Effect on car interior sound quality according to the variation of noisy components of tire-pattern noise

Sung-Hwan SHIN[1]; Takeo HASHIMOTO[2]; Shigeko HATANO[3]

[1] Kookmin University, Korea

[2,3] Seikei University, Japan

ABSTRACT

A tire noise is one of the important noise sources of vehicle. Especially, it becomes more dominant one for motor-driven vehicle such as electric or hybrid vehicle. The purpose of this study is to grasp the effects of the variation of noise components of tire-pattern noise on car interior sound quality. To this end, tire noises were recorded with a compact car but with different types of tire pattern. Noisy components of each tire noise were indicated and then the noisy components were modified with their peak level, half-power bandwidth, and position on frequency domain. By employing subjective listening tests whose target was to evaluate the extent of annoyance of the modified noises, the change tendency of annoyance according to the variation of the noisy components was investigated and an index was proposed that could estimate and predict the annoyance of tire-pattern noise. In addition, it was known that energy ratio of a noisy component to background noise in the frequency range that the noisy component exists was one of the important descriptors representing the annoyance of tire-pattern noise.

Keywords: Tire-pattern noise, Sound quality, Vehicle interior noise
I-INCE Classification of Subjects Number(s): 63.7

1. INTRODUCTION

There are several kinds of noise sources in vehicle such as engine, intake/exhaust system, tire-road interaction, and wind. Recently, a tire-road interaction has become a very important noise source in quiet vehicle such as electric and hybrid ones because they use an electric motor as the main power supplier not internal combustion engine (1). Among the noises due to tire-road interaction, the tire-pattern noise is strongly affected by tread pattern shape and its arrangement (2).

There are two kinds of noisy components in the tire-pattern noise influencing on car interior noise, whine and sizzle. The whine component is a narrow band noise with the characteristic more like the tonal component below 1.5 kHz and is similar to the whistling sound. The sizzle component is a broad-band tone with frequency bandwidth wider than about 500 Hz at the frequency range above 2 kHz. Authors found that the whine gave more dominant effect to the annoyance of car interior noise than the sizzle through the former research (3). Beating may be also a noisy component at the low speed. However, it is rarely heard due to the design innovation in the current commercial tires.

This study grasps the effects of the variation of the whine component of tire-pattern noise and proposes a sound quality index that estimates the annoyance of car interior noise. To this end, tire noises were recorded with a compact car on the proving ground at the constant cruising speed, 80 km/h. For the recording, tires with five different types of tread patterns were used for obtaining tire-pattern noise. Noisy components of each tire noise were indicated and then the noisy components were modified with their level, half-power bandwidth, and position on frequency domain. By employing subjective listening tests whose target was to evaluate the extent of annoyance of the modified noises, the change tendency of annoyance according to the variation of the noisy components related to the whine was investigated. To obtain objective data of the modified noises, sound pressure level, loudness, roughness, narrow band spectrum, and so on were calculated. The annoyance index of

[1] soulshin@kookmin.ac.kr
[2] hashimot@st.seikei.ac.jp
[3] hatano@st.seikei.ac.jp

tire-pattern noise was proposed by using stepwise regression.

2. NOISY COMPONENTS AND THEIR MODIFICATION

2.1 Extraction of Aurally Relevant Noisy Components

As above stated, five tire-pattern noises were obtained from a compact car with five different types of tread patterns: E1, E2, E3, E4, and E5, respectively. This study focused on noisy components related to the whine because it was known from the former research that the sizzle and beating gave very weak influence to the annoyance of car interior noise (3).

To detect the aurally relevant noisy components, it is necessary to select candidates among the several tonal or narrow band components on the frequency domain. Basically, the tonal or narrow band components with peak levels higher than spectrum curve of background noise could be regarded as the candidates. Here, the background noise of tire-pattern noise is one that is obtained by removing all noisy components from the tire-pattern noise. A sensation caused by the background noise is better and softer than that by the original tire-pattern noise, that is, the background noise is less annoying. For example, the candidates in E1 are indicated in Fig. 1 as A1, A2, etc.

