Development of Time Domain System for In-Vehicle Use

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Abstract

We have developed a completely new in-vehicle speaker system based on "time domain theory" that can play sound giving localization and "being there" sensations so realistic it's as if the performer is before one's eyes inside the car. This system is a further development of the home time domain system launched last year; to make it conform to in-vehicle requirements we made innovations in the functions and installation techniques and additionally implemented DSP correction, making it a total system providing the very best effects.

In this paper we first describe the concepts for the in-vehicle system, the structures of its speakers, and their installation structures. Then we present an overview of the speaker system brought on the market in November of this year, which is based on the content of the present development.

1 Introduction

In April last year, Fujitsu-TEN released a home time domain system, in order to raise the appeal of our technological levels, and to strengthen our brand image. Subsequently we have pursued further technical development to achieve an in-vehicle version of this system, believing that the application of time domain concepts to car audio would effect a breakthrough in its sound quality compared with conventional systems.

"Time domain systems" are products based on the "Time Domain Theory" advocated by President Hiroyuki Yoshii of Time Domain Corporation, a Nara-based venture firm. Whereas most conventional audio systems have been developed with the emphasis on frequency characteristics, so that the whole range of sounds from low to high will be reproduced as flat as possible, and with much effort devoted to reducing distortion, the Time Domain Theory has the principal feature of stressing the time axis characteristics. Specifically, the time domain approach is to reproduce the sound input waves as faithfully as possible, thereby delivering playback so lifelike that the performing artist seems to be actually present, reproducing the most delicate shades of expression in the sound.

This paper gives an account of the development of an in-vehicle time domain system based on the theory described above, focusing on how the difficulties in the way of applying such a system to an in-vehicle environment were resolved.

2 Problems with conventional car speaker systems, and ideas for improvement

In this section, we will begin by making clear the problems that exist in the vehicle-interior acoustic field with conventional car speaker systems, then go on to describe our ideas for using a time domain system to effect improvements with regard to such problems.

2.1 Problems with conventional car speaker systems

Broadly speaking the problems associated with conventional car speaker systems (having 2 speakers deployed at the front doors and 2 on the rear tray) may be enumerated as the following 4:

- The sound image is vague (its localization is not clear)
- Mid-range sounds are unclear
- Some sounds seem to have an "out-of-phase feeling"
- The sound image is at a low level

Looking at the first of these, the cause of the "vague image" is presumably the fact that the speakers are located at various non-uniform distances from the listening position, so that the sounds from the different speakers take non-uniform times to arrive.

Turning to the "unclear mid-range sounds", the main cause of these is presumably the vibration generated by the door speakers when they emit sound. This vibration propagates through the doors, making the doors themselves and their windows vibrate and generate unwanted sounds that result in an unclear playback sound. These unwanted sounds probably also have the effect of exacerbating the "vague sound image" problem.

As for the "sounds of out-phase feeling", the cause here can be presumed to be disturbances in the frequency characteristics and phase characteristics due to the effects of reflection, etc., from the windows (i.e. adverse effects of reflected sound).

Lastly the reason for the "low sound image" is presumably that the speakers are deployed at a considerably low level relative to the listening position.

2.2 Ideas for improvements for the problems

Our ideas for using a time domain system to effect improvements for the problems treated in the preceding item can be broadly divided into 2. We also had practical measures for improvement corresponding to these 2 ideas, but first let us state the ideas:

- Optimum layout and installation of the speakers plus improvements via the system, so as to reduce the effects of reflection by and unwanted vibration of the windows
- Improvements to prevent generation of unwanted vibration by the speakers

The improvement measures for putting these ideas into action were as follows.

Speaker layout and installation; system improvement

Layout: Place the speakers ahead of the listener, in positions selected to result in the smallest possible influence from reflected sound.

Installation: Use installation methods that will suppress as much as possible the transmission to the vehicle of vibration generated by the speakers.

System: Correct for the time differences among the speakers, using delay processing.

Speaker unit

Use structures for the speakers that will not result in transmission of the vibration generated by the speaker units to the speaker boxes.

3 In-vehicle system

Below we describe an in-vehicle system developed on the basis of the improvement ideas discussed in Section 2. Note however that this description focuses primarily on the front-seat position of the system.

①The speakers reproducing the bandwidths exerting the greatest effects on the sound image localization (i.e. the vocal bandwidth and above) are installed ahead of the listener, serving as the main speakers. These are newly-developed compact and high-performance (wide-range, high-power) box type speakers incorporating anti vibration measures.

②The bandwidths not covered by the above speakers (the mid-low range) are reproduced by a mid-low speaker and a woofer speaker, which likewise incorporate anti vibration measures.

③The time differences among the various speakers in this 3-way configuration are corrected using digital signal processing (time alignment) so that the sounds from each speaker reach the listener's ear simultaneously.

Fig. 1 is a block diagram of a concrete system embodying the above concepts, while Fig. 2 is a schematic of such system when installed in a vehicle.

