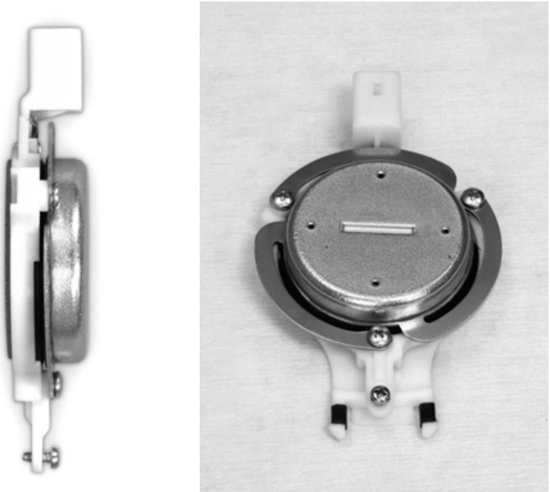
Development of "Headliner Speaker System"
-Realization of a New Sound Effect with Spacial Impression in Rear Seats-

Koichi Toyama
Yuichi Nakajima
Akira Nishikawa
Kiyoshi Ohtani



Abstract

The recent in-car audio systems for Mini Van are expected to have sound effect (spacial impression), especially, in vehicle's rear seat (second and third row). In order to improve our in-car audio systems in this respect, we have developed a "headliner speaker", which reproduces sounds from the direction of vehicle's headliners.

"The headliner speakers" radiate sounds by using headliner material as vibration board, and forming a "Distributed Mode", as a consequence that an exciter is fitted into the headliners of vehicles.

In order to adapt the speakers to the condition of vehicle interiors, such as narrowness, vibration and heat in the backside of vehicle headliners, we have also developed the following: 1) a thin exciter with new structure in terms of blade spring sound radiation, and 2) a method of fixation of the new exciters using brackets. In addition to these, this paper reports the requirements on our headliner speakers' mounting positions in a car that realizes a maximum sound effect.

All these developments as well as the listening evaluation with actual in-car audio system contributed to our achievement in creating spacial impression and sound image enhancement as sound effect.

1 Introduction

Conventionally, DSP signal processing technology has been commonly adopted in order to achieve sound effect (spacialimpression) in rear seats of Mini Van (second row and third row).

However, signal-processing technology has its limits, because there is a difference between the space information inside a vehicle and that in a listening room, especially in terms of the ambient information overhead. This made us aware of the need to install a wide directivity speaker on the car headliner and achieve reproduction of spacial information. Conventional speakers, however, have had some difficulties both in terms of installation issues and their ability to correctly express the spacial impression of sound. These issues would not have been improved without development of new type of speakers.

This led us to make efforts in developing a "headliner speaker" (interior direct drive speaker) in collaboration with Toyota Boushoku Corporation, aiming to achieve two new objectives: 1) spacial impression within the smallest possible space of the cabin and 2) enhanced sound image. The new "headliner speakers", unlike the conventional speakers, are of Distributed Mode type (distribution of vibration mode) in which electro-dynamic exciters vibrate the headliner, creating bending waves in the panel. This distributed mode technology provides us with two benefits: 1) the sound effect (spacial impression and enhanced sound image) that are not dependent on the size of vehicle interior, as a consequence of distributed multiple sound sources on the ceiling material, and 2) space-saving by working on the reduction of exciter in size and weight.

This paper will first describe the background of our "headliner speaker" development, and then explain how we developed this product in accordance with the following main points:

①Comparison of typical conventional thin-type speakers

②Structural comparison in regards to driving theory, between conventional speakers and the "headliner speaker"

③ Clarification of panel structure and installation conditions of exciter on to the panel to achieve expected sound effect.

2 Problems in Conventional In-car Audio Systems and Our Approach for Improvement

This section will report our 1) analysis of the sound effect in vehicle interior required in the market, 2) consideration of the problems of conventional speakers, and 3) clarification of our approach to solve the problems.

2.1 In-car Sound Experience Required in the Market

Firstly, we conducted a questionnaire survey on the points of individuals' disapproval or dissatisfaction with regard to the current speakers, and collected the opinions from approx.100 participants (both female and male) in their 20's to 40's.

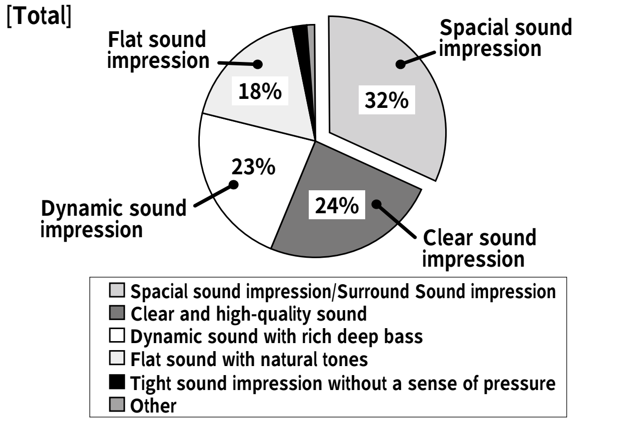


Fig.1 Questionnaire results (total)