To judge whether the candidates were audible or not, a subjective experiment was conducted. For E1, 9 test sounds were made by eliminating each candidate one by one from original tire-pattern noise E1 by using FIR filter. Fig. 2(a) and 2(b) shows the spectra of test sounds that A1 and A2 among the candidates are eliminates from E1, respectively. In the subjective experiment, a subject was asked to indicate whether a test sound was different in hearing impression with the original noise E1 or not after hearing and comparing two sounds. If the test and original noises were different with each other, the candidate eliminated for the test sound was regarded as an aurally relevant noisy component. 6 subjects who are employees working for tire manufacturer were participated in this experiment. Fig. 3 shows the result for E1. In the figure, the ordinate means how many indicated the candidate is as the noisy component. 'PA' and 'SA' indicate the primary and secondary noisy components.

The same tests were performed to find aurally relevant noisy components of tire-pattern noises: E2,

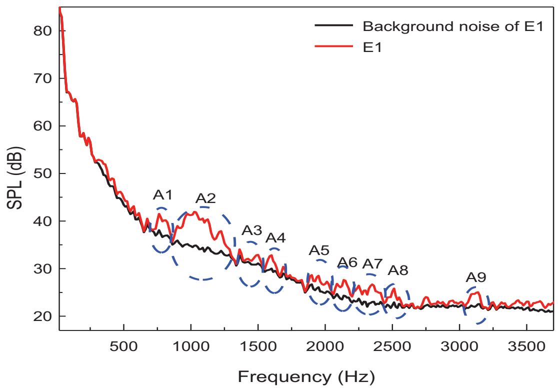

Figure 1 – Candidates for the annoyance components of E1.

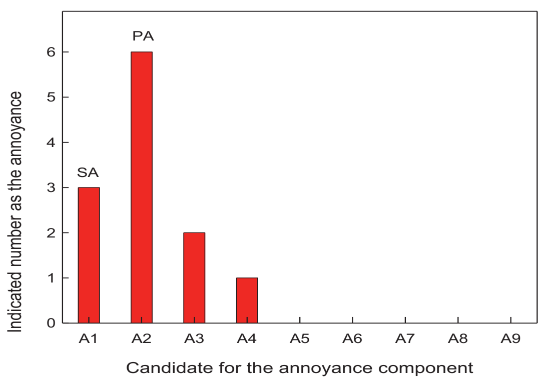

Figure 3 – Result of the subjective experiment indicating aurally relevant annoyance components on E1.

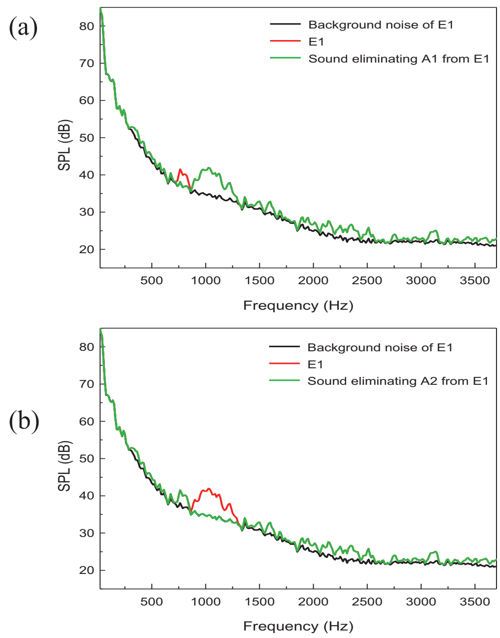

Figure 2 – Comparisons of spectra of E1 and its background noise with that of sound eliminating (a) A1 and (b) A2 from E1, respectively.

Table 1 – Noisy components of tire-pattern noises

Tire-pattern noise	Primary annoyance (center frequency)	Secondary annoyance (center frequency)
E1	A2 (1025 Hz)	A1 (762.5 Hz)
E2	A3 (962.5 Hz)	A6 (1587.5 Hz)
E3	A2 (962.5 Hz)	A1 (775 Hz)
E4	A2 (1037.5 Hz)	A1 (812.5 Hz)
E5	A2 (962.5 Hz)	A1 (762.5 Hz)

E3, E4, and E5. Usually, each tire-pattern noise had two noisy components and Table 1 summarizes the center frequency of indicated noisy components. The center frequency is the frequency related to the maximum peak within the noisy component.

