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BALANCE OF CAR INTERIOR NOISE COMPONENTS IN CONSIDERATION OF MASKING EFFECT

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ABSTRACT
The purpose of this study is to develop an objective method to evaluate car interior noise quality, which considered loudness and balance of interior noise components (engine noise, booming noise, road noise, and wind noise). We assumed an auditory processing model about car interior noise in consideration of masking effect, and made a method for calculating loudness of interior noise components, based on this model. This method can calculate loudness and balance of noise components, which considers mutual masking effect between periodic noise components and random noise components. And we showed that balance of noise components affects an impression of sound quality of car interior noise by doing a subjective evaluation test about road noise and wind noise.

1 - INTRODUCTION
Recently, quietness and sound quality in the passenger compartment of a car has been improved. However, in some cases, road noise or wind noise has become relatively more noticeable to the passengers even if its absolute level is passably low, so the passengers have an unfavorable impression. This means that loudness and balance of interior noise components (engine noise, booming noise, road noise, and wind noise) affect the impression of quietness and pleasantness in the passenger compartment of a car.
Therefore, for improving interior noise, a new approach that pays attention to the loudness and balance is necessary. For evaluating loudness and balance of interior noise components, not only the masking effect between frequency components but also the mutual masking effect between periodic noise components and random noise components should be considered. Relatively few studies have directly considered either balance or masking effect of interior noise components in the development of an objective sound quality evaluation method [1], [2].
The purpose of this study is to develop an objective method to evaluate car interior noise quality, which considered loudness and balance of interior noise components. The method will be based on an assumed auditory processing model about car interior noise in consideration of masking effect.

2 - AN AUDITORY PROCESSING MODEL ABOUT CAR INTERIOR NOISE
Fig. 1 shows an assumed auditory processing model about car interior noise in consideration of masking effect. At the peripheral auditory system, the processing similar to the frequency analysis is done to the interior noise signals received at the ears. As shown in this figure, interior noise is composed of periodic noise components (engine noise) and random noise components (road noise and wind noise), and the mutual masking effect exists between them.
In the following pattern recognition process at the cerebral cortex, car interior noise components, which have acoustical features such as frequency area, are recognized from masked periodic noise components and masked random noise components. Then the total impression of interior noise is perceived by integrating the perception of all interior noise components.

3 - CALCULATION METHOD OF LOUDNESS OF INTERIOR NOISE COMPONENTS

3.1 - Separation of periodic noise components and random noise components
For processing based on the assumed model, it is necessary that periodic noise components and random noise components should be separated from the interior noise. Fig. 2 shows an imitated frequency

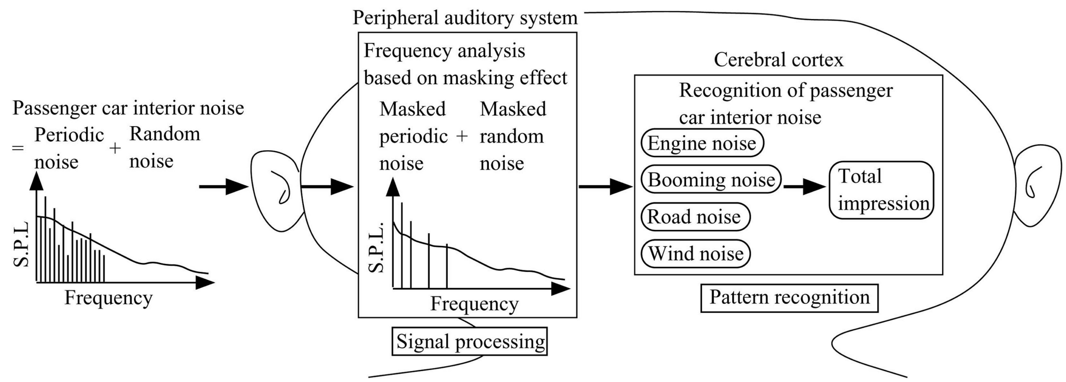

Figure 1: An auditory processing model.

spectrum of interior noise composed of periodic and random noise components. We used spectrum envelope analysis to separate random noise components from interior noise. Spectrum envelope is a good approximation of random noise components.
About periodic noise components, the difference between the loudness of the total noise and the loudness of the spectrum envelope is regarded as the perceived loudness of periodic noise components, in consideration of the masking effect by random noise components.