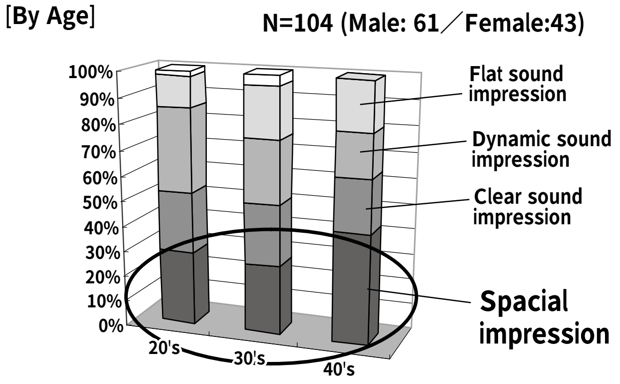


Fig.2 Questionnaire results (by age)

The result shows that users in general expect a sound experience with "spacial impression", "clear impression", and "dynamic impression". Among them, a sound effect with "spacial impression" is most expected by all generations.

2.2 Sound Image We Are Aiming at

Secondly, the sound image that we are aiming to achieve was decided by using the questionnaire survey as reference data. It is explained below in comparison with the current sound effect (spacial impression).

Current Sound Effect (Spacial Impression)

"Spacial impression is not felt"

Because:

= Speakers near the rear seat are positioned on the doors (in the lower position).

= Speakers cannot be installed in the positions effective to improve sound expansiveness.

= The degree of freedom for a speaker layout is limited.

Fig.3 Current sound effect (spacial impression)

Our Ideal Sound Effect (spacial impression)

Sound effects with spacial impression independent of speaker layout need to be realized.

Fig.4 Sound effect (spacial impression) we are aiming at

2.3 Problems in Conventional Speaker Systems

The reason why conventional in-car speakers cannot produce an acoustic space with recognizable spacial impression is, as Fig. 5 shows, due to the fact that there is a difference in space information between listening in room and in vehicle cabin. One reason for this is the interior materials (headliner/carpet/seat upholstery), work as sound-absorbing bodies in vehicle cabin. Furthermore, it is clear that the speaker layout causes much variation in projecting the space information from upper part of the car.

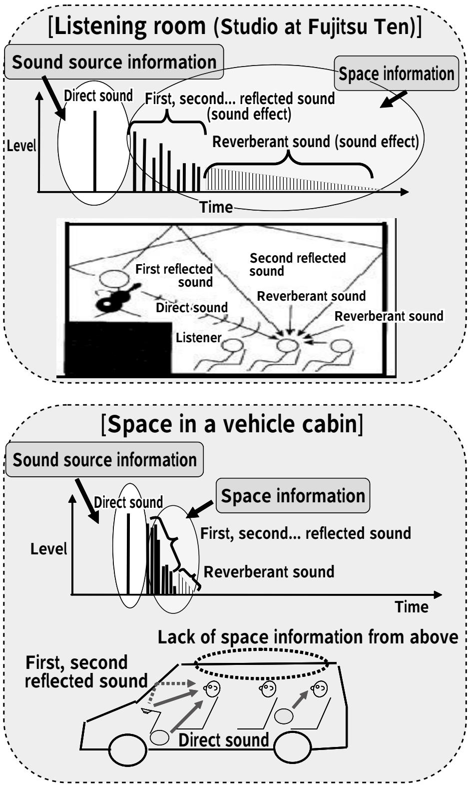


Fig.5 Comparison between listening room and vehicle interior

2.4 Our Approach for Improvement

This section deals with our Improvement measures to tackle the aforementioned problems.

In order to solve the problems of 'the different space information from overhead between listening rooms and the space in a vehicle cabin, we mounted a wide-directivity thin type speaker in a location where there was no obstacle between the speaker in the vehicle headliners and the passengers in -rear seats. This provides space acoustic information to each passenger and results in the reproduction of an effective reflected sound and reverberant sound (equivalent to 30msec) that corresponds to those of a listening room (approximately 36m^2). The best mounting location would be in the ceiling at the rear of the front seats. In order to overcome restriction of the ceiling space, thin-type speakers were adopted.

In the next section, our investigation on thin-type speakers will be reported and the potentially suitable speakers will be examined.

3 Comparison of Three Thin-type Speaker Systems

Currently, among conventional cone speakers (hereafter, conventional speakers), there are three different speaker systems that can be adopted to fit the shallow depth requirements of the headliner: ① NXT system, ② FPS system, ③ Protro system.

The features for each system are discussed below.

NXT System

Method: Unlike pistonic vibration mode (shown in Fig. 6) used for conventional speakers, this system uses resonance of bending vibration of flat panels, in a Distributed Mode fashion. (See Fig. 7.) Its rough schematic is shown in Fig. 8.

Feature: This method enables designing thin speaker profiles and can produces wide directivity with an effectively plane wave sound source through direct-drive of the panels of interior materials.