2.2 Modification of Noisy Components

To grasp the effect of the single noisy component on the annoyance of car interior noise, the noisy component was changed with its peak level, half-power bandwidth, and position on the frequency domain. At first, in the spectrum of a tire-pattern noise, only one noisy component was left and the rest portion was replaced with the spectrum of its background noise. At second, the peak level of the noisy component was varied as much as ±3 dB from the original level modified spectra were compared in Fig. 4(a). It was known in the former research (3) that subjects could certainly feel the difference in the annoyance when the peak level was change as much as 3 dB. Next, the half-power bandwidth of the noisy component was varied as much as ±50 %. Actually, professionals of tire noise indicated that it was very difficult to feel the annoyance difference when the amount of variation was narrow than 50%. Figure 4(b) shows an example that the half-power bandwidth of noisy component is changed. Finally, the position of noisy component on the frequency domain was shifted as much as ±15 % of its center frequency as shown in Fig. 4(c). It was also dependent on the professionals' comments that it was very difficult to indicate the different when the noisy component was moved within the range of ±15 % of its center frequency. The amount of variation in frequency is coincident with the critical bandwidth of the frequency range that the noisy components exist: from 700 Hz to 1.5 kHz (4).

Consequently, test sounds used for finding the effects of the single noisy component on the annoyance of car interior noise were made as changing ± 3dB of its peak level, extending and reducing 50 % of the half-power bandwidth, and shifting ±15 % of the center frequency. Figure 5 illustrates the modification of the noisy components. The number of full combination for the variation is twenty-seven as listed in Table 2. For the all variations, FIR filters were employed.

3. SUBJECTIVE EVAULATION

To evaluate the degree of the annoyance of car interior noise when a single noisy component exists alone, a subjective evaluation was conducted by employing magnitude estimation (ME) method. In the ME method, a subject is asked to allocate the annoyance scores of the test sounds with respect to the reference sound by moving the slide bar between 0 and 100. At that time, the score of reference sound is fixed. If the subject feels a test sound more annoying than the reference

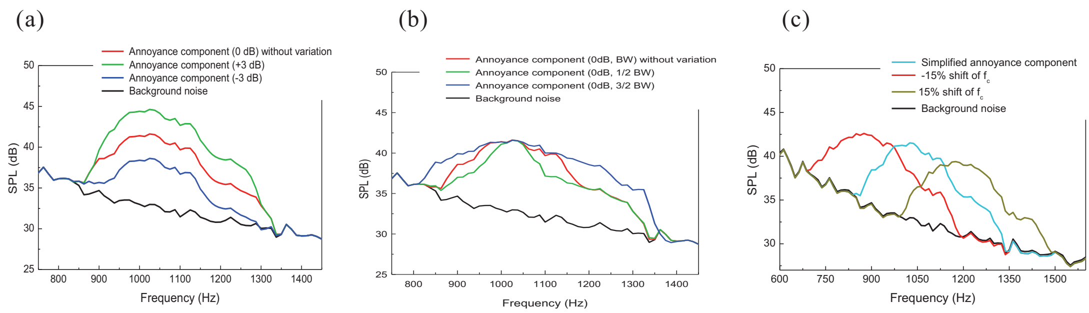

Figure 4 – Examples of modifying a noisy component in (a) peak level, (b) half-power bandwidth, and (c) position on the frequency domain.

