. 21**).

The rear tray woofer uses two channels of amplifier, since it applies dual voice coil system aiming to realize high power.



Speaker information

Location	Aperture	IMP
Front door	φ16cm	3Ω
Front door	φ16cm	3Ω
Instr. side	φ6.5cm	6Ω
Instr. side	φ6.5cm	6Ω
Instr. center	φ5cm	6Ω
Instr. side	φ5cm	6Ω
Instr. side	φ5cm	6Ω
Rear door	φ16cm	4Ω
Rear door	φ16cm	4Ω
Rear satellite	φ5cm	6Ω
Rear satellite	φ5cm	6Ω
Rear tray woofer	φ20cm	2Ω+2Ω
Seat	φ4cm (BOX)	8Ω
Seat	φ4cm (BOX)	8Ω
Seat	φ4cm (BOX)	8Ω
Seat	φ4cm (BOX)	8Ω
Ceiling	9.3×6.4cm	4Ω
Ceiling	9.3×6.4cm	4Ω

Fig.21 System Configuration

Here is the explanation about the signal processing part controlling acoustical space and a power amplifier.

4.1 Purpose and outline

(1) The degradation in sound quality is to be minimized with eliminating the noise factor by digitalizing all the procedures from input to just before the power amplifier stage.

(2) Processing capacity for spatial control, which requires a great deal of data processing was ensured, by changing the audio specific high performance DSP from 24 bit to 32 bit.

(3) The significant output of 90W was obtained (it used to be 50W under the conventional vehicle voltage), by applying high output digital amplifier in parallel. With these actions, we developed the power amplifier with higher processing capability for acoustical space and with higher power output than ever, while suppressing the outer size bigger.

4.2 Required Specifications

The specifications of the new power amplifier are as follows.

- The number of output channel: 19ch
- Total maximum output: 880W
  Analog amplifier block: 40W×15ch
  Digital amplifier block: 50W×2ch, 90W×2ch
- Distortion ratio to output: 0.1% or less (at the time of rated output)
- Residual noise: 0.3mVrms or less
- Dimensions: 346(W)×51(H)×128(D)mm
- Mass: 2,400g

4.3 Efforts Toward Higher Fidelity Sound

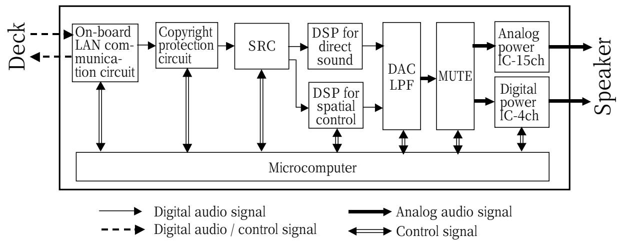


Fig.22 Block Diagram of Power Amplifier

1) Application of new DSP

With the DSP on the conventional models, the throughput was too short to control acoustical space. Therefore, the high performance DSP with high capacity of 32bit and floating-point processing function was newly applied in this system. With this application, the error calculation generated at the time of processing digital signals became less than the calculation by the fixed point DSP, and then the sound quality was improved. In consideration of the following issues, we have decided to use this IC.

(1) To minimize the mounting area of DSP on PCB

By applying BGA package with narrow pitch, the mounted area became smaller than the area for conventional DSP.

(2) To realize smaller size and minimize the degradation in sound quality caused by transmission, IC shall equip the functions of peripheral devices too.

For transmitting and receiving signals between devices before DSP stage and the DSP, sampling rate converter (hereinafter referred to as SRC) is used. Especially, this amplifier requires 12ch of SRC IC because 6ch of main audio for music source and 6ch of interruption audio such as for navigation and BEEP sound are used in its specifications. If this SRC IC is mounted on PCB separately, it will be too big to be installed into the limited area in the PCB. So, we selected the DSP with SRC function.

With the SRC function taken into DSP inside, the waveform jitter caused by noises at transmission between DSP and SRC becomes minimized, and the degradation in sound quality is less than the one generated in the case of the part with SRC function mounted externally and individually.

2) Application of digital amplifier and specific usage of PCB

Here are the explanations for our efforts toward power output circuit.