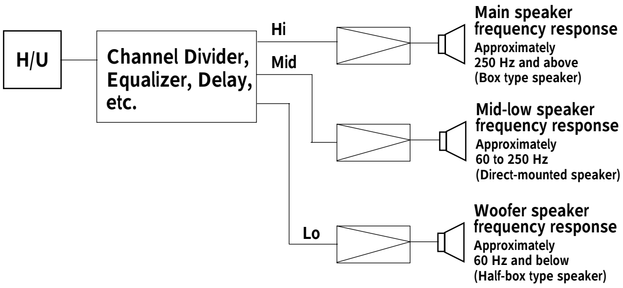


Fig.1 Block diagram of system

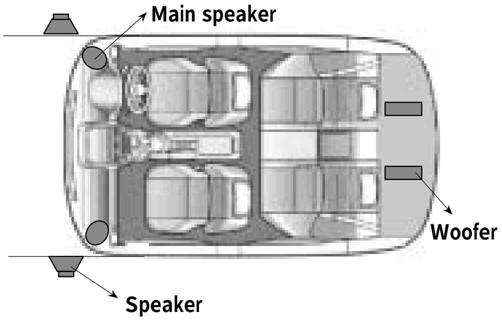


Fig.2 Schematic of system installed in vehicle

4 Features of each component

In this section, we discuss the specific structures of the various speakers for the in-vehicle system, time correction for installation in a car interior, etc., described in Section 3. The solutions for the difficulties in the way of applying the system to vehicles will be explained.

4.1 Main box speakers

Of the speakers in the 3-way speaker system, these are the ones with the greatest influence on sound quality, since they cover the entire bandwidth of frequencies determining the orientation and localization of the sound image.

4.1.1 Deliberation of structure

Fig. 3 shows the internal structure of an Eclipse TD512 home time domain speaker.

The basic structural concept here is that the speaker unit is installed so as to "float" without directly contacting the speaker box; the speaker unit is grounded to the floor surface via diffusion stays (see Note 1).

When we embarked on developing the in-vehicle main box speaker, we deliberated whether it would be possible to ground it to the car body in a similar manner to the grounding of the home use item. The prototype box fabricated for use in such deliberation is shown in Fig. 4. Its basic structure employed the same concepts as the Eclipse TD512 and it was experimentally mounted to the car body by means of stays extending from an anchor (see Note 2).

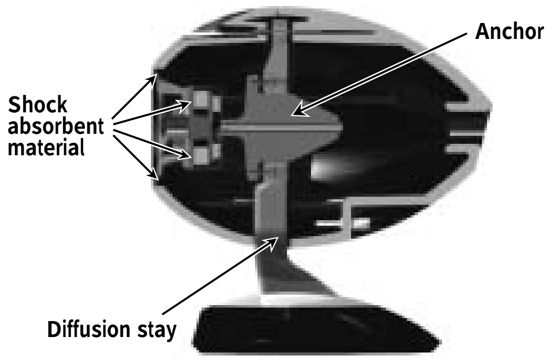


Fig.3 Internal structure of Eclipse TD512

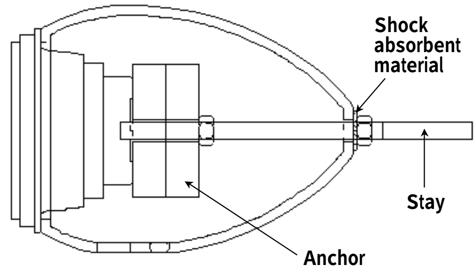


Fig.4 Structure of prototype box used for deliberations

In an in-vehicle application, the hard point which is the prime candidate for the ground is the car body frame. Accordingly we tried out installing the stays to the A-pillar (metal part) as a representative component of the frame in the instrument panel's vicinity.

When we listened to the music produced by this setup, sound appeared to be coming from many different parts of the vehicle and the localization of the sound image felt vague. The cause was that the speaker unit's vibration was propagating through the metal frame, and since its metal parts were connected to the entire car body, secondary reflection was occurring at various locations. A similar result was produced when the speaker was mounted to the door mirror base (metal component) due to secondary reflection from the door window. Accordingly we tried mounting the speaker not to a metal component but to a plastic component, namely the instrument panel. The resulting was free of superfluous sound and had clear tones. Mounting the speaker to a plastic component would seem to have reduced secondary reflection of the sound, thus

Note 1: Supporting struts that are directly joined to the base and extend outwards, having a unique structure designed for supporting the speaker unit.

Note 2: Solidly absorbs the reaction of the diaphragm by virtue of its mass, giving a structure providing ideal piston motion.

rendering it clear. Fig. 5 gives the impulse responses (measured at the driver's seat) when the speaker was installed to the right A-pillar (metal component) and to the right side-face of the instrument panel (plastic component).