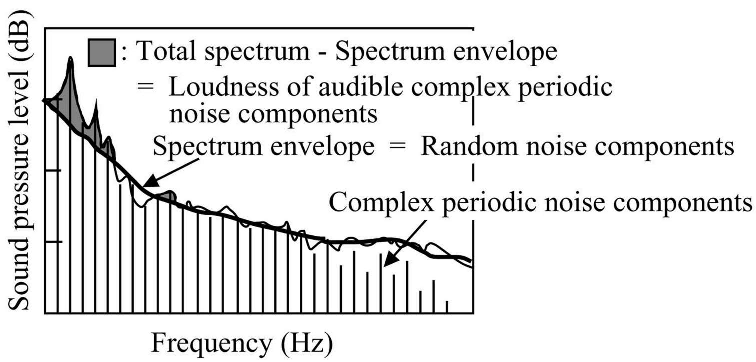

Figure 2: An imitated frequency spectrum of car interior noise.

3.2 - Calculation method of masked frequency spectrum

To calculate the loudness of each frequency band of a broad band noise such as interior noise, the masking effect must be considered. A calculation method to obtain a "masked frequency spectrum" that took the masking effect into account was proposed [3]. The masked frequency spectrum is the spectrum of the masked loudness of the sound in each critical band. The masked loudness in each critical band is the loudness partially masked by the other frequency components. The critical band is the virtual bandpass filter in the human auditory system, which has been found to be a successful approach for explaining the human perception of loudness. The total loudness is simply the sum of the masked loudness over all critical bands.
The masked loudness in each critical band is found by applying the method proposed by Zwicker, standardized in ISO 532B [4]. The method calculates loudness level in each critical band, and calculates masking level to the higher frequency bands. So the masked loudness can be calculated by subtracting the masking level from the loudness level in each critical band.
Zwicker's loudness calculation method is based on the critical bandwidth. Recently, equivalent rectangular bandwidth (ERB) has been used instead of critical bandwidth [5]. However, the method that uses critical bandwidth has a good correspondence to the perception of sound [6]. Therefore, in this study, the Zwicker's loudness calculation method was used.

3.3 - Loudness of interior noise components in consideration of masking effect

Fig. 3 shows the flow of calculating the masked frequency spectrum of car interior noise. First, frequency spectrum analysis and spectrum envelope analysis are done, and the 1/3 octave band levels of the total noise components and the random noise components are calculated. Next, the masked frequency spectrums of the total noise and the random noise are calculated from their 1/3 octave band levels. In this process, the masker to the frequency components of the random noise is the frequency components of the total noise. And the masked loudness of the periodic noise components is determined from the difference between the masked loudness of the total noise and the masked loudness of the random noise components.

