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Subjective Evaluation for Electric Brake Booster Sounds

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ABSTRACT

In order to investigate how the electric brake booster sound is evaluated, we conducted subjective evaluation experiments and confirmed the correlation between the subjective impression and the physical measures. We used the time-varying sounds that occur when stepping on the brakes of automobiles. The magnitude of the sound had a big influence on the impression of the brake sound. However, when there was no big difference in the magnitude of the sound, it was found that factors other than loudness were affected.

Keywords: Subjective evaluation, Loudness, Electric brake booster
I-INCE Classification of Subject Number: 63

1. INTRODUCTION

In recent years, quietness in the vehicle compartment has been greatly improved. Various sounds generated in the passenger compartment are required not only to have a low sound pressure level but also to have a sound quality that the occupant does not feel uncomfortable with.

Electric brake booster sounds generated when stepping on a brake of a car is also required to be "unpleasant" in a quiet vehicle compartment. Electric brake booster is located close to the driver (Fig.1), and consideration to sound is necessary. It is useful if it is possible to estimate the subjective evaluation for the operation sound at the design phase.

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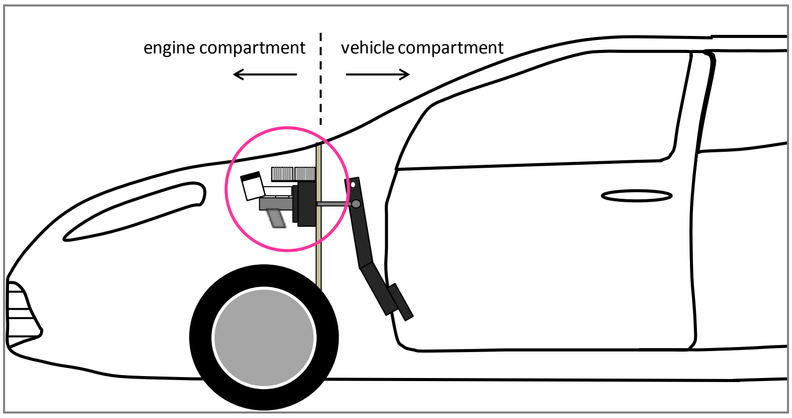


Figure 1.- Position of electric brake booster

We have conducted auditory tests[1] of time-varying sounds such as one-shot vehicle door locking sounds[2]. Therefore, in order to clarify how people evaluate the electric brake booster sound which is longer than one-shot sounds, we conducted a subjective evaluation experiment and physical analysis on the sound.

As preparation for the experiment and analysis described in this paper, we conducted small subjective evaluation experiments and physical analyzes on a small number of sounds. The evaluation word frequently used in the evaluation of brake booster sound is "unpleasant". For that reason, we investigated the physical quantity that affects the "unpleasant" brake booster sound. As a result, "gravity center frequencies" and "pitch change" came up as physical quantities that may be related to evaluation. The experiments and analyzes described in this paper were carried out based on this information.

2. EVALUATION SOUNDS

10 kinds of brake booster sounds of different models and mechanisms were recorded in the laboratory. The brake booster sound was generated by a person stepping on the brake in the cabin while the car was stopped. The microphones were placed in the driver's ear position.

For experiments and analysis, we used 20 sounds, including recorded sounds and these edited sounds.

1. Recorded Electric brake booster sounds of different models and mechanisms
   : A, B, C, D, E, F, G, H, I, J (10sounds)
2. Sounds edited non-steady-state sounds loudness (5sounds)
   : A_N-max , B_N-max ... Edited loudness to almost the same value as D
   C_N-min, D_N-min, E_N-min ... Edited loudness to almost the same value as A
3. Sounds edited features of brake booster sounds (5sounds)
   :A_Pitch_Down, A_Pitch_Up, C_Pitch_Reduce ... Edited pitch change
   I_ball+10dB, I_ball-10dB ... Edited sound of ball screw

3. SUBJECTIVE EVALUATION EXPERIMENT

Subjective evaluation experiment by SD method using 20 evaluation sounds was carried out in semi-anechoic chamber. 10 kinds of evaluation words were selected based on the characteristics of brake booster sound acquired from questionnaire results of 6 brake developers. The list of evaluation words is shown in Table1. There were 12 participants (4 brake developers and 8 experts in sound and vibration). The 20 kinds of brake booster sounds were played in random order by using headphones, and were evaluated in seven stages on 10 kinds of adjective pairs. Experiments were conducted 3 times per participant. The sound was played repeatedly for 35 seconds which is the evaluation time of one sound so that the participant can listen many times.