Fig. 6 shows the cumulative spectra (see Note 3) for the different mounting locations. From the impulse responses it can be observed that with the A-pillar (metal component) there are larger amounts of energy in the initial stages. Similarly the cumulative spectra show that with the A-pillar there are far more lingering frequencies, so that the unwanted vibration persists for longer. From these results it was determined that using the car body as the ground for the speakers would be problematic with the in-vehicle system. Accordingly we decided to adopt a structure whereby the speaker unit "floats" completely clear of the speaker box that houses it. Fig. 7 shows this internal structure, in which the speaker unit and the anchor are held between the front and rear cases. The diameter of the speaker unit was set at 5 cm in consideration for their power input tolerance, and because the reproduction bandwidth for the box speakers, which are regarded as the main speakers, require a higher frequency of around 250 Hz.

Having the speaker unit "float" inside the box, completely free of contact with it, greatly inhibits propagation of the speaker unit's vibration to the exterior. This means that even if the speaker is secured inside the vehicle interior by means of the brackets commonly used for the purpose, there will be little propagation of its vibration to the vehicle.

Fig. 8 shows an installation method that was examined as a means of further heightening the damping effects, namely by sandwiching the speaker box with noise suppressant material, when mounting to the vehicle. This greatly reduces the amount of unwanted secondary reflection from the vehicle.

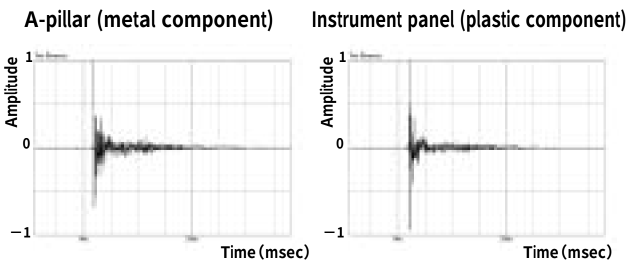


Fig.5 Comparison of impulse responses of A pillar metal portion and instrument panel resin portion

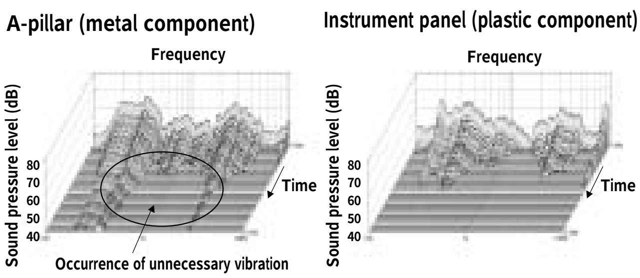


Fig.6 Comparison of cumulative spectra

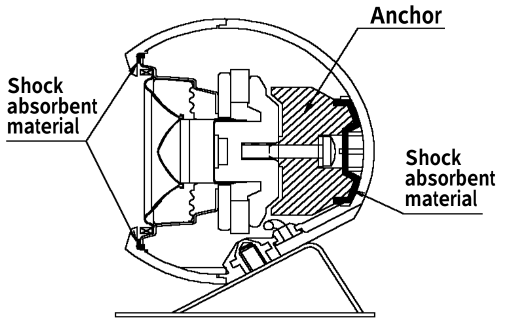


Fig.7 Internal structure of main box speaker

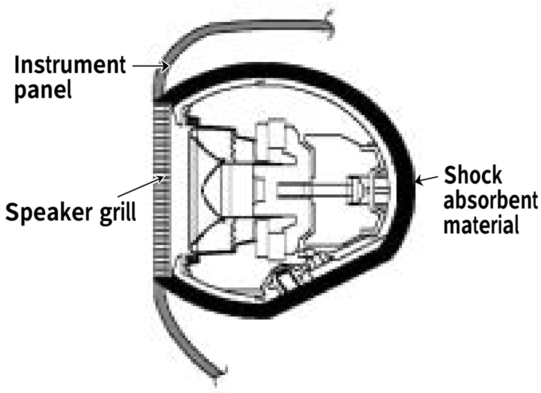


Fig.8 Structure of installation of main box speaker to vehicle

4.1.2 Deliberation of installation position

We had in mind the upper area of the sides of the instrument panel, or the vicinity of such, as the installation position for the main speakers. To determine the optimum position here we installed the prototype speakers in several likely locations and examined the resulting sound.

The representative installation positions examined are listed below. In order to obtain a clear central localization of the sound image, the speakers were orientated toward the central portion of the front seats in each case.

①Far end (windshield sides) of the instrument panel sides
②Forward end (car interior sides) of the instrument panel sides
③Upper forward position of front doors

Figs. 9 through 11 give the results of measurement of energy response, which can be used to infer the sound reflection situation (see Note 4), with each of these installation positions. The position of the microphone for these measurements was on the driver's seat. The numeric value appearing at the top of each figure represents the total energy summed over the range 0 to 20 msec and normalized using the peak value. The lower this numeric value, the less the reflected sound. From these results it can be

Note 3: Graphs plotting a 3-dimensional representation of the change over time in the various frequency components derived from the frequency responses.