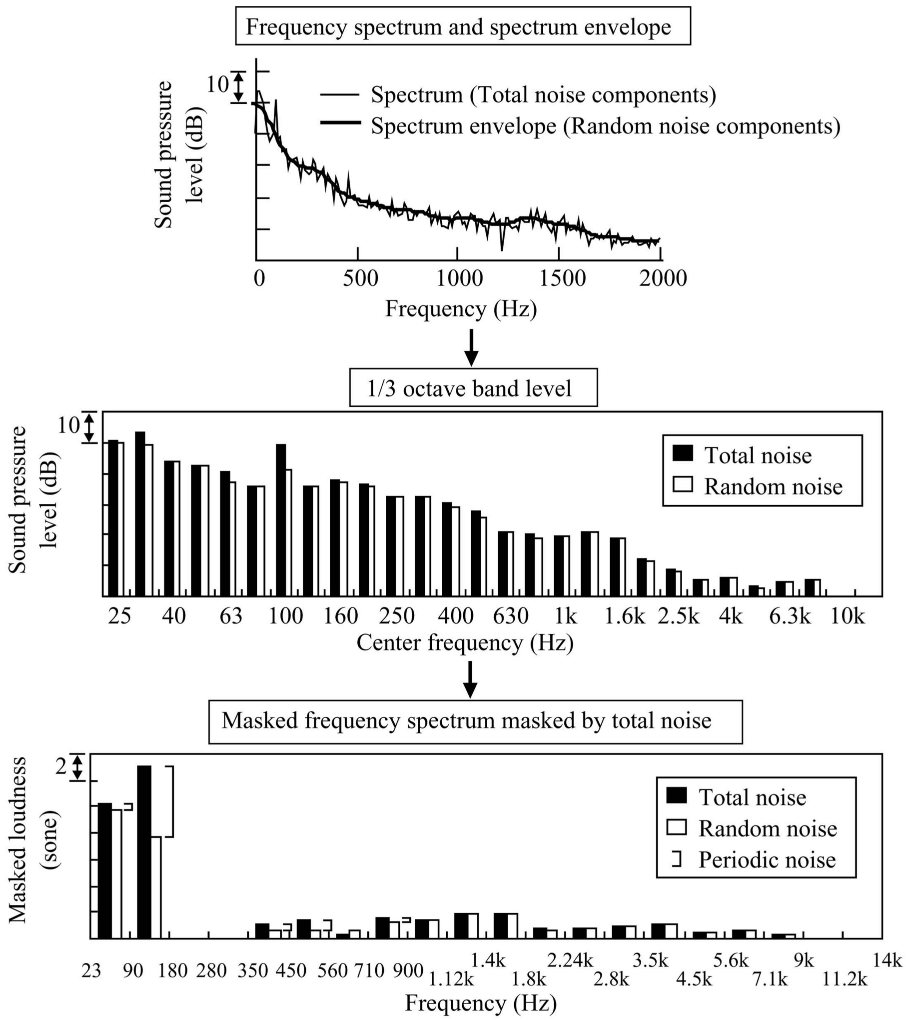

Figure 3: Flow of calculating the masked frequency spectrum of car interior noise.

Loudness of each interior noise component is calculated as follows, based on its frequency area.

- Engine noise: Sum of masked loudness of periodic noise components
- Booming noise: Sum of masked loudness of total noise components below 180 Hz
- Road noise: Sum of masked loudness of random noise components below 900 Hz
- Wind noise: Sum of masked loudness of random noise components above 450 Hz

3.4 - Experimental results

To examine the effectiveness of the method, we did a subjective evaluation test about loudness of interior noise components by using simulated interior noise and real interior noise. The conditions of the test are shown in the following:

- Hearing method: Headphones in a soundproof chamber
- Rating method: Five steps scale rating on subjective loudness (1: low, 2: rather loud, 3: loud, 4: very loud, 5: extremely loud)

- Subjects: Five persons for engine, booming, and road noise, and twelve persons for wind noise

Relations between the calculated loudness and the subjective evaluation results are shown in Fig. 4(a). For the comparison, we calculated the physical value of each noise component without considering masking effect as follows:

- Engine noise: The difference between the overall level of the frequency spectrum and the overall level of the spectrum envelope
- Booming noise: Partial level of the frequency spectrum below 180 Hz
- Road noise: Partial level of the spectrum envelope below 900 Hz
- Wind noise: Partial level of the spectrum envelope above 450 Hz

Fig. 4(b) shows the relations between the calculated physical values and the subjective evaluation results. These results show that the proposed method is more effective to estimate subjective loudness than the method without considering masking effect.

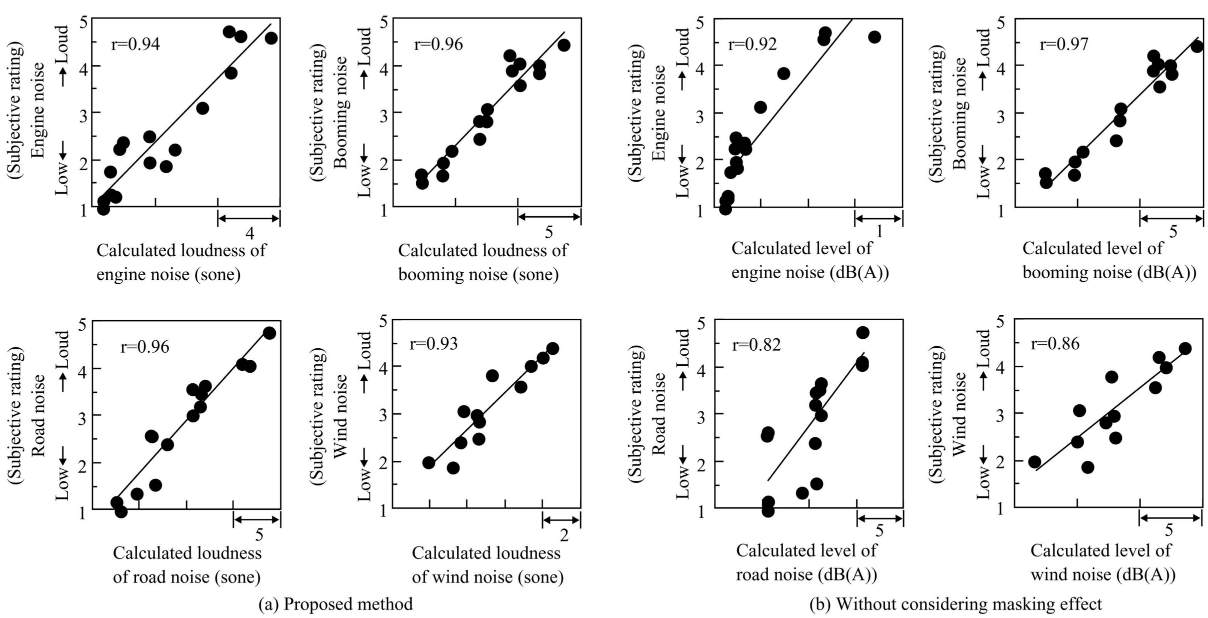

Figure 4: Relations between the objective evaluation results and the subjective evaluation results.