Prior to the experiment, participants listened to the brake booster sound, practiced evaluation using 10 kinds of evaluation sounds and 10 evaluation words. The participants received explanation that "the evaluation sound is the sound when stepping on the brake before starting the engine". Because the time-varying brake booster sound could be difficult to evaluate, participants orally explained the meaning of the evaluation word. Especially "with high-pitched sound – without high-pitched sound" and "High - Low" was explained using evaluation sound.

The profile which is the result of the SD method is shown in Fig.2.

Table 1.- Evaluation words

unpleasant	⇔	pleasant
insecure	⇔	secure
loud	⇔	soft
cheap	⇔	high-grade
with shock at the beginning of movement	⇔	without shock at the beginning of movement
with magnitude of sound change	⇔	without magnitude of sound change
with pitch change	⇔	without pitch change
rough	⇔	smooth
with high-pitched sound	⇔	without high-pitched sound
high	⇔	low

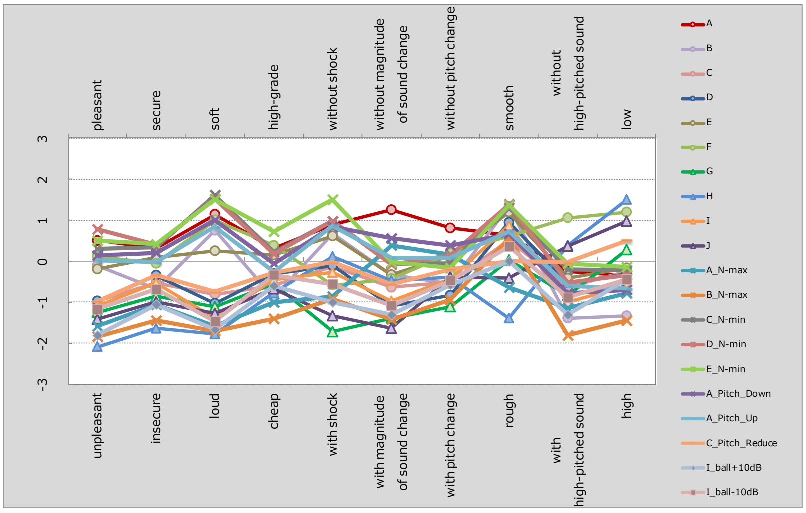


Figure 2.- Result of the SD method

4. PHYSICAL ANALYSYS

We confirmed the physical characteristics by physical analysis of the sound. Representatively, the color map of the A-weighted sound pressure levels is shown in Fig.3.