Note 4: By means of graphs that represent the impulse responses as energy displays, permitting observation of the change over time in the energy components.

seen that the positions at the far end of the instrument panel sides produce larger amounts of sound reflection. This is due to the major reflective effects of the windshield and causes a reduction in the perceived clarity of the central localization of the image, resulting in fluctuation in the tones.

Such reflected sound produced by reflection from the windshield, windows and so forth within the car interior is in close proximity to the direct sound and therefore impairs the tones and the sound image localization. In view of this we considered that the ideal installation position for the main box speakers would be the one that produced the smallest possible amount of sound reflection.

On the other hand, there was no great difference between the energy response values for the instrument panel side forward end and for the front door upper area; both of these positions produced lower levels of sound reflection than the instrument panel side far end and gave a perceptually clearer sound image.

Besides ① through ③, various other installation positions in the area around the instrument panel were examined in the same way. It was found however that the most appropriate installation positions for these speakers in a time domain system, producing the lowest level of sound reflection, were the forward area of the instrument panel sides, centering around the door mirror bases.

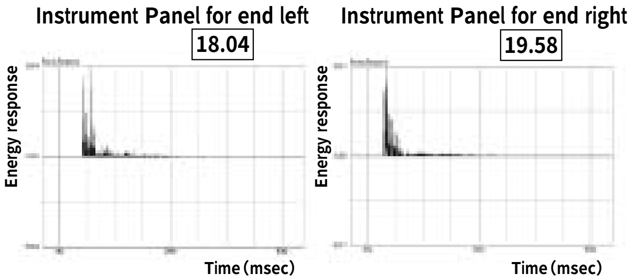


Fig.9 Energy response at the far end of instrument panel sides

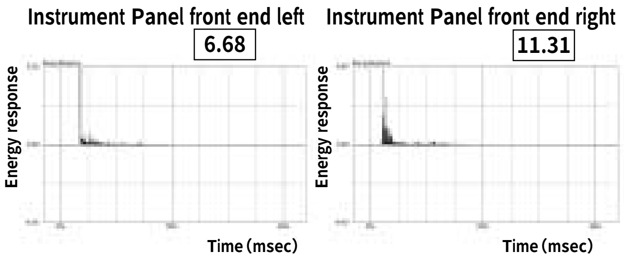


Fig.10 Energy response at the forward end of instrument panel sides

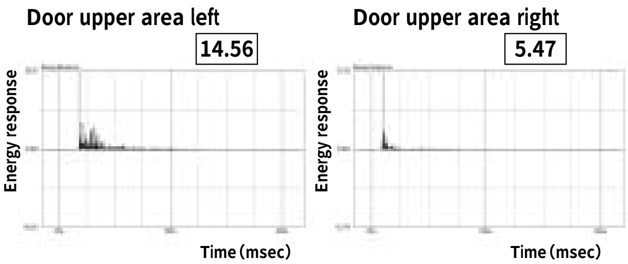


Fig.11 Energy response of upper forward portion of front door

4.2 Mid-low speaker

This speaker reproduces the bass range not covered by the main box speakers, dealing with sounds under approximately 250 Hz as its reproduction bandwidth. Since its crossover frequency with the main box speaker falls within the lower end of the vocal bandwidth, it should preferably be installed forward of the car occupants in order to obtain a stable perceptual localization of the sound image. The possible locations forward of the occupants to be considered for installation of this speaker were the lower area of the front doors, or else the cowl sides (refer to Fig. 12).

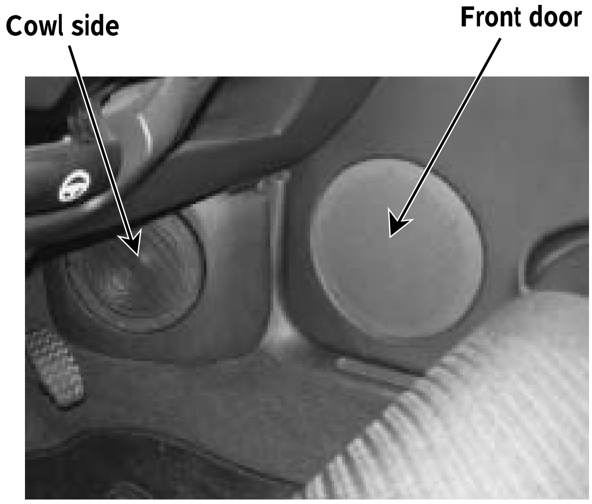


Fig.12 Installation position of mid-low speaker

Though the ideal form for the mid-low box would be a fully-closed box structure, which would prevent it from propagating vibration, such a box would have to be large-sized in order to reproduce the bass range. Accordingly we adopted a grill-type mid-low speaker for use in the deliberations.