Table 2 –Full combinations for the variation of a noisy component

Test sound No.	Variations			Test sound No.	Variation			Test sound No.	Variation		
	Center freq.	Level	Half-power bandwidth		Center freq.	Level	Half-power bandwidth		Center freq.	Level	Half-power bandwidth
1	-15%	-3 dB	1/2×BW	10	Original	-3 dB	1/2×BW	19	+15%	-3 dB	1/2×BW
2	-15%	-3 dB	Original	11	Original	-3 dB	Original	20	+15%	-3 dB	Original
3	-15%	-3 dB	3/2×BW	12	Original	-3 dB	3/2×BW	21	+15%	-3 dB	3/2×BW
4	-15%	Original	1/2×BW	13	Original	Original	1/2×BW	22	+15%	Original	1/2×BW
5	-15%	Original	Original	14	Original	Original	Original	23	+15%	Original	Original
6	-15%	Original	3/2×BW	15	Original	Original	3/2×BW	24	+15%	Original	3/2×BW
7	-15%	+3 dB	1/2×BW	16	Original	+3 dB	1/2×BW	25	+15%	+3 dB	1/2×BW
8	-15%	+3 dB	Original	17	Original	+3 dB	Original	26	+15%	+3 dB	Original
9	-15%	+3 dB	3/2×BW	18	Original	+3 dB	3/2×BW	27	+15%	+3 dB	3/2×BW

∗ Test sound 14 is a noisy annoyance component without any variation.

sound, then he/she should be the slider bar the annoyance part near 100. Otherwise, he/she should move the slide bar to opposite part near 0. The reference was identical with the background noise that was rated as ten points in the rating range. Totally, 21 subjects who are composed of 19 males and 2 females aged from 20 up to 60 with normal hearing participated in this subjective evaluation.

As shown in Table 1, each tire-pattern noise has two noisy components relate to the whine: the primary and secondary. For E1, the primary and secondary noisy components had peaks at 1025 Hz and 762.5 Hz, respectively. At first, the primary noisy component of E1, PE1 as the abbreviated expression, was basically changed by the combination listed in Table 2. However, PE1 was impossible to make test sounds 1 and 3 because its half-power bandwidth was not clearly defined when the peak level was reduced as much as 3 dB. For this, totally 25 test sounds were made and then subjective experiment for evaluating their annoyance was conducted.

Figure 5(a) is the result of subjective experiment on the primary noisy component of E1. In order to check whether the difference of annoyance according to the variation is significant or not, the main effects by the variation are plotted for a visual inspection in Fig. 5(b). As a whole, the difference of annoyance was prominent when peak level was change. It was also slightly influenced by the change of half-power bandwidth. The shifting of the peak position on the frequency domain rarely changed the annoyance.

The secondary noisy component of E1, SE1 as the abbreviated expression also changed according to the combination shown in Table 2. In the case of SE1, 14 test sounds were made because its peak level was not able to be decreased. Figure 6(a) and 6(b) are the result of the subjective experiment and the main effects by the variations, respectively. For the peak level and half-power bandwidth, we were obtained similar results to those for PE1. However, The effect due to the shift of SE1 had different tendency with that of PE1. The result showed that the change of the annoyance of car interior noise is influenced by the shift of the peak position.

The same subjective experiments were applied to other tire-pattern noises: E2, E3, E4, and E5. The results related to the primary noisy components of the noises are shown in Fig. 7. From the results of the subjective experiments on the tire-pattern noises, it was investigated that the variation of the peak level of the noisy component most strongly influenced the perceptual feeling, i.e.

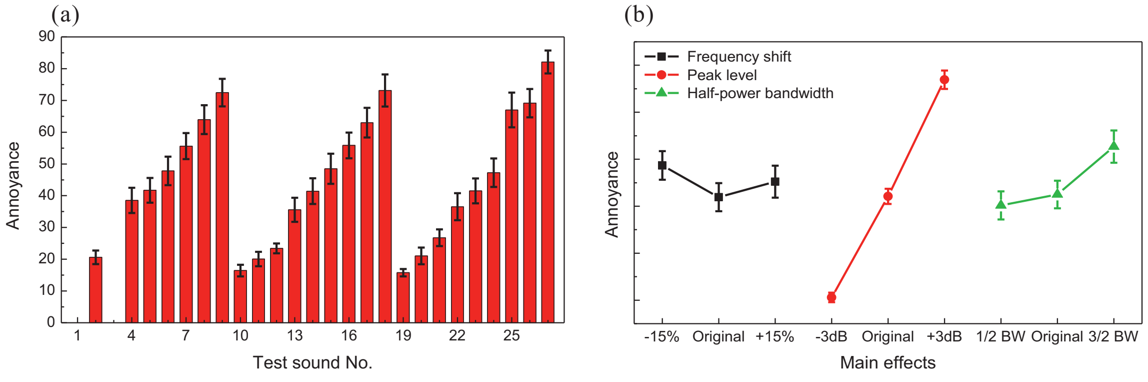

Figure 5 – (a) Result of subjective experiment on PE1 and (b) effect of each variation factor in the annoyance. In the figure, error bar means 95% confidence interval.