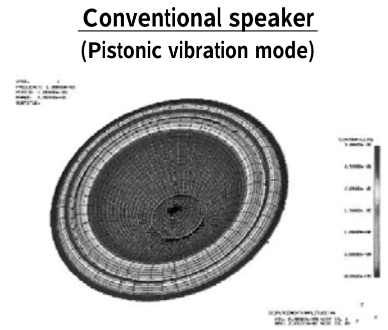


Fig.6 Piston vibration mode (conventional speakers)

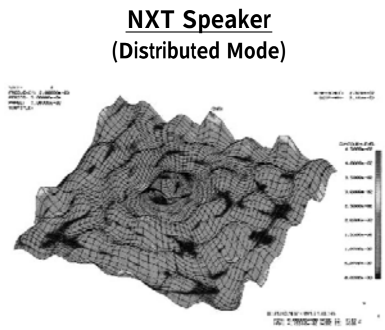


Fig.7 Distributed mode

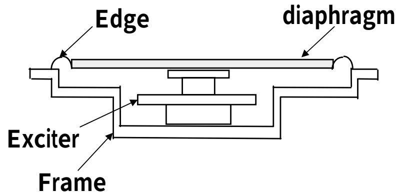


Fig.8 Rough schematic of NXT system

FPS System

Method: The system activates multiple drive points on a flat vibration board and produces a pistonic motion. Its structural outline is shown in Fig. 9.

Feature: This system enables to produce a thin-type speaker with a good transient characteristic, by using multipoint-drive, which generates pistonic motion of the whole vibration board.

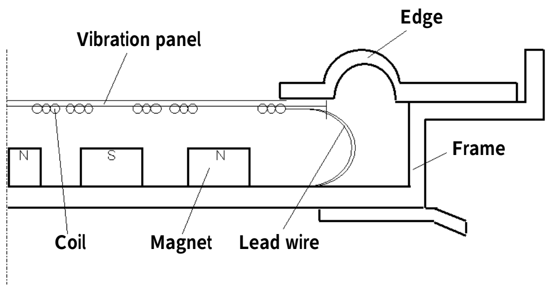


Fig.9 Rough schematic of FPS system

Protro System

Method: The system uses a special multiple polarization method on two anisotropic plastic magnets, which activate a pistonic motion by placing a thin film between 2 magnet boards. Its structural outline is shown in Fig. 10.

Feature: It enables to produce thin-type speakers. However, it is hard to reproduce a higher sound quality due to its transient characteristic where the sound quality depends on aperture ratio and depth of the magnet. Moreover, it has a narrow directivity.

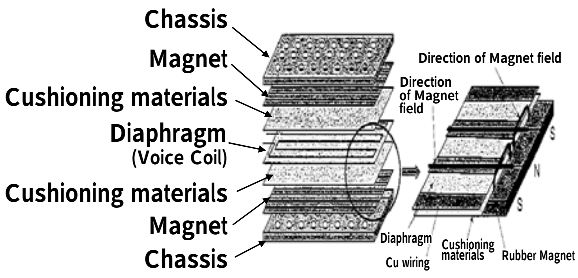


Fig.10 Rough schematic of Protro system

The table below shows the comparison of the characteristics among these three speaker systems.

Table 1 Comparison between the three speaker systems

		Target value	NXT System		FPS System		Protro System	
Mass		100g and below	100 (Exciter as single item)	○	50 (50mm×88mm)	○	2000 (298mm×210mm)	×
Thickness		20mm and below	100 (Exciter as single item)	○	50	○	40	○
Sound effect performance	Sound pressure	75dB/w.m and above	100	○	100	△	90	×
	Playback bandwidth	400～10kHz	130～20kHz		150～55kHz		25～6kHz	
	Directivity	Value for Conventional speakers and above	**Wide**		Controllable, though within the same range as that of conventional speakers		Narrow	

※As for the description of mass, thickness, and sound pressure, the figure for NXT System is a reference as 100. ○ is good, △ is fair, and × is bad.

The above comparison shows that NXT speaker system has a better performance in directivity (wider directivity). This led us to conclude that it is the most appropriate system for our purpose, that is to improve our products in terms of spacial impression.

The structure of our headliner speaker (NXT system) shall be discussed together with our results of examinations in deciding the requirements for the most appropriate mounting position to achieve maximum effect.

4 Structure of New Headliner Speaker

Our newly developed headliner speaker consists of two major parts: 1) the exciter (oscillator), which generates vibration, and 2) the headliner material as a vibration board. The structure contributes to form a Distributed Mode action (distribution of vibration mode) as shown in Fig. 7. To fit this exciter into the space between the headliner and the car roof, a thin and light exciter is required. Fig. 11 shows the image of a conventional speaker mounted on the headliner, while Fig. 12 shows the image of the structure of the headliner speaker.