4.2.1 Deliberation of installation structure I: anchor

We examined the effectiveness of using a ground anchor for the grill-type speaker as a means to improve the transient characteristics.

Fig. 13 shows a comparison of impulse responses with and without a 500g weight attached at the rear of the magnet of the 13 cm speaker when installed to a door, while Fig. 14 shows a comparison of the cumulative spectra for those same conditions.

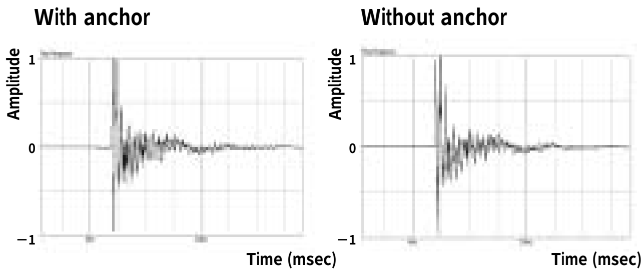


Fig.13 Comparison of impulse responses with and without anchor

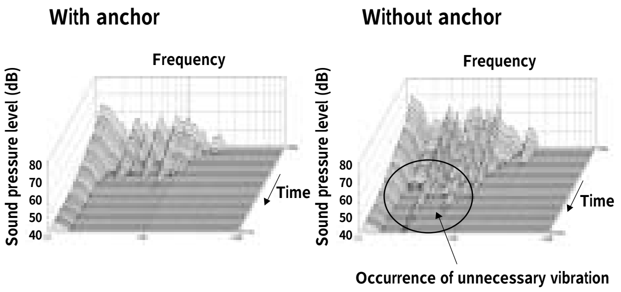


Fig.14 Comparison of cumulative spectra with and without anchor

It can be seen from the impulse response comparison that rear vibration is slightly less with the weight attached, and the cumulative spectra show even more clearly that there is less unwanted vibration with the weight in place. One could also tell by ear that the low frequency response was tighter with this arrangement. And data for anchors show that the heavier the weight of the ground anchor the clearer the effect produced. Thus it is desirable to attach as heavy a weight as practicable.

4.2.2 Deliberation of installation structure : "floating" structure

For this grill type speaker too, we adopted an installation method that sandwiches the speaker with shock absorbent material when mounting to the vehicle shown in Fig. 15, so as to prevent as far as possible transmission of the speaker's vibration to the car body. Additionally the mounting screw holes were lined with shock absorbent material so that the speaker's metal parts would not contact with any of the car's metal parts. Fig. 16 provides a comparison of the speaker's cumulative spectra with and without this shock absorbent material. It will be seen from this figure that unwanted vibration was less with the shock absorbent material interposed. We experimented with various materials for the shock absorbent and adopted the one that gave the best damping effect, namely felt.

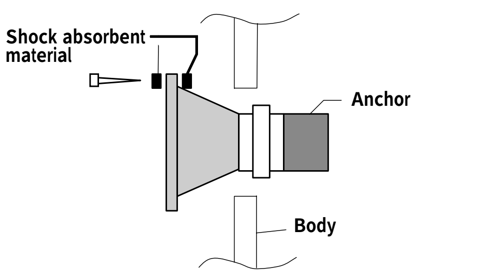


Fig.15 Structure of installation of mid-low speaker

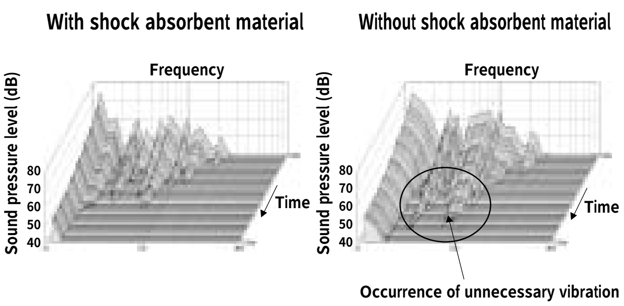


Fig.16 Comparison of cumulative spectra with and without shock absorbent material

4.2.3 Deliberation of installation position

A comparison was made of the performance of an 13 cm diameter speaker when installed to the lower area of a front door and to a cowl side. Fig. 17 gives a comparison of the cumulative spectra produced by the two positions. It can be seen that the front door lower area resulted in a clearly larger amount of unwanted vibration. This is because the front door is low in strength and moreover the vibration propagates to its window, while the cowl side is high in strength because it has few plane surfaces. Though installation of the speaker on the cowl side is to be recommended in this respect, it may on the other hand be problematic due to the presence of fuse boxes and the proximity to the wheelhouse, etc. Accordingly we adopted the installation position on the door when we proceeded to deliberation of the improvement measures.