The reason why the proposed method shows a better performance is described as follows. Fig. 5 shows the frequency spectrum and the masked frequency spectrum of a simplified interior noise. As shown in these figures, a periodic noise component (that simulates engine noise) masks random noise components (that simulate road noise) in the frequency range from 180 to 350 Hz. If the masking effect is not considered, the loudness of road noise in the frequency range is evaluated larger than the subjective loudness.

The results of this experiment suggest the validity of the process of perceiving each interior noise component based on the mutual masking effect in the assumed auditory processing model.

4 - BALANCE OF INTERIOR NOISE COMPONENTS

Car interior noise is significantly dominated by road noise and wind noise at speeds on the order of 100 km/h, under cruising conditions. Therefore, the impression of quietness and sound quality is mainly affected by road noise and wind noise. Furthermore, even if the absolute level of interior noise is passably low, the passengers have an unfavorable impression when either road noise or wind noise is relatively noticeable. This means that there is a possibility that balance of interior noise components affects the impression of interior noise.

We investigated whether the balance of interior noise components affects an impression of sound quality of car interior noise by doing a subjective evaluation test about road noise and wind noise. In this experiment, we used simulated interior noise based on real interior noise of two cars at a vehicle speed of

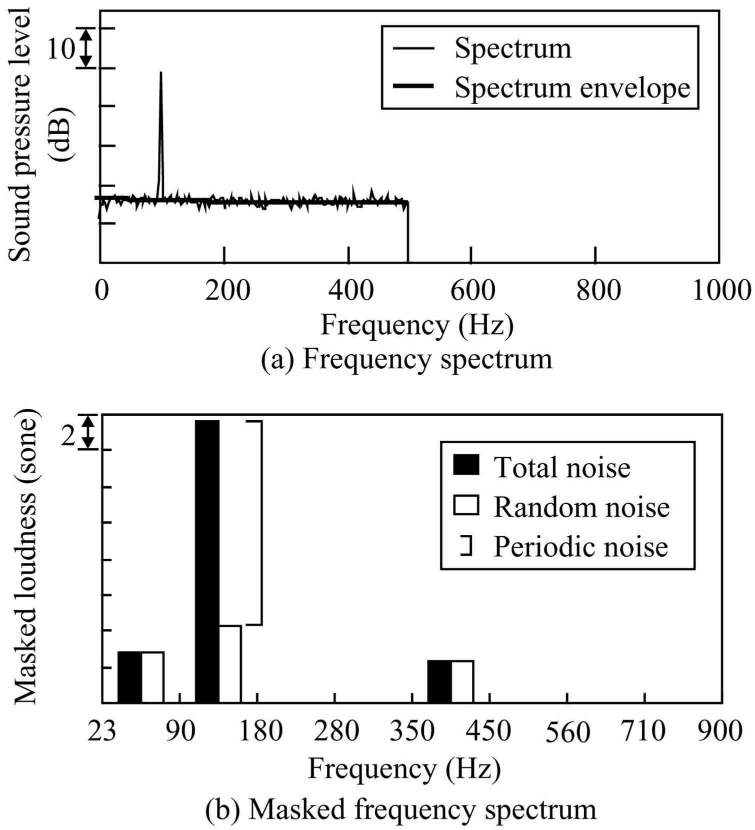

Figure 5: The frequency spectrum and the masked frequency spectrum of a simplified interior noise.