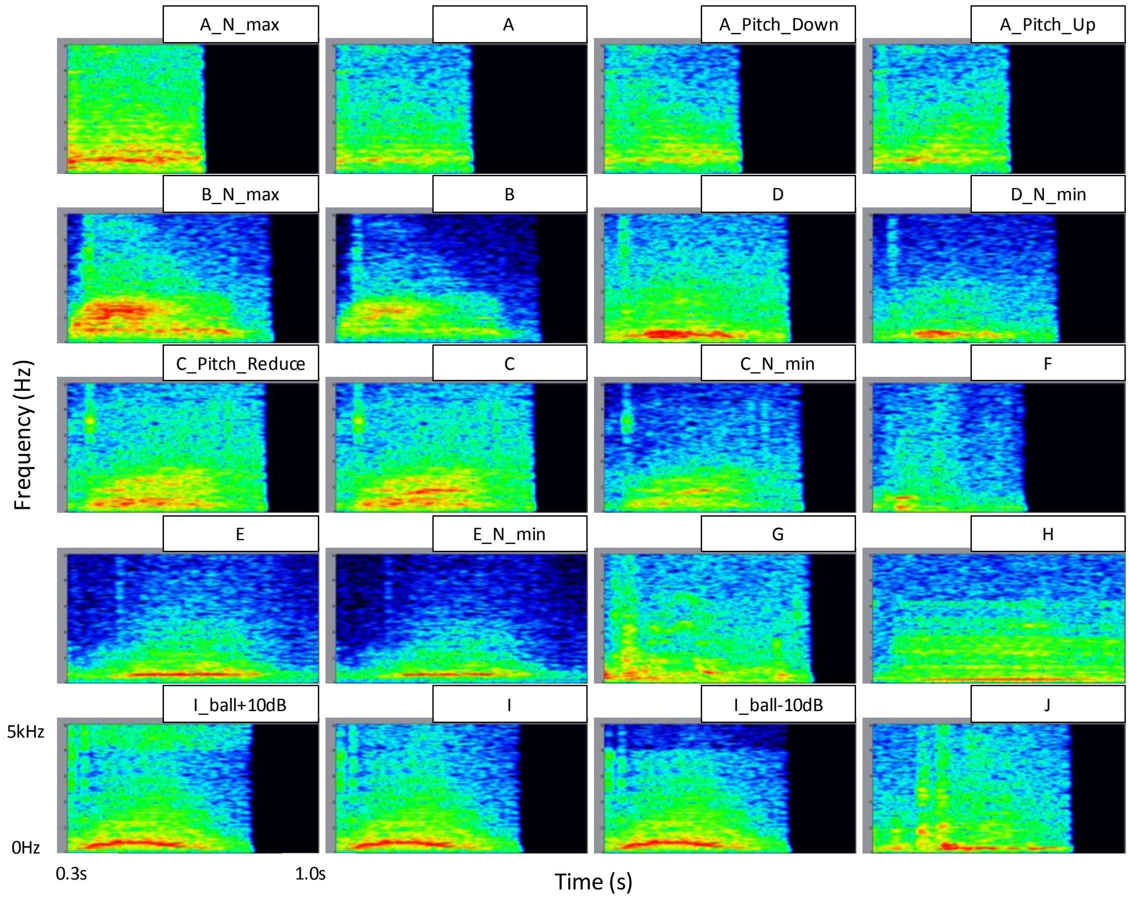


Figure 3.- Color map of the A-weighted sound pressure levels

5. CORRELATION BETWEEN SUBJECTIVE EVALUATION AND PHYSICAL QUANTITY

We calculated the correlation coefficient between subjective evaluation and various physical analysis results. Representatively, the correlation coefficient between the A-weighted sound pressure level and the subjective evaluation is shown in Fig.4.

	unpleasant	secure	soft	high-grade	without shock	without magnitude of sound change	without pitch change	smooth	without high-pitched sound	low
POA[0～1kHz]	-0.647	-0.443	-0.752	-0.339	-0.482	-0.615	-0.503	-0.251	-0.304	-0.039
POA[0～2kHz]	-0.701	-0.538	-0.793	-0.482	-0.503	-0.658	-0.592	-0.228	-0.441	-0.167
POA[1k～10kHz]	-0.709	-0.746	-0.668	-0.910	-0.477	-0.322	-0.473	-0.440	-0.608	-0.373
POA[2k～10kHz]	-0.786	-0.673	-0.794	-0.659	-0.733	-0.311	-0.260	-0.777	-0.248	0.072
OVERALL[0～10kHz]	-0.705	-0.541	-0.797	-0.486	-0.507	-0.656	-0.589	-0.235	-0.442	-0.167
Gravity Center Frequency [0～18.75kHz]	0.106	-0.047	0.178	-0.373	0.135	0.348	0.099	0.143	-0.489	-0.616
Gravity Center Frequency [0～10kHz]	0.111	-0.042	0.182	-0.370	0.141	0.348	0.100	0.153	-0.493	-0.623

Figure 4.- Correlation coefficient between the A-weighted sound pressure level and the subjective evaluation

When the overall sound pressure level was low, the sound was evaluated as "unpleasant". In addition, when the sound pressure level from 1 k to 10 kHz is low, the sound was judged to be "high-grade".

Subsequently, the correlation coefficient between the Non-steady-state Sounds loudness and the subjective evaluation is shown in Fig.5.