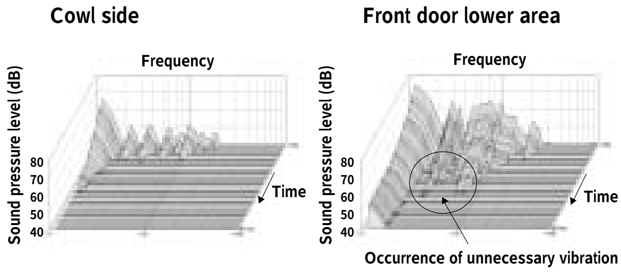


Fig.17 Comparison of cumulative spectra of cowl side and door

4.3 Woofer speaker

When we examined the use of an anchor for installation of the mid-low speaker, we found that the anchor needed to be of considerable weight in order to yield its full effects in the low frequency range. Accordingly for the woofer we came up with other ideas and developed a new compact speaker with excellent transient characteristics. The structure of this new woofer is shown in Fig. 18.

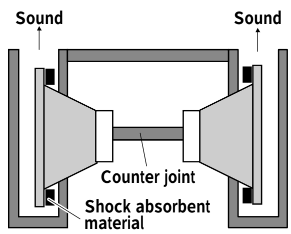


Fig.18 Structure of woofer speaker

The yoke parts of the 2 speaker units are connected by counter joints (non-magnetic metal connecting rods); thus the structure employed is a rear surface connecting one whereby the vibrations of the speaker units cancel each other out. It is intended to achieve an effect similar to what one might imagine that an infinitely large anchor would produce. Further, the speaker units are provided with a front surface load (see Note 5), and with slits through which the sound is radiated into the vehicle interior - a structure

Note 5: Such load is mounted directly in front of the speaker's diaphragm and has the effect of raising the efficiency of the speaker's sound radiation.

that achieves improved characteristics in the low frequency range. The trunk room is used as the speaker units' back cavity.

4.3.1 Effects of rear surface connection

Fig. 19 shows the differences in the sound pressure/frequency characteristics with and without rear surface connection. Connecting the speakers by their rear surfaces produces a drop in their Qo (from 0.6 to 0.45), yielding the same effects as when magnetic force is increased. Fig. 20 shows the differences in the cumulative spectra with and without rear surface connection. As can be seen, the rear surface connection results in a reduction in unwanted vibration around the 250 Hz level.

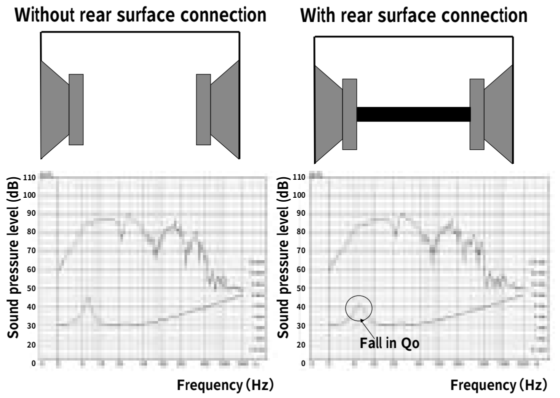


Fig.19 Comparison of sound pressure / frequency characteristics with and without rear surface join

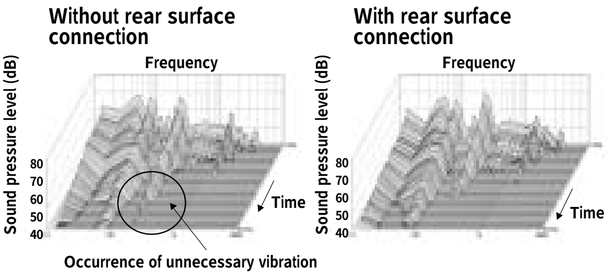


Fig.20 Comparison of cumulative spectra with and without rear surface join

4.3.2 Effects of front surface load

Fig. 21 shows the differences in the sound pressure/frequency characteristics with and without front surface load.

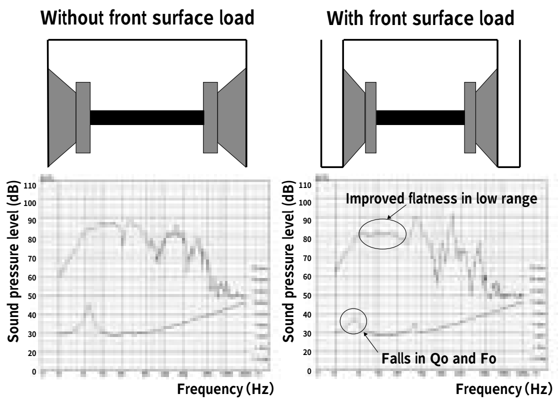


Fig.21 Comparison of sound pressure / frequency characteristics with and without front surface load

Providing a load on the front surfaces yields a further drop in Qo (from 0.45 to 0.41), as well as a drop in Fo (from 60 to 40 Hz). As can be seen, this results in an expansion of the flat area in the low frequency range. In fact, providing front surface load permitted an expansion in the flat range from 80 Hz and above to 40 Hz and above.