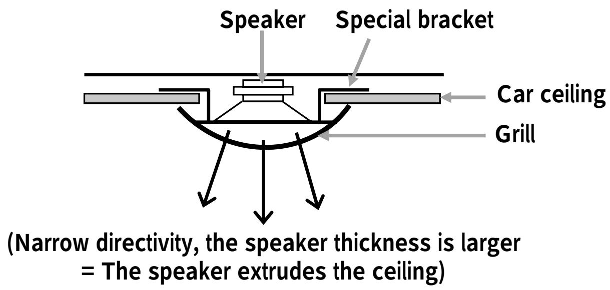


Fig.11 The diagram of a conventional speaker installed in the ceiling

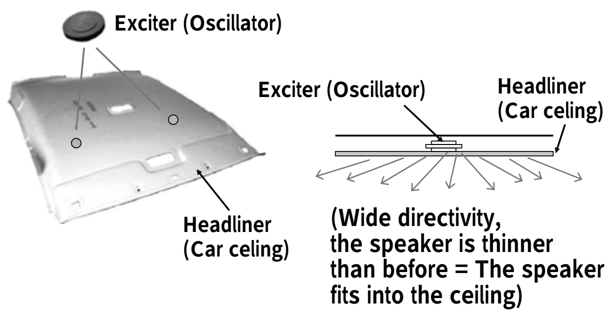


Fig.12 Structure of a headliner speaker

The table below shows the difference between conventional speakers and our headliner speakers.

Table 2 Comparison between the three speaker systems

	Item	Conventional Speakers	Headliner Speaker
Perfor-mance	Total height	34mm	14mm
	Weight	180g	100g
	Directivity	×	○
Structure	Bulge from the ceiling	Yes	No
	Number of components	3	2

5 Requirements in Mounting Headliner Speakers

It is assumed that unlike the conventional speakers, the headliner speakers are possibly affected in sound quality by the mounting conditions, because they use headliner material itself as a vibration board. Therefore, our analysis with regard to mounting headliner speakers is discussed below on the following six aspects:

- **Fitting structure of the exciter and bracket**
- **Exciter structure that can resist the temperature on the backside of a car roof.**
- **Necessary dimension for the headliner material to function as a vibration board.**
- **Optimal installation location for the exciter (antero-posterior direction in a car)**
- **Optimal installation location for the exciter (transversal direction in a car)**
- **Bending radius of the headliner material**

5.1 Analysis of Mounting Structure of Exciter and Brackets

The following four conditions are needed to be satisfied as precondition for mounting structure of the exciter and the brackets.

①Ensuring long-term stability of fastening strength between the joint part and the interior material

②Ensuring easy after-sales service (Availability of exciter desorption)

③Ensuring strength of fastening mechanism and exciter damper resistant to vehicle vibration

④Ensuring total thinness of the exciter including the joint part (Exciter must be thinner.)

As for ensuring the fastening power mentioned in ①, ① has a strong association with ②, thus, ② has to be simultaneously satisfied in order to ensure the fastening power (mentioned in ①). We have tried to realize it by adopting a particular structure for screws shown in Fig. 13.

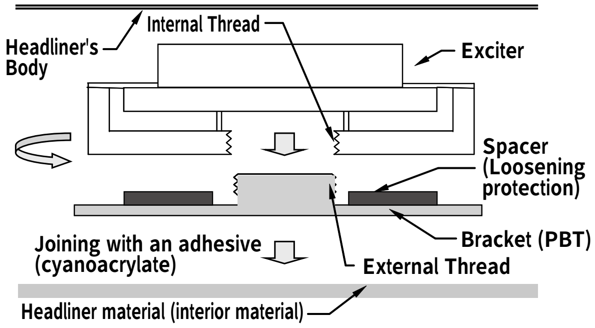


Fig.13 Structure of exciter and bracket

As for the exciter damper strength mentioned in ③, we observed an occurrence of an exciter breakdown due to vehicle vibration, which led us to realize a necessity to design a damper form durable to vehicle vibration. Fig. 14 shows our process of paying attention to stress distribution by simulation.

As for ④, it was realized by reviewing the designs many times, with implementing measurements of characteristics of the prototypes.

Fig. 15 shows the appearance of the newly developed product that satisfies all the requirements ① through ④.