	unpleasant	secure	soft	high-grade	without shock	without magnitude of sound change	without pitch change	smooth	without high-pitched sound	low
Loudness	-0.937	-0.806	-0.954	-0.686	-0.689	-0.632	-0.616	-0.691	-0.232	0.172
Percentile Loudness(5%)	-0.858	-0.697	-0.918	-0.654	-0.706	-0.658	-0.598	-0.494	-0.349	-0.026
Percentile Loudness(10%)	-0.883	-0.721	-0.938	-0.675	-0.720	-0.638	-0.565	-0.544	-0.359	-0.027
Loudness Level	-0.915	-0.771	-0.943	-0.673	-0.671	-0.628	-0.613	-0.648	-0.272	0.124
[Trend]Peak	-0.833	-0.666	-0.901	-0.608	-0.699	-0.676	-0.600	-0.461	-0.322	-0.006
[Trend]Peak Time	-0.082	0.024	-0.063	0.232	0.342	-0.105	-0.032	-0.022	0.241	0.284
Sharpness	-0.665	-0.617	-0.554	-0.463	-0.363	-0.339	-0.378	-0.653	-0.012	0.348
45Hz	-0.586	-0.549	-0.568	-0.334	-0.626	-0.521	-0.492	-0.641	0.352	0.666
125Hz	-0.691	-0.664	-0.648	-0.385	-0.495	-0.458	-0.385	-0.813	0.341	0.701
224Hz	-0.657	-0.493	-0.727	-0.318	-0.638	-0.782	-0.589	-0.411	0.075	0.385
315Hz	-0.292	-0.087	-0.394	0.043	-0.168	-0.523	-0.428	0.123	-0.170	-0.009
400Hz	-0.427	-0.227	-0.542	-0.155	-0.276	-0.530	-0.507	0.055	-0.413	-0.204
500Hz	-0.599	-0.501	-0.656	-0.659	-0.423	-0.253	-0.390	-0.198	-0.740	-0.566
630Hz	-0.701	-0.647	-0.700	-0.699	-0.417	-0.021	-0.137	-0.634	-0.462	-0.246
800Hz	-0.520	-0.414	-0.515	-0.599	-0.328	-0.151	-0.285	-0.308	-0.455	-0.309
1000Hz	-0.638	-0.637	-0.594	-0.798	-0.409	-0.220	-0.375	-0.440	-0.495	-0.297
1250Hz	-0.667	-0.711	-0.613	-0.821	-0.326	-0.313	-0.478	-0.384	-0.502	-0.286
1600Hz	-0.729	-0.753	-0.674	-0.818	-0.374	-0.265	-0.444	-0.534	-0.408	-0.159
2000Hz	-0.833	-0.780	-0.827	-0.792	-0.605	-0.268	-0.341	-0.799	-0.283	0.032
2500Hz	-0.808	-0.738	-0.805	-0.721	-0.679	-0.321	-0.380	-0.810	-0.216	0.124
3150Hz	-0.731	-0.639	-0.729	-0.663	-0.596	-0.189	-0.279	-0.769	-0.185	0.104
4000Hz	-0.658	-0.491	-0.660	-0.474	-0.628	-0.273	-0.186	-0.635	-0.168	0.097
5000Hz	-0.627	-0.513	-0.602	-0.451	-0.588	-0.203	-0.159	-0.620	-0.227	0.053
6300Hz	-0.724	-0.621	-0.697	-0.486	-0.677	-0.400	-0.351	-0.665	-0.175	0.190
8000Hz	-0.702	-0.600	-0.671	-0.414	-0.714	-0.430	-0.301	-0.695	-0.054	0.313
10000Hz	-0.706	-0.625	-0.664	-0.481	-0.674	-0.365	-0.237	-0.738	-0.071	0.276
12500Hz	-0.637	-0.579	-0.568	-0.392	-0.579	-0.355	-0.267	-0.723	-0.021	0.343

Figure 5.- Correlation coefficient between the Non-steady-state Sounds loudness and the subjective evaluation

It was evaluated that "sound with small loudness is not pleasant" in all frequencies.

Since the magnitude of the sound has a high correlation with the loudness, it is considered that the subjective evaluation is strongly influenced. However, due to the large influence of loudness, there is a possibility that other evaluation criteria became difficult to confirm.

We compared the evaluation results of the larger and smaller loudness sound, and tried to extract the evaluation criteria other than the magnitude of sound (Fig.6)

[sound with larger loudness]

	unpleasant	secure	soft	high-grade	without shock	without magnitude of sound change	without pitch change	smooth	without high-pitched sound	low
POA[0～1kHz]	0.213	0.354	-0.195	0.348	0.141	-0.187	-0.014	0.556	-0.378	-0.477
POA[0～2kHz]	0.083	0.203	-0.304	0.071	0.113	-0.249	-0.125	0.636	-0.577	-0.679
POA[1k～10kHz]	-0.402	-0.448	-0.252	-0.827	-0.050	0.154	0.007	-0.022	-0.472	-0.478
POA[2k～10kHz]	-0.384	-0.312	-0.259	-0.347	-0.523	0.354	0.463	-0.522	-0.112	-0.004
OVERALL[0～10kHz]	0.081	0.201	-0.308	0.067	0.106	-0.243	-0.119	0.632	-0.581	-0.682
Gravity Center Frequency [0～18.75kHz]	-0.156	-0.220	-0.026	-0.723	-0.104	0.240	-0.023	0.133	-0.564	-0.594
Gravity Center Frequency [0～10kHz]	-0.149	-0.212	-0.025	-0.719	-0.097	0.237	-0.022	0.146	-0.569	-0.603

