NOTE

Approaches to Simulation in In-vehicle Acoustic Design

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1 Introduction

In recent years, the prototype-less vehicle development has been advanced and the development period has been shortened in automobile manufacturers. Thus, automobile parts manufacturers are also strongly demanded to develop a high-quality and low-cost product in a short period of time. The design using a simulation is frequently practiced as a method for satisfying this requirement. By using a simulation, we can closely observe the behavior of an object without an actual object, or can confirm the influence by the change of a component in a short time. In addition to the development of algorithm research, the performance-improved PC by the development of semiconductor technology significantly contributes to the practical application of the simulation.

The same trend applies to the acoustic category. About 20 years ago when the phenomenon analysis by acoustic simulation started to be performed, an investment of tens of millions of yen was required for a set of equipment such as workstation and analysis software. Here is an example of the in-vehicle sound field analysis. Regardless of the continued calculation for a few days, we could obtain the practical results only for low band of 500Hz or less and for high band of 2kHz or more, and there were no prospects for the most needed middle band. Extremely-large-scale computer had been required to simulate the frequencies from the low band to the high band.

In contrast to this, currently, even if a general PC performs the same calculation, we can obtain the practical calculation result from the low band to the high band in a few hours.

In such a situation, FUJITSU TEN has advanced the practical application of simulation technology by combining the accumulated know-how of sound design in a vehicle, on the basis of the general simulation methods called "Boundary Element Method", "Finite Element Method", or "Sound ray tracing method". This paper introduces the examples of the loudspeaker simulation and the examples of the in-vehicle sound field simulation.

2 Simulation in Acoustic Category

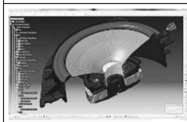
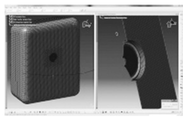
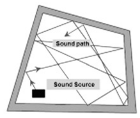
The simulation in the acoustic category mainly calculates "the behavior of a device through which sound comes out (such as loudspeaker)" and "the spatial propagation of sound".

In the former case, the behavior of a part that composes the vibration system is examined to suppress the unnecessary vibration. When the material and the shape are changed, we can consider the effect of the improvement in advance by examining how this behavior changes.

In the latter case, the sound pressure distribution and the phase distribution are calculated to examine the effects of a sound source and an obstacle. When the positional relation between the sound source and the obstacle is changed, we can consider the improvement effect without an actual measurement as well as the former case, by examining what change occurs in the distribution.

Sound has two properties: wave and beam, depending on the wavelength. Of these properties, the methods such as the finite element method (FEM) and the boundary element method (BEM) are commonly used for the "wave propagation" simulation. In addition, since a wave has linearity as the frequency becomes higher, the method called "sound ray tracing method" that views the sound progression as beam is also used. **Table 1** shows the characteristics of each method.

Table 1 Acoustic analysis methods

	FEM	BEM	Sound ray tracing method
			
Characteristic	An object is divided into elements inside of it. Method focusing on internal behavior	Only the surface of an object is divided into elements. Method focusing on surface behavior Infinite radiation problem is figured out.	Method focusing on reflection and diffusion, treating sound as beam Analysis precision is reduced in low band.
Analysis upper limit frequency	A side length of an element: 1/6 of the wavelength e.g.) Analysis upper limit frequency: 20kHz A side = (340 [m/s] / 20 [kHz]) / 6 = 0.28 [mm] An object is divided into elements whose side length is 0.28 mm.		No limit
Calculation time	Proportional to the square of the number of elements		Proportional to the frequency of reflection and the number of sound rays

FUJITSU TEN conducts acoustic simulations with the following combination, making full use of these characteristics.

- **FEM: Simulation of loudspeaker vibration**
- **BEM: Simulation of loudspeaker frequency response**
  In-vehicle sound field simulation
- **Sound ray tracing method:**
  In-vehicle sound field simulation

In the next section, the challenges to be tackled and approaches to utilizing the simulation are described.

3 Challenges in Simulation

FUJITSU TEN's mission is to provide a comfortable in-vehicle sound field to our customers. In order to measure the in-vehicle sound field characteristic and design the loudspeaker based on the characteristic, we need to correctly understand what phenomenon occurs when listening to sounds in a vehicle. Simulations are used for that purpose; however, there are basically two challenges.

[Challenges]

①To be a good correlation between the simulated value and the actual measured value

②To establish an effective handling of the calculation results, for providing a better sound field

- Challenge 1 -

We aim that "the in-vehicle sound field simulation is equal to the listening feeling". First, regarding the frequency response and the sound pressure distribution that have a significant impact on the listening feeling, we set the following targets for the loudspeaker simulation and for the in-vehicle sound field simulation, respectively.

[Loudspeaker simulation]

- **Correlation coefficient between the calculated value and the measured value, on the frequency response: 0.85 or more**

[In-vehicle sound field simulation]

- **Correlation coefficient relative to actual measurement, in the distribution of the sound pressure in the vicinity of the listener: 0.85 or more**

- Challenge 2 -

If the phenomenon in a vehicle cabin can be reproduced, the next step is to create a more comfortable sound field. To achieve this, we make the following efforts.