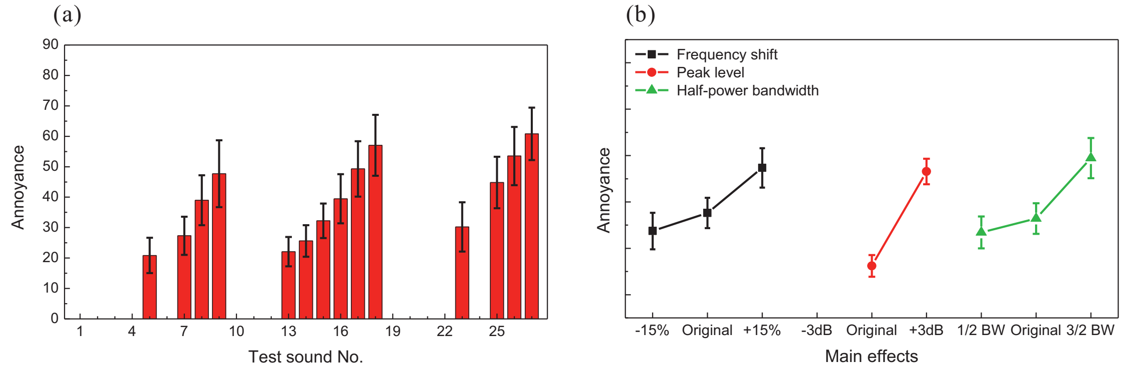

Figure 6 – (a) Result of subjective experiment on SE1 and (b) effect of each variation factor in the annoyance. In the figure, error bar means 95% confidence interval.