[sound with smaller loudness]

	unpleasant	secure	soft	high-grade	without shock	without magnitude of sound change	without pitch change	smooth	without high-pitched sound	low
POA[0～1kHz]	0.746	0.637	0.650	0.526	0.615	-0.071	-0.066	0.507	0.036	0.034
POA[0～2kHz]	0.523	0.255	0.431	0.128	0.697	-0.202	-0.403	0.731	-0.341	-0.330
POA[1k～10kHz]	-0.669	-0.670	-0.647	-0.873	0.075	0.193	-0.202	-0.105	-0.760	-0.773
POA[2k～10kHz]	-0.305	0.008	-0.488	-0.207	-0.181	0.640	0.680	-0.835	-0.094	-0.120
OVERALL[0～10kHz]	0.526	0.264	0.425	0.128	0.706	-0.181	-0.386	0.716	-0.349	-0.339
Gravity Center Frequency [0～18.75kHz]	-0.699	-0.652	-0.674	-0.815	-0.029	0.254	-0.097	-0.231	-0.660	-0.674
Gravity Center Frequency [0～10kHz]	-0.699	-0.654	-0.673	-0.818	-0.025	0.250	-0.104	-0.224	-0.665	-0.678

Figure 6.- Comparison of evaluation results of sound with larger and smaller loudness sound

The correlation between "gravity center frequencies" and "unpleasant" of sound with smaller loudness was rather high.

[For all sounds]
The sound with smaller loudness was a positive evaluation such as "pleasant", "soft" and "secure"

[For sounds with similar loudness]
A comprehensive evaluation word such as "pleasant" was evaluated positively as the "gravity center frequencies" was lower.

6. MULTIVARIATE ANALYSIS (FACTOR ANALYSIS)

In order to confirm the evaluation criteria other than the magnitude of sound, we conducted a factor analysis (main factor method, Varimax rotation) on the auditory test results. The result of factor analysis is shown in Fig.7. There were three factors with an eigenvalue of 1.0 or more. Based on the meaning of the evaluation words and the correlation with the physical quantity, each factor can be explained as follows.

Factor 1: Comprehensive evaluation including "unpleasant"
Factor 2: time-varying of sound
Factor 3: Frequency balance of sound, impression of sound

Since "comprehensive evaluation" of factor 1 also has a load amount of factor 2, it can be said that the "time-varying" also contributes to "comprehensive evaluation".

Based on this result, we confirmed the difference in evaluation by editing and braking mechanism. The main results are shown below.

6.1 Comparison of "Soft" Sound

Subjective evaluation scores of "A", "B" and "F" evaluated as "soft" were compared(Fig.8). "Soft" shows almost the same value for the three models, but there are differences in other evaluation words such as "unpleasant" "secure". According to the results of the factor analysis, the evaluation word with a large factor loading of factor 1, the factor loading of Factor 2 was also large. Therefore, we confirmed the physical quantity considered to be related to Factor 2. "with pitch change – without pitch change" constituting factor 2 was compared with "time variation of peak frequency" and its "change width". Although it is a small sample number, it seems that the "pitch change" may affect the comprehensive evaluation.

6.2 Edited Sound of "A" (Edit "Pitch Change")

The evaluation result of pitch change editing sound of "A" is shown in Fig.9. Although pitch change is small, it is perceived from participants. Moreover, it seems that there is a correlation also with "unpleasant".

6.3 Edited Sound of "C" (Edit "pitch change")

The evaluation result of the sound with the "pitch change" flattened is shown in Fig.10. Although the "pitch change" is recognized, there is no change in "unpleasant" or "loud". As a difference from "A", "**C**" is a sound with larger loudness.