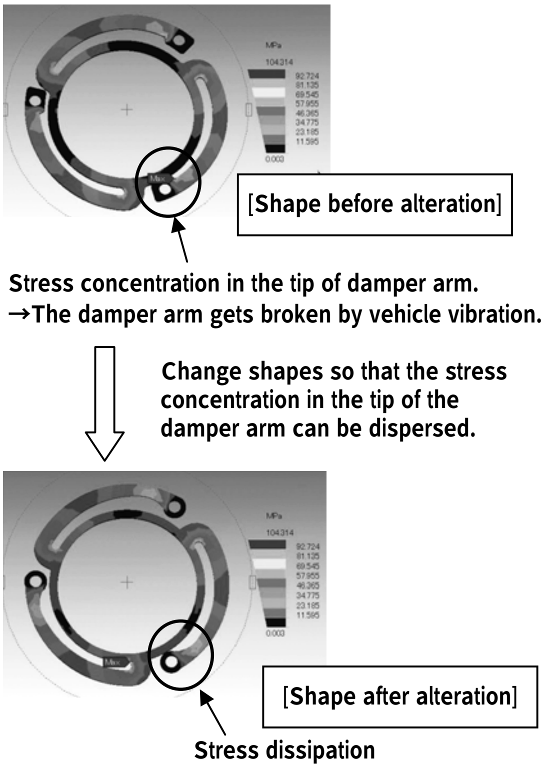


Fig.14 Form of the damper and its simulation results

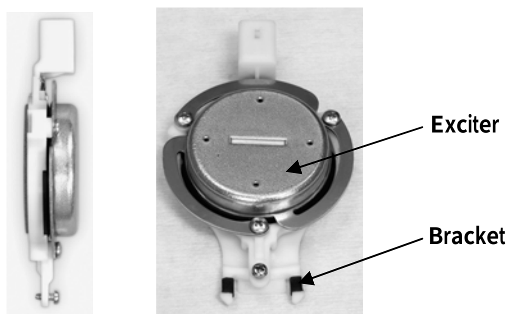


Fig.15 The newly-developed product

5.2 Development of Exciter's Structure to Resist High Temperatures on Backside of Car Ceiling

Temperature on the backside of a headliner increases tremendously depending on the ambient conditions. Thus, the structure of the exciter that can resist such high temperatures must be clarified.

As shown in Fig. 16, small heat dissipation holes were put on the yoke, in order to make the air flow faster and improve heat dissipation of the car ceiling. Fig. 17 shows the effects of the heat dissipation holes.

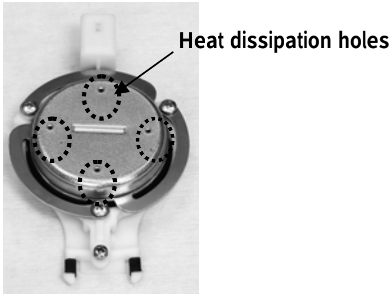


Fig.16 Application of heat dissipation holes

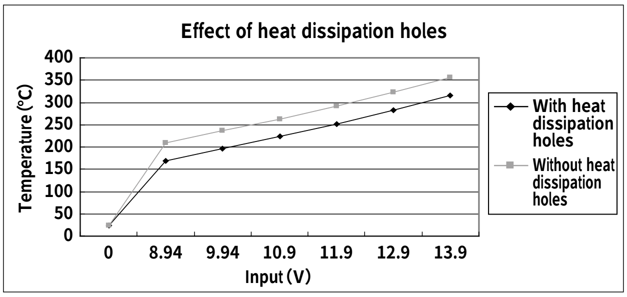


Fig.17 Effect of heat dissipation holes (Comparison of the temperature of the voice coil)

5.3 Analysis of Necessary Dimensions for Headliner Material as Vibration Board

In this section, the necessary dimension shall be clarified for the headliner materials to vibrate and gain the sound pressure frequency response as high and flat as possible in the operating bandwidth (400Hz and above) with headliner speakers.

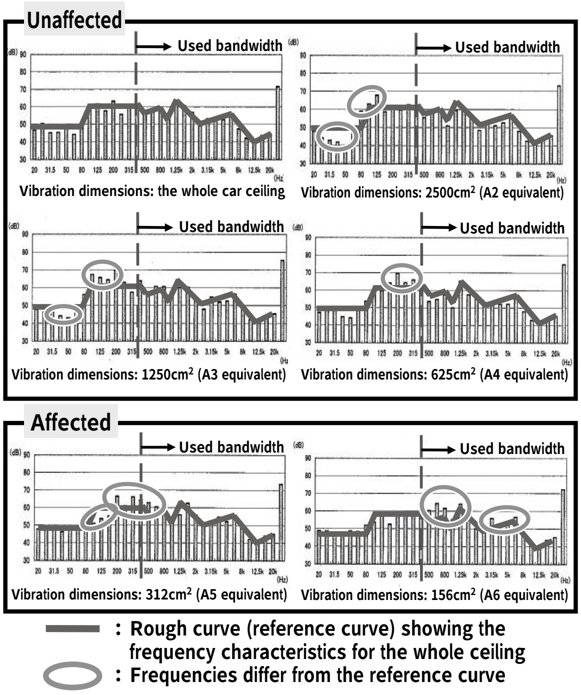


Fig.18 1/3oct sound pressure level in each dimension

Fig. 18 shows the acoustic characteristics of the headliner materials when their vibrating areas are limited.

This data shows that the sound pressure differs from its standard curve at frequencies below the operating bandwidth when a vibration area is 625 cm^2 or larger, while the sound pressure difference occurs within the operating bandwidth when a vibration area is $312cm^2$ or smaller .

The result indicates that the necessary vibration area of headliner material must be $625cm^2$ or larger, in which there is no sound pressure difference within operating bandwidth.

5.4 Optimal Location of the Exciter (Anteroposterior Direction in a Car)

In this section, the optimal location of the exciters in anteroposterior direction in a car shall be discussed.

The new headliner speakers need to realize similar sound effects (spacial impression) in both front and rear seats by providing even acoustic space information (reflected sound and reverberant sound) from the headliner to each passenger. Thus, the optimal positions for mounting speakers are the locations in which the overall sound pressure level difference between front seats and rear seats is minimum.

Fig. 19 shows the locations evaluated for installation of the exciters. Table 3 indicates the overall sound pressure level difference between the front and the rear seats of a vehicle.