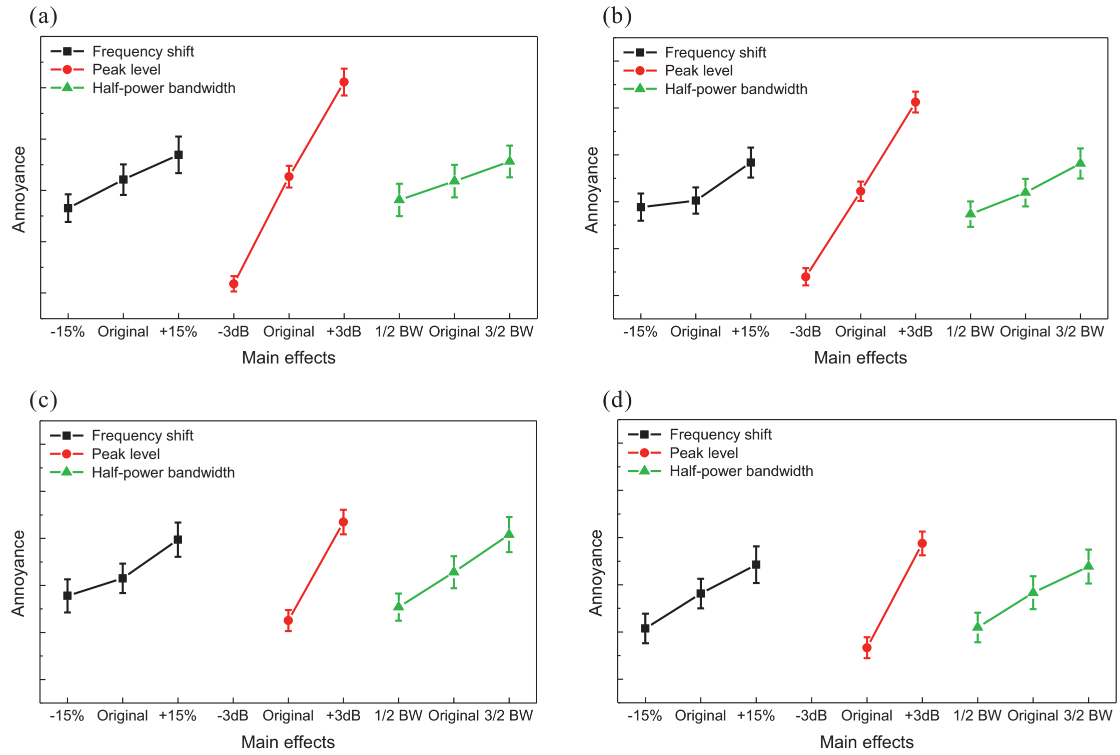

Figure 7 – Effect of each variation factor in the annoyance for (a) PE2, (b) PE3, (c) PE4 and (d) PE5. In the figure, error bar means 95% confidence interval.

annoyance of car interior noise. That was, the variation of subjective evaluation was relatively large when the peak level was varied. The variation of its half-power bandwidth and its shift on the frequency domain were also affected the annoyance although the extent of influence was relatively small compared with that caused by the variation of peak level. Consequently, it was concluded that tire-pattern noise having a high peak level, a wider half-power bandwidth, and a center frequency of a peak located at higher frequency side was more annoying.

4. ANNOYANCE INDEX FOR TIRE-PATTERN NOISE

It was necessary to merge all subjective data in order to make an annoyance index because each subjective experiment was conducted on individual noisy components of each tire-pattern noise. For this, an additional subjective experiment was conducted and then a linear mapping process for unifying all subjective data was employed (3).

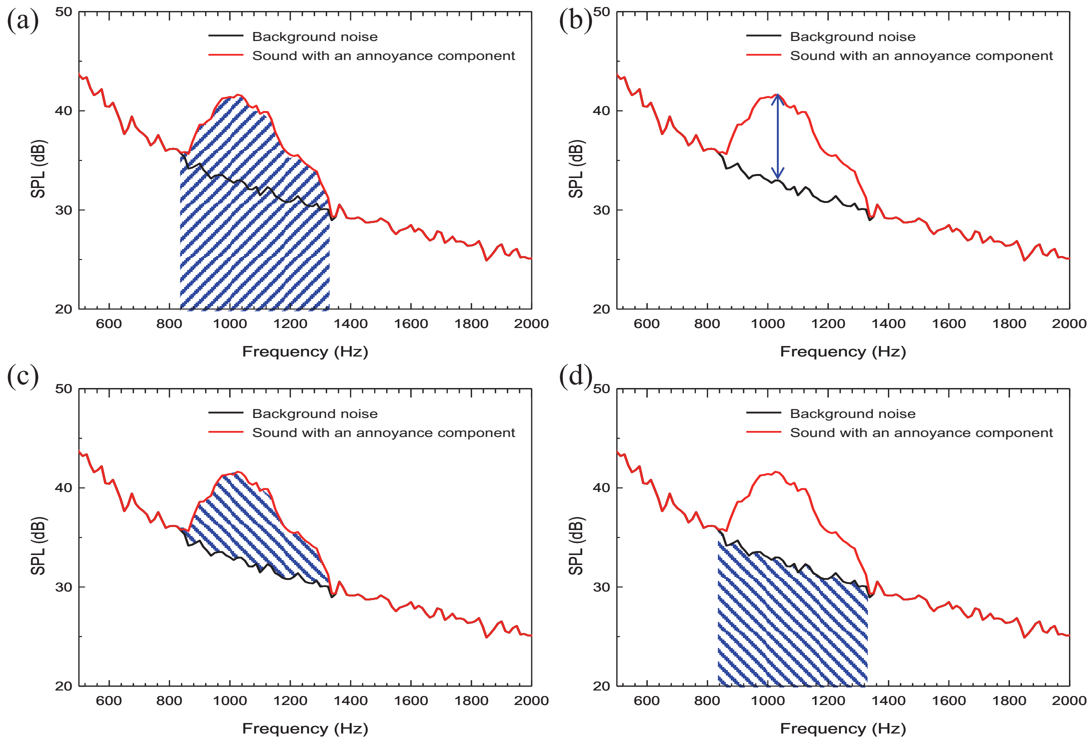

Figure 8 – Calculated objective factors: (a) Banded SPL (dB), (b) peak-level difference (dB), (c) energy ratio (dB) of an annoyance component to background noise, and (d) SPL (dB) of background noise.