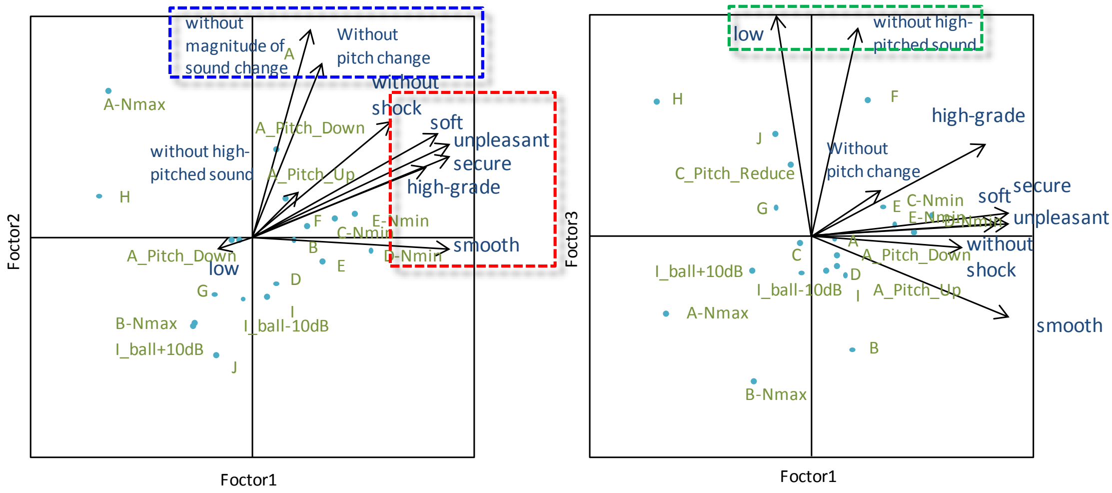


Figure 7.- Result of factor analysis

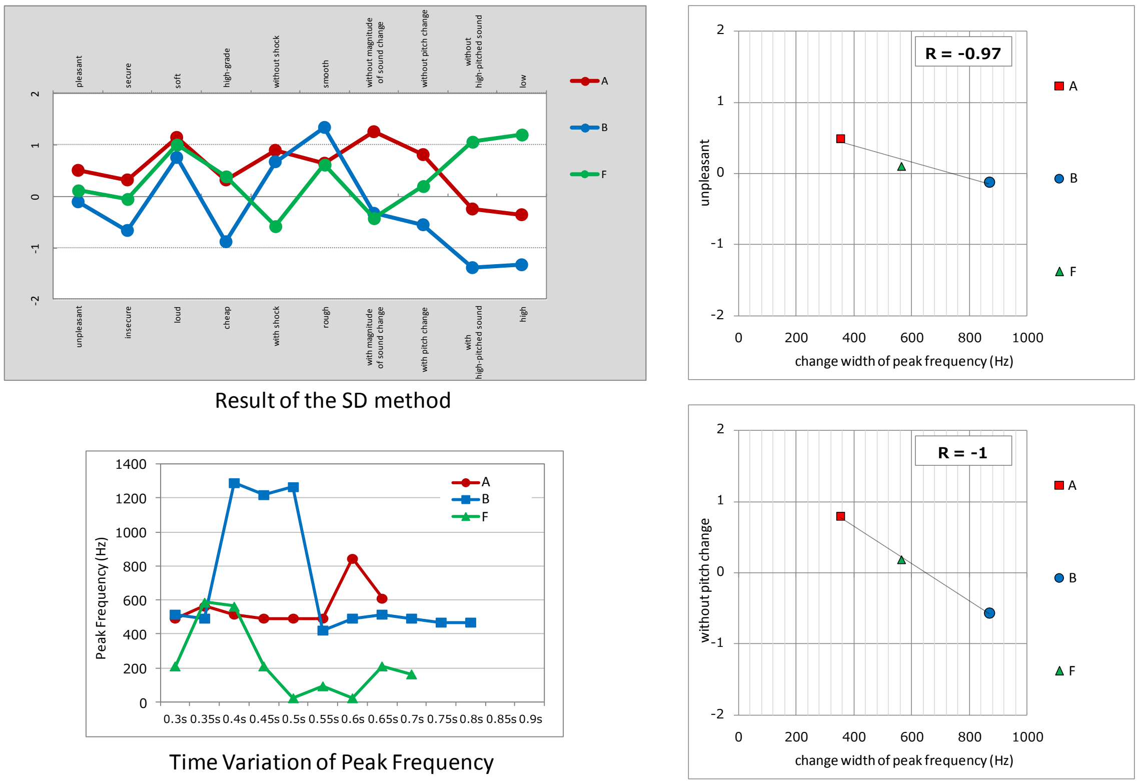
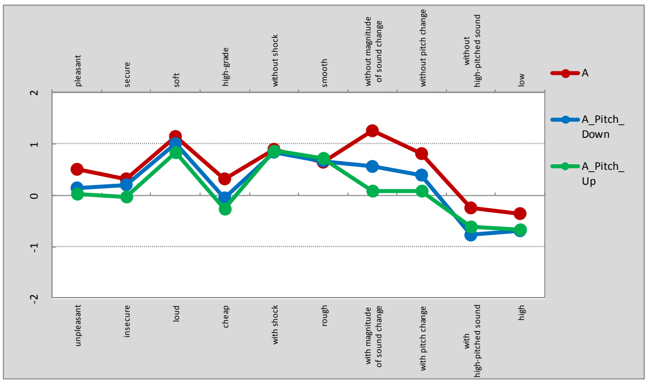
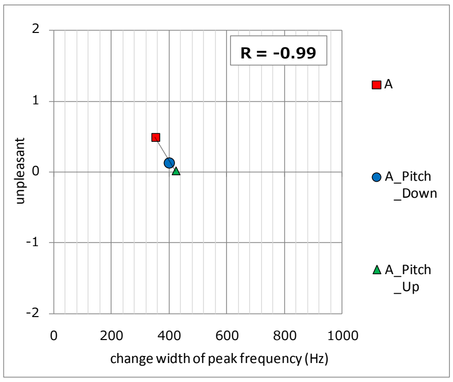
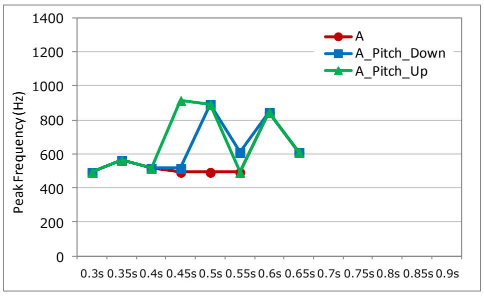