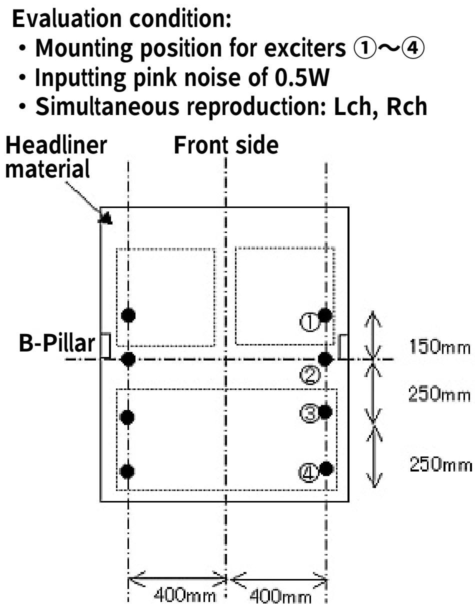


Fig.19 Various mounting positions of the exciter evaluated

Table 3 Overall sound pressure level difference by mounting positions

Mounting Position	FR Seat	RR Seat	Level difference
①	86dB	81dB	**5dB**
②	84dB	82dB	**2dB**
③	84dB	84dB	**0dB**
④	80dB	83dB	**3dB**

The level differences shown in Table 3 could lead us to conclude that the locations ② and ③ are both optimal to achieve a minimum sound pressure level difference between front and rear seats. However, the listening test we implemented at the same time proved that ③ has a problem of too high a sound image localization (Refer to below※1.), which led us to decide that ② as the optimal position.

Consequently, the optimal location of the exciter (anteroposterior direction in a car) has been decided as the position near the back-end of B pillar indicated above as ②.

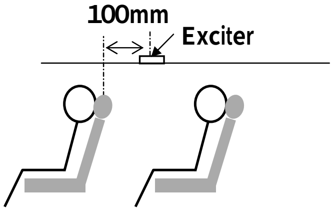


Fig.20 Most appropriate mounting position of the exciter (anteroposterior direction in a vehicle)

5. 5 Optimal Location of the Exciter (Transversal Direction in a Car)

In this section, the optimal position for mounting the exciter shall be discussed in terms of transversal direction in a car.

Table 4 shows the results of listening test when changing the distance between exciters in transversal direction in a car, while Table 5 shows the findings that the frequency response change with exciter locations. This evaluation shows that the optimal locations of the exciters (transversal direction in a car) should be furthest possible between leftward and rightward and at least 700 mm. However, the installation location needs to be on the flat part of the headliner, since the installation of speakers on the rounded part would be a deterioration factor in sound quality.

Table 4 Listening evaluation results

No.	Exciter-to-exciter distance	Sound quality (tone quality)	Special impression (Realistic concert sound)
1	700mm (Flat part of the ceiling)	◎	○
2	900mm (Flat part of the ceiling)	◎	○
3	980mm (On bending radius/Surrounding area of car ceiling)	×	○

Table 5 Comparison of frequency characteristics

No.	Exciter-to-exciter distance	Hi-Mid Lch	Hi-Mid Rch	Hi-Mid Lch+Rch	Judgments
1	700mm (Flat part of the ceiling)	-14.3dB	-13.0dB	-13.0dB	○
2	900mm (Flat part of the ceiling)	-15.2dB	-10.4dB	-12.5dB	○
3	980mm (On bending radius/Surrounding area of car ceiling)	**-17.1dB**	**-21.9dB**	**-18.9dB**	×

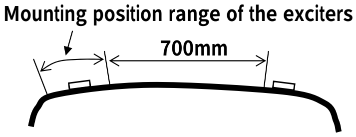


Fig.21 Mounting position range of the exciter (horizontal direction in a vehicle)

5.6 Analysis on Measurement of Bending Radius for Headliner Materials

The acoustic characteristics on each measured bending radius for the headliner material are listed below in Table 6 and Fig. 22.

Table 6 Comparison of acoustic characteristics by different bending radius of the ceiling

Bending R measurement	Output sound pressure level (300,400,500,600Hz average)	Frequency bandwidth (10dB down from output sound pressure level)
R＝5.0×10³mm or larger	75.95dB/W･m	75Hz～20KHz ※2
R＝1.0×10³mm	75.26dB/W･m	80Hz～20KHz ※2
R＝700mm	76.06dB/W･m	85Hz～20KHz ※2
R＝500mm	77.07dB/W･m	95Hz～20KHz ※2
R＝300mm	76.60dB/W･m	100Hz～20KHz ※2

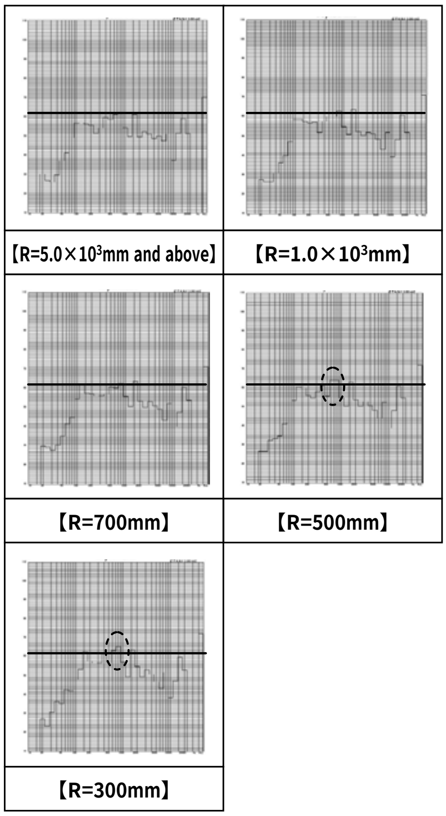


Fig.22 1/3oct sound pressure level by the ceiling materials with different bending radius

The above measurement result has proved the following points:

※1 The term, "sound image localization" is used for spacial information such as directions or distances when listening to a sound.
※2 Excludes some dips

①The smaller the bending radius is (steeper bending), the higher the lowest limit of reproduction frequency becomes.