[Loudspeaker simulation]

- **Compile the improved patterns and the improvement results in a database, from the analysis of correlation before and after the parts improvement**

By using this database, we promote the improvement of loudspeaker design efficiently.

[In-vehicle sound field simulation]

- **Obtain a psychological index value from the calculation result, and predict the listening feeling.**

We believe this simulation can provide the frequency requiring adjustment and the control means.

4 Loudspeaker Simulation

4.1 Approach to Improvement of Precision

First, we introduce our approach to improving the correlation in the loudspeaker simulation. **Fig. 1** shows a cross-sectional view of a loudspeaker.

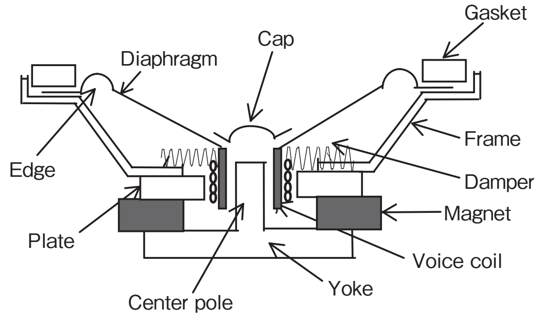


Fig.1 Cross-sectional view of loudspeaker

The loudspeaker simulation is, as described in the section 2, to closely examine the behavior of the loudspeaker by the vibration simulation. According to **Table 1**, the loudspeaker simulation is practiced by use of FEM that is suitable for the vibration simulation. **Table 2** shows the parameters used for calculation and their setting methods.

Table 2 Parameters and setting methods

	Main setting methods	
Density [g/cm^3]	Quoted from handbook, etc.	Measured from an actual object
Thickness [mm]	Use the designed value	Measured from an actual object
Young's modulus [N/m^2]	Quoted from handbook, etc. (Metals and others)	Measured from an actual object (Diaphragm, etc.)
Poisson's ratio	Most materials have values of about 0.3.	
Excitation force against voice coil [N]	Electromagnetic force to be generated through a voice coil is calculated from design information.	The value of current through a voice coil and the magnetic flux density of magnetic circuit are actually measured.

Physical properties except the excitation force apply to all components. If the same values as the actual object are input in these parameters, the vibration obtained by calculation is the same as the actual object.

Among these parameters, the Young's modulus of the "diaphragm" and the "edge" shown in **Fig. 1** has an especially large impact on the precision of calculation. Young's modulus is one of the indicators of the stiffness of an object. The higher Young's modulus is, the stiffer material is. In the case of the fibrous materials used for a diaphragm, a cap, and an edge of loudspeaker, the Young's modulus varies significantly depending on the fabric, the force when compressed, and the presence or absence of waterproofing. Therefore, the calculation precision is inferior in the generally used values.

Then, we asked for the parts manufacturers' cooperation, and compiled a database of the Young's modulus of the diaphragms of various materials. Further, we developed the system for estimating the Young's modulus from the part specifications such as density and thickness, based on the database **(Fig. 2)**.

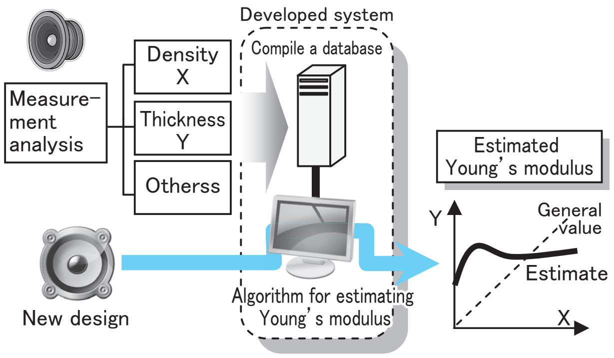


Fig.2 Schematic diagram of system estimating optimum Young's modulus

This system improved the calculation precision before the prototype trial of the diaphragm, and contributed significantly to the reduction of time and cost by decreasing the frequency of prototype trials. Besides, we became able to understand the behavior of loudspeaker more precisely. Toward a further precision improvement, we continue to carry out the activities to compare the Young's modulus before and after the prototype trial, review the difference factor, and feed back the difference to the Young's modulus estimating system. In addition, for the deformable materials such as edge which are extremely difficult for us to actually measure the Young's modulus, we also established the method for estimating the Young's modulus from the relation between the mass and the resonant frequency.

Next, the excitation force against a voice coil is calculated from the current through the voice coil of a loudspeaker, magnetic flux density generating between the plate and the yoke, and the length of the coil across the magnetic flux.

By using the result of the vibration simulation thus obtained, the acoustic simulation by BEM is practiced. **Table 3** shows the correlation coefficient between the measured value and the simulated value. It shows that the correlation coefficient is improved by the estimating system.