Figure 8.- Comparison of "soft" sound



Result of the SD method





Time Variation of Peak Frequency

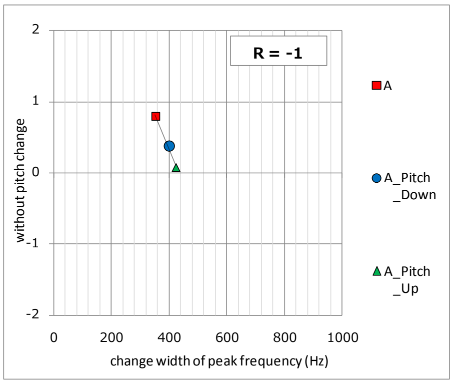
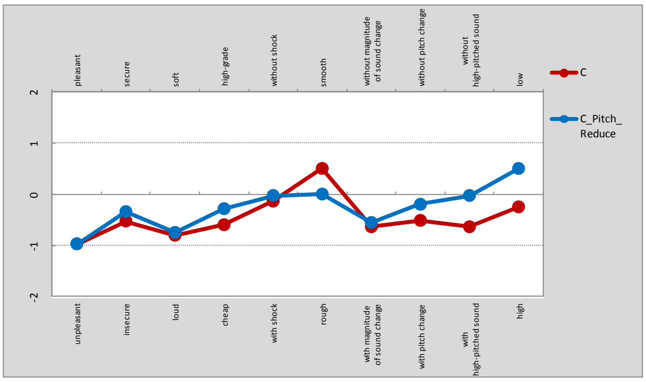
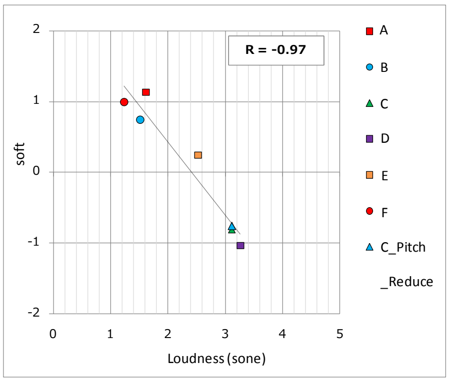
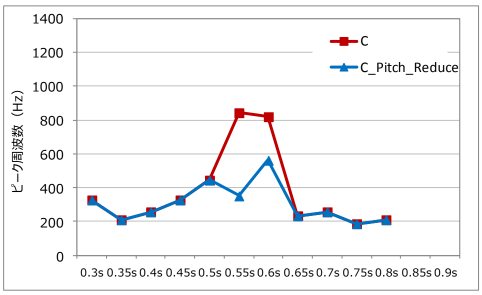


Figure 9.- Comparison of edited sounds of "A"



Result of the SD method





Time Variation of Peak Frequency

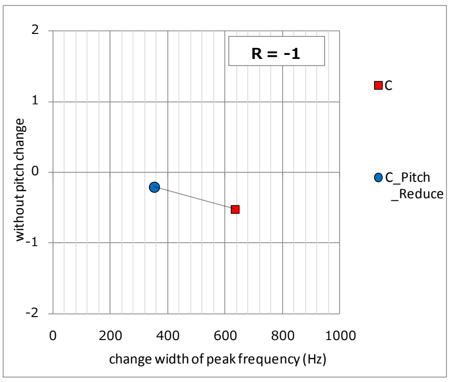


Figure 10.- Comparison of edited sounds of "C"

6.4 Editing the Loudness

The evaluation result of the sounds that edited loudness is shown in Fig.11. As the magnitude of the sound (loudness) changes, the evaluation of factor 1 also changes greatly. Factor 2 and factor 3 also change with the magnitude of the sound, but it is not a change as much as factor 1. It turns out that Factor 1 strongly influences "magnitude of sound".