②If the bending radius is below 500mm, the peak in the vicinity of 700 or 800Hz rises. (The peak in the middle range gets higher.)

The result has proved that 700mm or more is desirable for a bending radius to achieve a required performance.

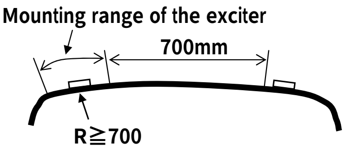


Fig.23 Mounting position range of the exciter

6 Conclusion

The experiment above led us to conclude that the improved sound effects are available with the newly developed headliner speakers. The experiment was performed where the headliner speakers were installed in an audio system usually used in a Mini Van with all the necessary conditions. The results have proved that we succeeded in reproducing a pervasive sound that any other conventional in-car audio systems could have never achieved.

6.1 Achievements

Fig. 24 shows our analysis of the speaker layout, while Fig. 25 shows the system block diagram of the amplifier. Fig. 26 through 30 show the amplifier's frequency response of respective speakers, while Fig. 31 shows the data (1/3 octave sound pressure) measured with and without headliner speaker.

The listening test results are shown in Table 7.

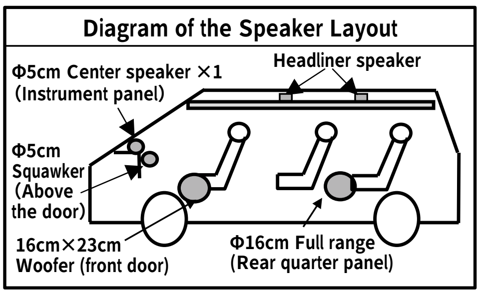


Fig.24 Diagram of the speaker layout

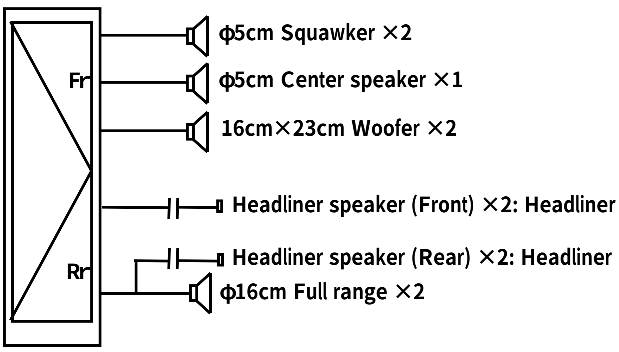


Fig.25 System block diagram of the amplifier

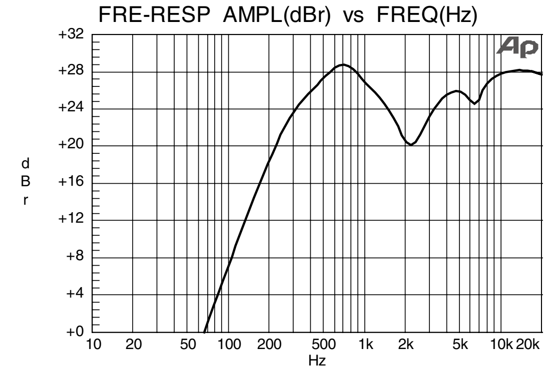


Fig.26 Frequency characteristics of the amplifier (Φ5cm squawker)

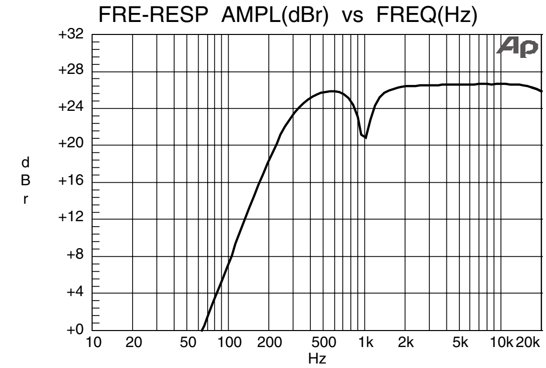


Fig.27 Frequency characteristics of the amplifier (Φ5cm center speaker)