4.4 Time alignment

Even with the adoption of vibration-damping structure and installation methods for the speaker boxes, the times taken for the sounds from the various speakers to reach the occupants will all be non-uniform since their distances from the occupants are different. Fig. 22 shows an example where sound is emitted from a front left-channel speaker and from a woofer on the rear tray; the sound from the left channel speaker arrives first because it is close to the driver's seat, while the sound from the woofer arrives after a lag. Even with improved time domain response of the speakers, their high capability will not be properly exploited if their sounds arrive at non-uniform times. This makes it necessary to implement correction for the distance differences. By using digital processing to delay the sound from the left channel speaker by an amount equal to the woofer sound's time lag T1, the arrival times of the sounds from the 2 speakers can be made the same. Accordingly we applied this method to the whole system, implementing delay processing (time alignment processing) proportional to closeness to the occupants for each of the speakers except the furthest, whose arrival time served as the standard for determining the delays. In this way we were able to equalize the arrival times of the sounds from all of the speakers at the point of perception.

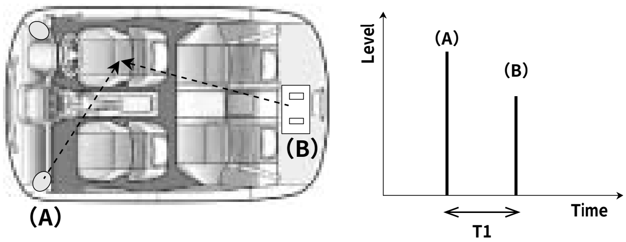


Fig.22 Conceptual diagram of time alignment

5 Overview of product developed for market

In this section we relate the major issues we faced in commercializing the system for sale on the market, and the specifications of the products (5 cm box speakers and 12 cm speakers) in the commercialized system.

5.1 Main issues in the commercialization

To achieve the best sound which the system as a whole including its speaker installation methods makes possible, we opted to commercialize it via Fujitsu-TEN's top-brand Eclipse Sound Monitor product range. We also expanded installation know-how so that installation of the system by specialist dealers would yield its optimum sound. As regards the woofer speaker however, further deliberation is required and we do not plan to commercialize it until its merchantability has been improved.

In the course of the commercialization development we conducted interview surveys of representative specialist dealers and studies of actual installation in sedans, SUVs and various other vehicle types, as a result of which we adopted for the main 5 cm box speakers a design that would allow both embedded installation and installation direct to the instrument panel or other component.

5.2 Main box speaker

The frequency characteristics of this speaker are shown in Fig. 23, its impulse response in Fig. 24 and its multi impulse response in Fig. 25. Its structure was shown in Fig. 7 above.

The specifications of this speaker are listed below.

- Diameter: 5 cm
- Impedance: 6Ω
- Allowable input: rated 20 W, instantaneous 80 W Max.
- Sound pressure level: 83 dB/W•m
- Reproduction frequency range: 200 Hz to 30 kHz
- Recommended crossover point: 250 Hz
- Outer dimensions: width 74 × height 90 × depth 71 mm
- Mass: 500 g approx.

We close this brief account of this speaker with the technical features employed for it:

- "Floating" structure box
  → refer to previous section
- Anchor
  → refer to previous section
- Composite speaker unit (shown in Fig. 26)
  → achieves broader bandwidth using small diameter
- PEN (Polyethylene Naphthalate) base-material woven fabric microfiber diaphragm (shown in Fig. 27)
  → achieves high rigidity while assuring internal loss
- Edge-wise voice coil
  → permits effective utilization of magnetic energy
- Out-flux neodymium magnet
  → enables powerful magnetic energy to be secured
- Bombshell shaped center cap (shown in Fig. 28)
  → achieves reduction in unwanted vibration in high frequency range