Table 3 Correlation coefficient between measured value and simulated value

	Correlation coefficient (20Hz to 15kHz)
General value	0.78
Simulated by estimating system	0.93

Currently, it becomes possible to ensure the correlation coefficient of 0.9 or more (extremely-high correlation) even in about 15kHz band, and the target was achieved. **Fig. 3** shows an example of the comparison with actual measurement.

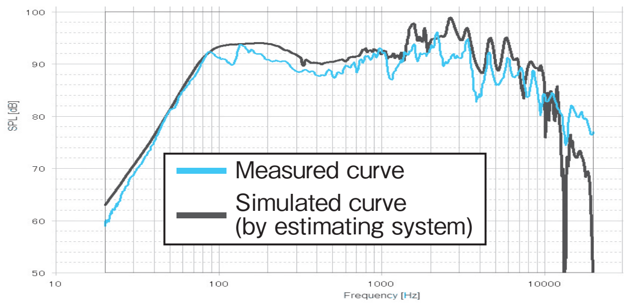


Fig.3 Comparison of frequency response between measured curve and simulated curve

4.2 Approach to Establishing Improvement Means

Regarding the activities for improving the characteristics, we analyze the contents in the following process, and compile a database of their results.

- **Extraction of the most effectively improved part from the calculation result**
- **Recalculation after changing the shape and the physical property**
- **Correlation analysis of the difference**

As for the correlation analysis, we focus on the weakening of the correlation of the frequency at which vibration has been changed because of the change in the shape and the physical property, etc., visualize the influence rate of the improvement, and compile a database to predict the improvement effect. As with the Young's modulus estimating system, we also feed back the change into this database, and accumulate the data by loudspeaker design model.

5 *In-vehicle Sound Field Simulation*

5.1 Approach to Improvement of Precision

This section introduces the examples of practical use of the in-vehicle sound field simulation. The following two points are the differences from the loudspeaker simulation.

- **Since the spatial volume is large in a vehicle cabin, the propagation characteristic of sound wave must be considered.**
- **Since there are many interior materials and obstacles that reflect / absorb sounds, the propagation characteristic in the air is complex.**

Therefore, if the same FEM and BEM as the loudspeaker design are used, the number of elements is increased, thus several weeks may be needed to calculate the audible frequency range: 20Hz to 20kHz. Then, as shown in the calculation time in **Table 1**, we intended to shorten the calculation time by using the different simulation methods depending on the band to be calculated. As shown in **Table 4**, when the BEM and the sound ray tracing method are used depending on the situation by setting the frequency of 1kHz as the boundary, the calculation time can be kept within five hours.

Table 4 Analysis method suitable for the characteristics of each band

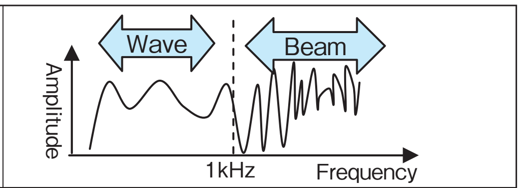
		
Charac-teristic	Sound is steady. It is calculated by wave equation.	Linear sound beam It is calculated by geometry and statistics.
Method	BEM	Sound ray tracing method

Fig. 4 (a) shows an example of distribution of sound pressure in the vicinity of the listening position by BEM, and **(b)** shows an example of the direction of arrival of sound by the sound ray tracing method.

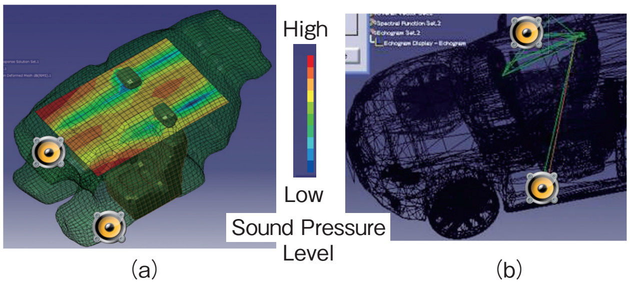


Fig.4 (a) Distribution of sound pressure in the vicinity of listening position by BEM
(b) Direction of arrival of the sound by Sound ray tracing method

5.2 Approach to Improving Correlation Coefficient

With this method, we are at the stage of simulating the loudspeaker placed in the predetermined position in a vehicle and verifying the correlation coefficient between the measured physical property and the simulation result. If the correlation coefficient is improved, utilizing the result of in-vehicle sound field simulation for the loudspeaker layout design and for the sound field adjustment process can be expected. Further, by calculating the characteristic for listening feeling, we concurrently predict the psychological value when listening to sounds.

5 Conclusion

The correlation between the loudspeaker simulation and the physical property was improved, and this result was included in the in-vehicle sound field simulation. Therefore, we were able to visualize the subjects from the design to the sound spatial characteristics.

However, sounds are eventually judged by listening feeling. Even if the sound pressure characteristics seem the same, listening feeling is different by human ears. Therefore, predicting the listening feeling without focusing on only minimizing the simulation error in the physical property is required for the future simulation technology. We will verify the physical property that correlates strongly with listening feeling, and will promote the technological development in the acoustic category.

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