[Unedited sounds] [Unedited sounds & Edited sounds]

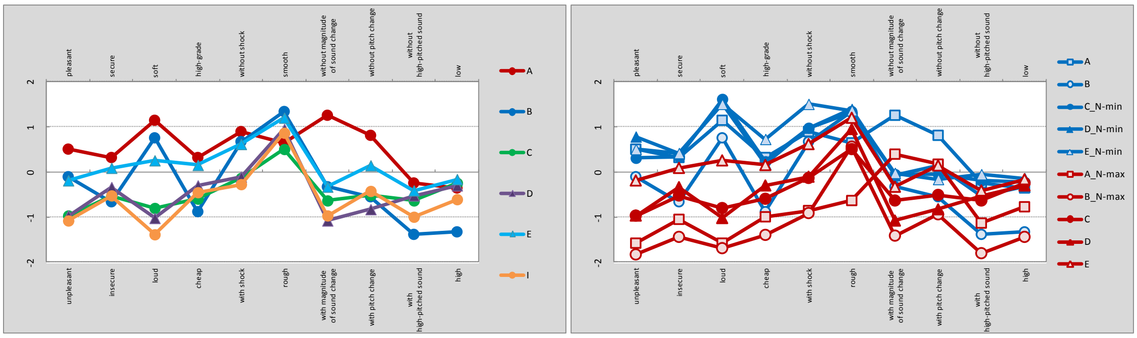


Figure 11.- Evaluation change by editing loudness

6.5 Relationship between physical quantity and "unpleasant"

Based on the results so far, the relationship between "loudness", "change width of peak frequency" and "gravity center frequencies" is shown in Fig.12. Even at the same loudness, there was a difference in "unpleasant". Also, as a result that Factor 2 has an influence on Factor 1, it can be confirmed that the "change width of peak frequency" is correlated with "unpleasant". The correlation with "gravity center frequencies" obtained in preliminary experiments was also high.

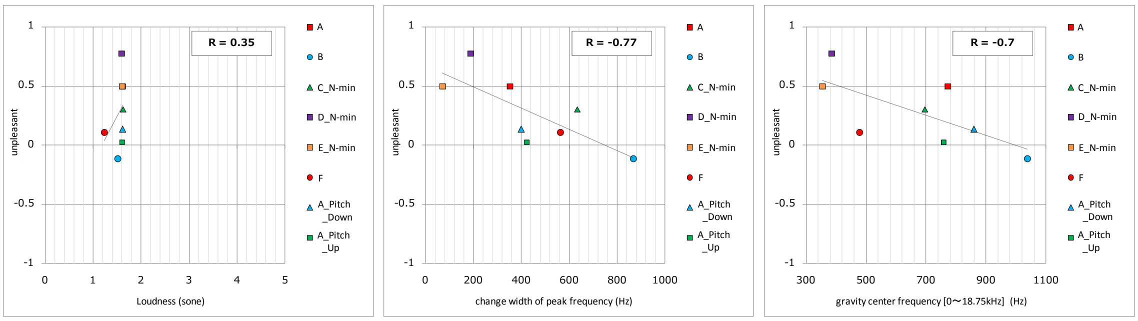


Figure 12.- Correlation between "unpleasant" and physical quantity

[Multivariate analysis Summary]

"Magnitude of sound (loudness)" had a big influence on the comprehensive evaluation (factor 1) including "unpleasant". Also, even with the same loudness, there was a difference in "unpleasant", and "time-varying of sound" was mentioned as an influencing factor.

7. CONCLUSIONS

We confirmed factors affecting the evaluation of brake booster sound by auditory test and factor analysis using various sounds.

The magnitude of the sound had a big influence on the impression of the brake booster sound. If there is no big difference in the magnitude of the sound(loudness), elements other than loudness were affected. "pitch change" and "gravity center frequencies "are examples.

Previously we evaluated the brake booster sound only with the sound pressure level, but it turned out that other physical quantities also affected the evaluation. As a result of predicting the subjective evaluation score by the multiple regression equation using the physical quantity revealed this time, the accuracy was 80% or more[3]. With this technology, it became possible to quantitatively and accurately estimate the subjective evaluation of the electric brake booster sound targeted this time at the design phase.

It is necessary to verify physical quantities other than loudness in the future. We also plan to apply technology to other automotive parts.

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