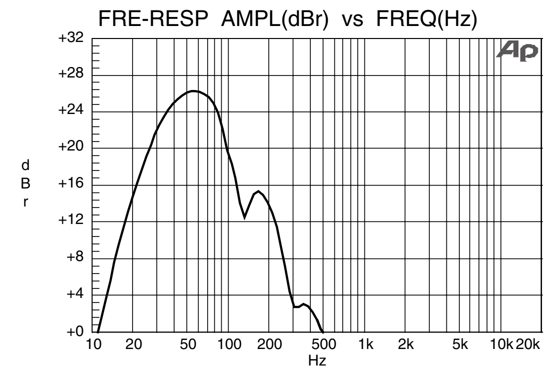


Fig.28 Frequency characteristics of the amplifier (woofer)

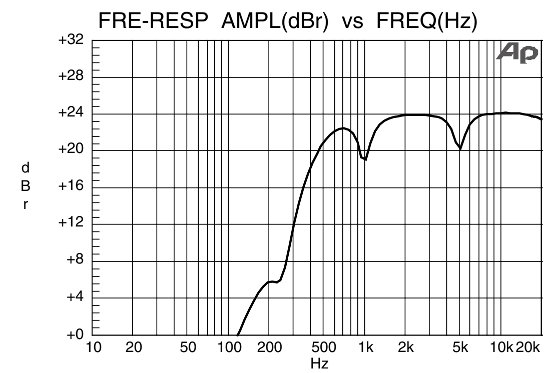


Fig.29 Frequency characteristics of the amplifier (headliner speaker)

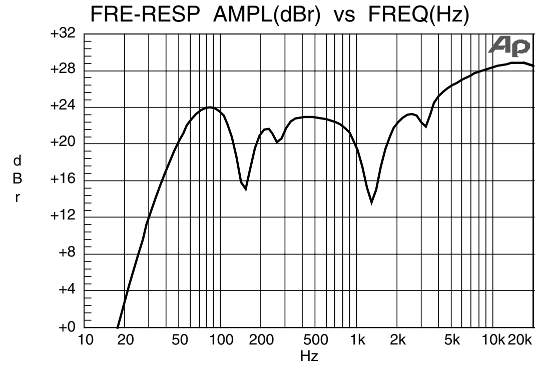


Fig.30 Frequency characteristics of the amplifier (rear speaker)

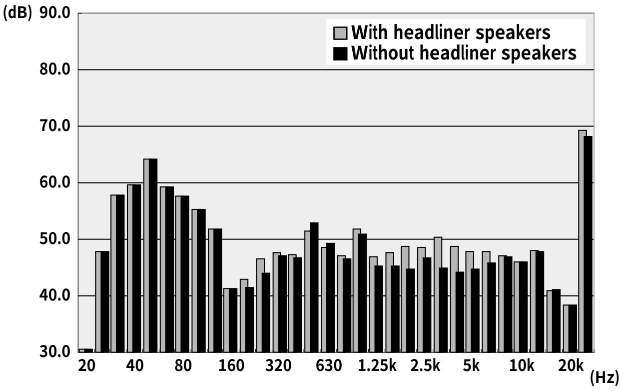
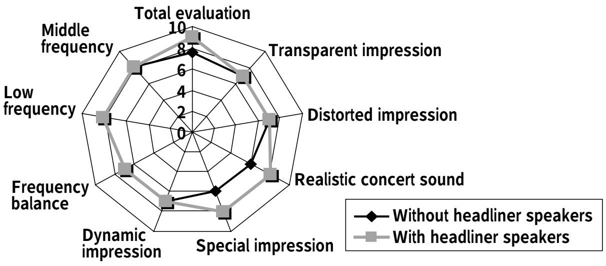


Fig.31 1/3oct sound pressure level with/without headliner speaker

Table 7 Listening evaluation results



The adoption of the headliner speaker system contributed to the improvement of sound characteristics in our speaker systems, improving the sound pressure level by 2 to 5dB at 1.25k to 7.5kHz, as well as in leveling the sound pressure frequency responses at the middle and high frequencies. Furthermore, listening test using an actual vehicle in terms of "spacial impression" has been confirmed in the rear seats.

Currently, 14 patent applications (99 claims) relating to the headliner speaker system have been filed, including joint application with Toyota Boshoku Corporation.

6.2 Future Prospects

We now intend to move ahead in applying this innovative technology to application development, and make an effort to improve acoustic space exceeding current expectations.

Finally, we would like to express our sincere thanks to Toyota Boshoku Corporation for their great support in our development of new headliner speaker system.

※This new speaker uses NXT flat panel speaker technology developed by New Transducers Limited. NXT® is a registered trademark of New Transducers Limited.

Profiles of External Writers

Koichi Toyama

Entered TOYOTA BOSHOKU CORPORATION in 2001. Since then, has engaged in advanced development of interior trim. Currently the Interior Trim Group Assistant General Manager of the Advanced Development Division.

Profiles of Writers

Yuichi Nakajima

Entered the company in 1998. Since then, has engaged in speaker development by way of production technology development. Currently in the Acoustic Engineering Department of Audio Business Division, CI Group.

Akira Nishikawa

Entered the company in 1990. Since then, has engaged in development of in-car sound systems. Currently in the Acoustic Engineering Department of Audio Business Division, CI Group.

Kiyoshi Ohtani

Entered the company in 1990. Since then, has engaged in development of in-car sound systems. Currently the Manager of the Acoustic Engineering Department of Audio Business Division, CI Group.