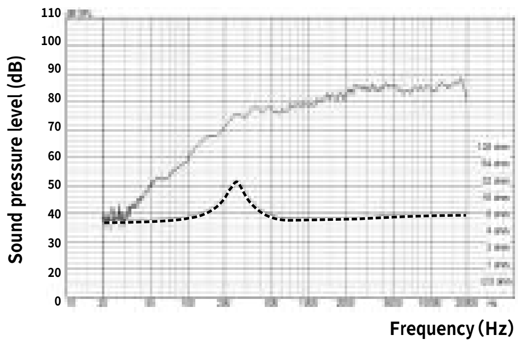


Fig.23 Sound pressure / frequency characteristic of main box speaker

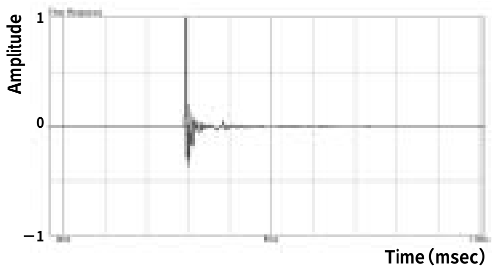


Fig.24 Impulse response of main box speaker

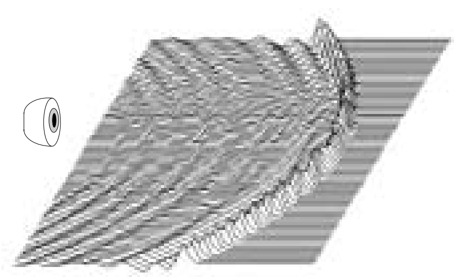


Fig.25 Multi impulse response of main box speaker

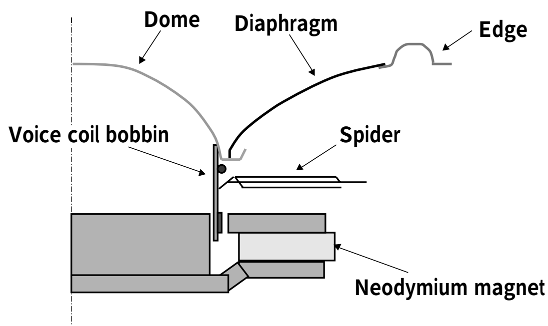


Fig.26 Composite speaker unit

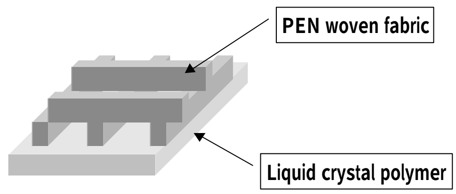
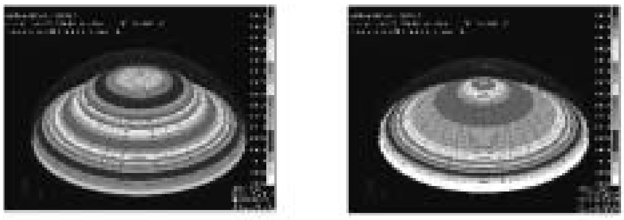


Fig.27 PEN base-material woven fabric microfiber diaphragm



Conventional type　　　Bombshell type (increased tip strength)

Fig.28 Break up mode analysis using simulation

5.3 Mid-low speaker

The frequency characteristic of this speaker are shown in Fig. 29 and its impulse response in Fig. 30. Its installation structure was shown in Fig. 15 above.

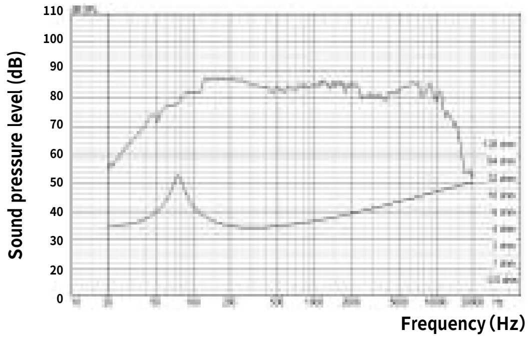


Fig.29 Sound pressure / frequency characteristic of mid-low speaker

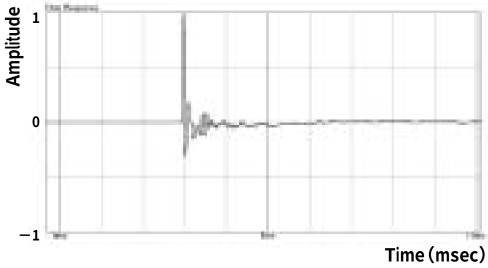


Fig.30 Impulse response of mid-low speaker

The specifications of this speaker are listed below:

- Diameter: 12 cm
- Impedance: 4Ω
- Allowable input: rated 40 W, instantaneous 160 W Max.
- Sound pressure level: 86 dB/W•m
- Reproduction frequency range: 50 Hz to 13 kHz
- Recommended crossover point: 250 Hz
- Outer dimensions: width 144 × depth 66 mm
- Mass: 900 g approx.

We close this brief description of this speaker, like that of the previous one, with a list of the technical features employed for it:

- "Floating" installation using shock absorbent material
  → refer to previous section
- Anchor
  → refer to previous section
- Non-woven fabric microfiber diaphragm
  → achieves high rigidity while assuring internal loss

6 Conclusion

Above we have presented the features of the newly-developed in-vehicle time domain system and an overview of the commercialized version product to be launched on the market.

We believe that the playback by the commercialized product delivers a sound image so realistic it's as if the artist is performing before one's very eyes, achieving faithful reproduction right down to the finest expressive details in the recording. We are confident that the thrill of this sound quality will capture more and more users on the market, creating a whole new world of car audio.

In the times ahead we will be undertaking improvements to the individual speakers and their installation methods in pursuit of even higher sound quality. At the same time we will be looking at ways to establish this technology as a genuine system, including making it compact and lightweight.

Finally we would like to express our deep gratitude to all those inside and outside the company who have assisted in the development of this system. We hope we will continue to enjoy their cooperation in its further development in the future.

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