100 km/h. The random noise components were edited for variously changing the loudness of road noise and wind noise [7]. The sound levels of the stimuli were equalized at 65 dBA because the difference of sound level influences subjective evaluation results.
Subjects evaluated "relative loudness of road noise and wind noise" and "total sound quality of interior noise". The conditions of the test are shown in the following:

- Hearing method: Headphones in a soundproof chamber
- Rating method: five steps scale rating on "relative loudness" and "total sound quality"
- Subjects: Ten persons

The relation between the proportion of the calculated loudness of wind noise to the calculated loudness of road noise and the subjective evaluation results on relative loudness is shown in Fig. 6. This figure shows there is a good correlation (r=0.89).
Fig. 7 shows the relation between the subjective evaluation results on relative loudness and the subjective evaluation results on total sound quality. This figure shows that total sound quality becomes worse when either road noise or wind noise is relatively loud and becomes best when the loudness of road noise and wind noise is balanced. This relation can be approximated as the solid line in this figure.
By applying the relation of Fig. 6, the abscissa in Fig. 7 can be replaced with the proportion of calculated loudness of wind noise to calculated loudness of road noise. The balance of road noise and wind noise can be objectively evaluated from the relation of Fig. 7, and the balance becomes an objective measure to evaluate sound quality of car interior noise under cruising conditions.
The results of this experiment suggest the validity of the process of perceiving the total impression of interior noise after integrating the perception of all interior noise components in the assumed auditory processing model.

5 - CONCLUSION

We assumed an auditory processing model about car interior noise in consideration of masking effect, and made a method for calculating loudness and balance of interior noise components. It was shown

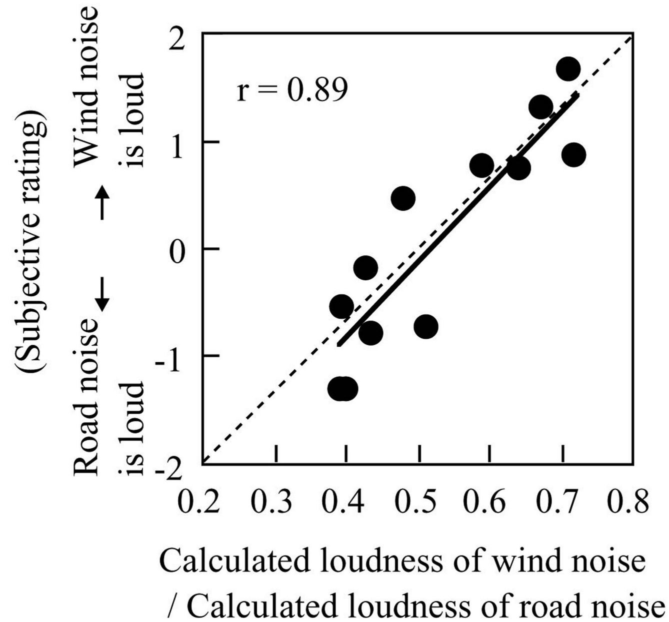

Figure 6: Relation between the objective evaluation values and the subjective evaluation results on relative loudness.

that the balance is an effective index to evaluate car interior noise quality. The proposed method will be a helpful tool for the engineer desiring to achieve improvements in car interior noise.

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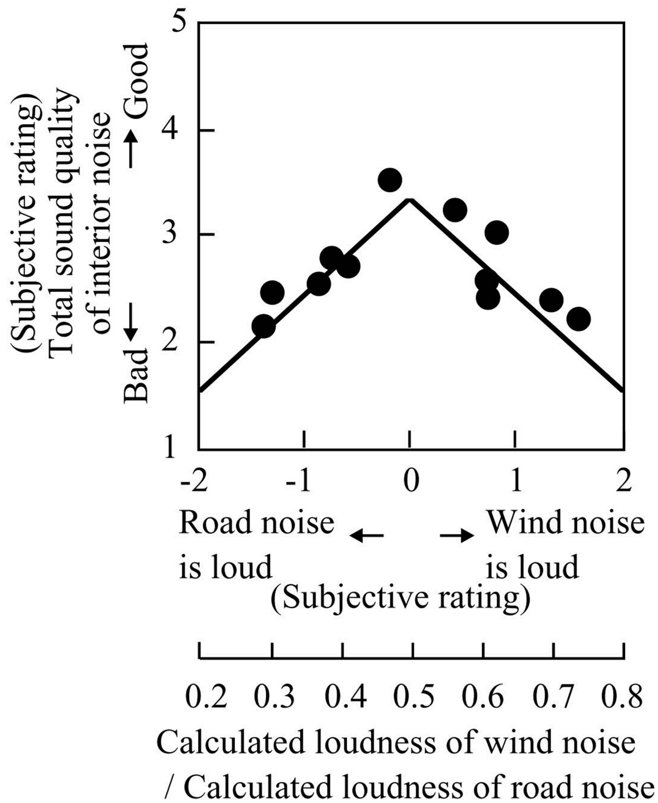

Figure 7: Relation between relative loudness and total sound quality.