To make an annoyance index for evaluating and predicting the annoyance caused by individual noisy component, it was necessary to find objective factors which could represent the features of the noisy component. For the objective factors, sound pressure level (SPL) in dB and dBA and sound quality (SQ) metrics such as loudness (sone), roughness (asper), and fluctuation strength (vacil) were calculated. Based on the former factors, banded SPL, peal-level difference (dB), energy ratio, and SPL (dB) of background noise were also calculated. Specially, energy ratio defined as the level difference between a noisy component and background noise within the frequency range in which the noisy component existed. Figure 8 shows above four objective factors. Additionally, partial level and partial sound quality metrics were done within the two bands. 'Range1' is a frequency range between 500 and 2000 Hz where the whine is dominant and 'Range2' is a frequency range that a noisy component exists.

After conducting correlation analysis between merged subjective data by the linear mapping and objective factors, we knew that partial SPL and partial loudness related to Range1 had high correlation with the subjective data. In spite of that, these kinds of objective factors should not be simultaneously used for the candidate of the explanatory variable for making an annoyance index because they were the variables having the identical function in the regression analysis.

To determine explanatory variables for an annoyance model, the stepwise regression analysis method was employed in this study. Table 3 summarizes t-statistics and p-value according to the objective factors in each step and indicates the variables for the annoyance index. T-statistic and p-value in the step 0 are values obtained when one of the objective factors was used as the explanatory variable in tern in the regression analysis. The higher t-statistic and the lower p-value, the objective factor can represent the subjective data well. Because t-statistic related to SPL (dBA) of Range1 was the highest, it was selected as the first variable in the step 1. In the step 1, t-statistic values for other objective factors except SPL (dBA) in Range1 can be a tip when the second explanatory variable is selected. By the recalculated t-statistic, center frequency was selected as the second variable in the step 2. After adding center frequency as a variable, R^2 was increased and RMSE was decreased. It means the index is improved. In the step 3, energy ratio was selected as the third variable. R^2 and RMSE were also increased and decreased respectively. In the step 4, SPL of background noise in range 4 was selected as the fourth variable. This process calls the forward selection. Additionally, based on the information given from the stepwise regression steps and the correlation between objective

Table 3 – T-statistic and p-value according to the objective metric in each step for the regression analysis and selected variables. Bold numbers indicate statistical values of selected variables in each step. Here, N is loudness, R roughness, BG background, R^2 coefficient of determination, and RMSE root mean square error.

		t-statistic / p-value						
		Step 0	Step 1	Step 2	Step 3	Step 4	Extra 1	Extra 2
Range 3 (500 Hz ~ 2 kHz)	SPL (dB)	15.58 / 0.000	-5.84 / 0.000	-2.19 / 0.030	-1.60 / 0.110	-0.37 / 0.711	5.54 / 0.000	-0.68 / 0.499
	SPL (dBA)	19.73 / 0.000	**19.73 / 0.000**	**25.30 / 0.000**	**12.51 / 0.000**	**6.17 / 0.000**	6.17 / 0.000	0.12 / 0.907
	N (sone)	19.16 / 0.000	1.82 / 0.070	-1.52 / 0.130	2.24 / 0.020	2.55 / 0.012	6.77 / 0.000	**6.77 / 0.000**
	R (asper)	17.59 / 0.000	3.22 / 0.002	-2.96 / 0.004	0.55 / 0.585	-2.12 / 0.036	3.47 / 0.001	-3.43 / 0.001
Range 4 (noisy component)	SPL (dB)	7.79 / 0.000	-3.63 / 0.000	9.50 / 0.000	5.50 / 0.000	0.32 / 0.750	1.23 / 0.221	0.96 / 0.340
	Peak-level difference	14.40 / 0.000	5.87 / 0.000	8.25 / 0.000	1.19 / 0.236	2.03 / 0.043	2.46 / 0.015	2.19 / 0.023
	Energy ratio	18.03 / 0.000	7.05 / 0.000	11.01 / 0.000	**11.01 / 0.000**	**13.42 / 0.000**	**26.04 / 0.000**	**17.24 / 0.000**
	SPL (dB) of BG	4.25 / 0.000	-5.20 / 0.000	1.06 / 0.029	6.16 / 0.000	**6.16 / 0.000**	**12.51 / 0.000**	**6.51 / 0.000**
Center freq. (Hz)		4.67 / 0.000	10.78 / 0.000	**10.78 / 0.000**	**14.38 / 0.000**	**15.68 / 0.000**	**19.13 / 0.000**	**14.75 / 0.000**
R^2			0.664	0.789	0.870	0.891	0.870	0.89
RMSE			7.577	6.019	4.74	4.34	4.74	4.27