(1) Application of high-power digital amplifier

A high-power digital amplifier is applied for the bass sound for 4ch out of 19ch: door woofer (50W×2ch) and rear tray woofer (90W×2ch). The digital amplifier characteristics are as follows.

①It is possible to drive the circuit and obtain high power with the driving power increased at low load, by connecting output stages in parallel with the vehicle battery voltage (without using booster).

②The digitized output stage improves efficiency and reduces loss of power.

③Since the heat generation is decreased, while it used to be a issue under the high power with a conventional analog amplifier used, the heatsink area can be narrower. It leads to weight saving and downsizing of package.

(2) Specific usage of PCB for digital and analog amplifier

A digital amplifier may generate noises of high-frequency band due to the PWM switching system applied, and may influence the output circuit of analog amplifier through ground a power supply. Although the PCB used to be combined for analog and digital amplifier, by setting specific usage of PCB for digital amplifier and setting power circuit to each amplifier individually, the problems such as noise transmission from the power supply / ground were solved.

Besides, the specific use of power circuit enabled enhancing the power supply capacity at a drastic change of sound volume and improving sound quality.

3) Approach to high fidelity sound by parts

(1) Capacitor: Applying the decoupling capacitor of power supply for audio use with large capacity of 11,000μF. With repeating numbers of sound evaluations, sound quality has been adjusted to the specific use for this model.

(2) PCB: Changing from four-layer PCB for digital processing part to six-layer PCB. By making the GND layer for specific usage, digital noise was completely separated and blocked from audio signals.

5 Effect of Spatial Control Technology

Here is an explanation of effects of the spatial control technology in a vehicle cabin, mentioned in Section 3. **Fig. 23** shows the impulse response and incoming direction of reflected sound in a targeted living room.

Fig. 24 and **Fig. 25** show the impulse response and incoming direction of reflected sound in a vehicle cabin with the spatial control (suppression of reflected sound and addition of spatial information) ON / OFF. These figures show that both of the impulse response and incoming direction of reflected sound became extremely closer to the conditions in a living room by turning the control ON.

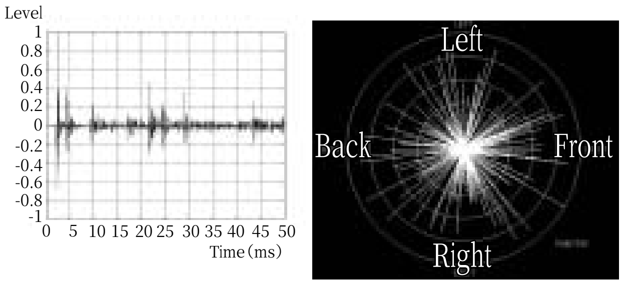


Fig.23 Impulse Response and Incoming Direction of Reflected Sound in Living Room (Target)

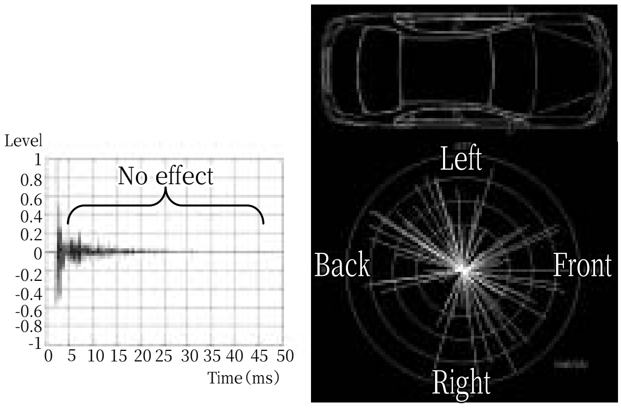


Fig.24 Impulse Response and Incoming Direction of Reflected Sound in Vehicle Cabin (Spatial Control OFF)