factors, two extra regressions were also performed.

Based on the result of the regression analysis, this study obtained an annoyance index as using four objective factors: energy ratio, partial loudness for Range1, SPL of background noise for Range2, and center frequency as follows.

$$Annoyance\ Index = (C_1 \times Energy\ ratio) + (C_2 \times PN_3) + (C_3 \times SPL_{BG4}) + (C_4 \times Freq.) \quad (1)$$

where PN_3 is a partial loudness for range 3, SPL_{BG4} a SPL (dB) of background noise for range 4, *Freq.* a center frequency, and C_i coefficients of selected objective factors. Figure 9 shows the regression result comparing between estimated value by the annoyance index and the merged subjective data.

5. CONCLUSIONS

The purpose of this study was to grasp the effects of the variation of noise components of tire-pattern noise on car interior sound quality. To this end, five tire-pattern noises were used. As a result, following results were obtained.

1) On the frequency domain, tonal and narrow band components could be candidates for noisy component in a tire-pattern noise. Subjective experiments which indicated aurally relevant noisy components among the candidates were conducted by professional tests. After comparing the results of the subjective experiment with physical features of noisy component, the energy ratio was an important factor for featuring a noisy component from its candidates as well as the peak-level difference.

2) The degree of annoyance when a single noisy component in a tire-pattern noise exist was evaluated by subjective experiments employing ME method. For this test, each noisy component was modified its peak level and half-power bandwidth and the component was shifted to the high or low frequency side on the frequency domain. As a whole, a test sound having a higher peak level, a wider half-power bandwidth, and a center frequency at the higher frequency side was more annoying.

3) Stepwise regression analysis was employed to propose an annoyance index for evaluating and predicting the annoyance caused by individual noisy component and then four main variables were

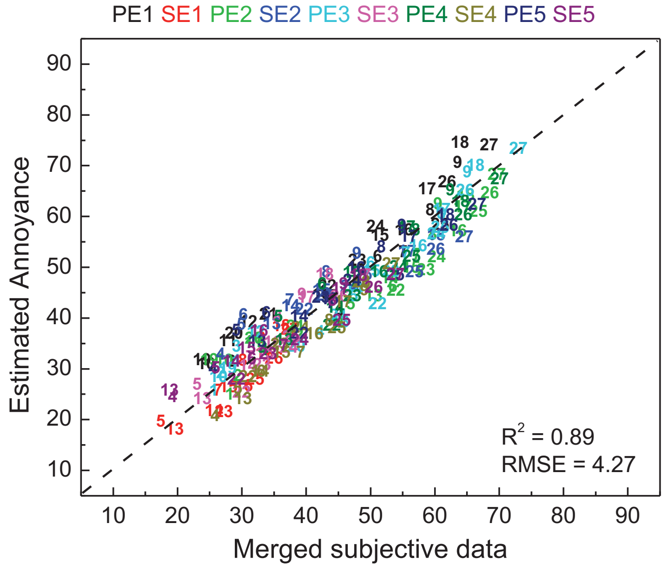

Figure 9 – Comparisons of the estimated value by the proposed annoyance index with the merged subjective data. Dashed line is a 45°.

selected: a partial loudness between 500 Hz and 2 kHz, an energy ratio of an noisy component for background noise in frequency range where the noisy component exists, SPL (dB) of background noise at the same range, and center frequency of the noisy component.

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