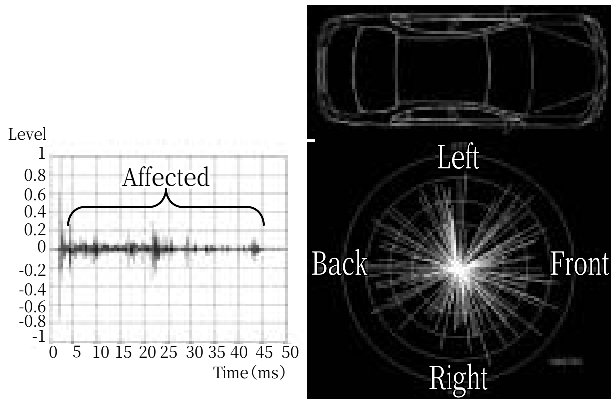


Fig.25 Impulse Response and Incoming Direction of Reflected Sound in a Vehicle Cabin (Spatial Control ON)

6 Conclusion

This report has explained the sound creation by "Toyota premium sound system" which is installed in the new CROWN in 2008, along with the development history and introduction of system contents.

Fig. 26 shows the radar chart of comparison on sound quality with the general premium sound system (10 speakers system), tested among Fujitsu Ten staff.

The spatial control technology enabled dramatically improving a sense of expanse ("forward depth sense" and "backward-surrounded sense"), and at the same time, the pure sound explained by "texture", "powerfulness" and "sense in ranges (bass / midrange / treble)" received better points than the sound through a general premium sound system. With this result, we deem that the both the pure sound and the sense of expanse were achieved at the same time.

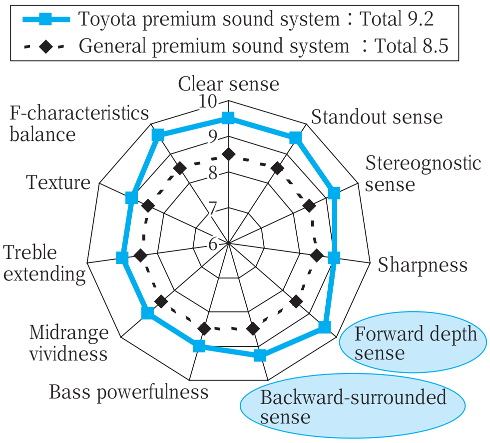


Fig.26 Radar Chart of Comparison on Sound Quality

This system received high reputation, such as "the sound provides a sense of expanse" at the evaluation meeting with panelist targeted as users before the release, and such as "it's hard to believe being in a vehicle" and "splendid!" at the workshop for dealers. Besides, the system received "Technical Development Award" of a project award from TOYOTA MOTOR CORPORATION.

We are willing to make further efforts toward prevailing "spatial control technology," as well as to make full use of the know-how developed in this "Toyota premium sound system" to carry on the sound creation for other future car models.

<Acknowledgment>

Special thanks to the staff of TOYOTA MOTOR CORPORATION, who help us to complete this development gratefully.

All brand names and product names are trademarks or registered trademarks of their respective companies.

Profiles of External Writers

Hisao TAKAHASHI

Entered TOYOTA MOTOR CORPORATION in 1986 and engaged in the W / H and switch design. Since 2000, has engaged in the multimedia design. Currently in the DESIGN DEPT. NO3 VEHICLE ELECTRONICS ENGINEERING DIV.

Profiles of Writers

Junji TABAYASHI

Entered the company in 2005. Since then, has engaged in the planning / proposing to the mass production design of car audio systems. Currently in the Acoustic Engineering Dept, Audio Business Div, CI Grp.

Shinichi NAKAISHI

Entered the company in 1989. Since then, has engaged in the development of digital audio devices by way of software development of car multimedia devices. Currently in the Acoustic R&D Dept, Audio Business Div, CI Grp.

Yuji TOMITA

Entered the company in 1993. Since then, has engaged in the development of car sound systems. Currently in the Acoustic R&D Dept, Audio Business Div, CI Grp.

Tadashi IMAMURA

Entered the company in 1992. Since then, has engaged in the development of car audio power amplifier. Currently in the Acoustic Engineering Dept, Audio Business Div, CI Grp.

Masayoshi KAGEYAMA

Entered the company in 1986. Since then, has engaged in the planning / proposing to the mass production design of car audio systems. Currently in the Acoustic Engineering Dept, Audio Business Div, CI Grp.

Shinichi YAMASAKI

Entered the company in 1988. Since then, has engaged in the planning / proposing to the mass production design of car audio systems. Currently General Department Manager of Acoustic Engineering Dept, Audio Business Div, CI Grp.