Proceeding of KSNVE Spring Annual Conference 2001, pp. 19~26.

Sound Quality Study and its Application to Car Interior and Exterior Noise

Takeo Hashimoto
Department of Mechanical Engineering,
Faculty of Engineering, Seikei University
3-3-1 Kichijoji Kitamachi, Musashino-shi,

1. Introduction

There passed almost 15 years since our sound quality studies in Japan related to the emitted noise from the industrial products have been started. The sound under consideration are interior and exterior noise from cars, noise from the electric appliances such as electric shavers, electric cleaners and washing machines and the sound emitted from earth moving machines and etc. After a little while since sound quality studies have been started, the products with better sound are gradually on sale on the market.

Before the era of sound quality treatment, our main countermeasure with the product on noise was focused merely on the reduction of its noise level using absorption, dumping and isolation techniques and etc. In that stage, the noise level itself was too much to endure by the customers. But once the noise level of the products has been reduced to some extent, further treatment for the reduction of noise level sometime does not match its cost even in the case its quality of noise is unbearable. In order to overcome this situation, sound quality treatment has been introduced for better impression of noise emitted from the products because customers buy things with better sound quality even in the case where the initial cost of the product is a little bit higher.

Our definition of the terminology of sound quality is a little bit different from our usual understanding on the one of the three attributes of sound, i.e., loudness, pitch and timbre. The word timbre is sometimes said as a tone quality of sound but the meaning of this word is the difference of the impression of more than two sounds provided that the loudness and the pitch of the sounds are the same with each other. But in case of noise emitted from the industrial products, it is usually impossible to control the loudness and the pitch of sounds emitted from the two different products in the same values. So, in case of sound quality study, our common understanding on the loudness and the pitch of the noise emitted from the products is that each of this two are different from each other for the different product. So our aim for obtaining better impression of sound from the products is usually studied under various loudness and pitch.

2. The number of factors affecting to the sound quality of sounds

In Figs 1 and 2 are plotted the results of two dimensional display of the factor loading obtained by the 40 juries using various sounds from industrial products through semantic differentials (SD method). The 14 adjective pairs used are shown in Table 1. According to Fig.1, the adjective pairs that have large factor loading on the 1st axis are 6.strong---weak, 11.powerful---unsatisfactory and this axis are considered to express the powerfulness of the sound. The adjective pairs that have large factor loading on the 2nd axis are 5.clear---thick, 9.harmonic---

discordant, 10.pleasant---unpleasant, 12.flat•• ---rumbling, 13.cheap---expensive and this axis is considered to express our sensation on the pleasantness of the sound.

The adjective pairs that have large factor loading on the 3rd axis are 4.deep---metallic and 4.booming---ringing metallic factor or a booming sensation of the sound.

These three factors of sound, i.e., powerfulness, pleasantness and metallic or booming factor usually appear in any case when we use different sound group and different juries. We can conclude that in case of product sound quality, these three factors, i.e., powerfulness, pleasantness and metallic or booming factor are important for the better impression of sound.

Table 1 Adjective pairs used at SD experiment

1	soft	---	hard
2	distinct	---	dull
3	clamorous	---	quiet
4	deep	---	metallic
5	clear	---	thick
6	strong	---	weak
7	booming	---	ringing
8	calm	---	shrill
9	harmonic	---	discordant
10	pleasant	---	unpleasant
11	powerful	---	unsatisfactory
12	flat	---	rumbling
13	cheap	---	expensive
14	smooth	---	harsh

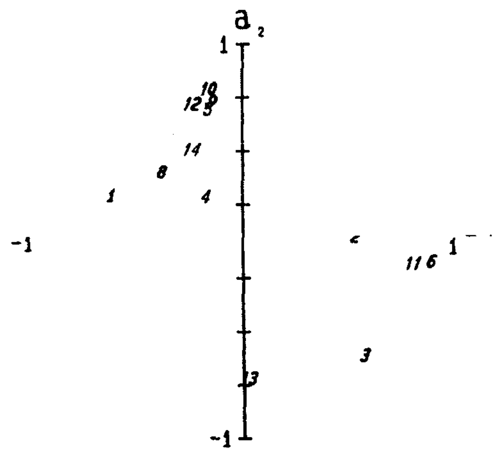

Fig.1••factor loadings (1st and 2nd factors)

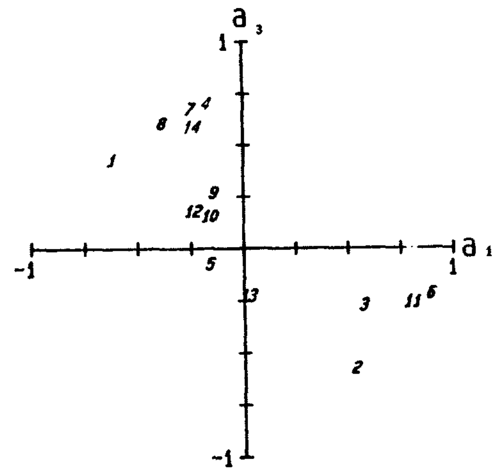

Fig.2 factor loadings (1st and 3rd factors)

3. Quantification of sound quality attributes

As in the previous chapter, three factors. i.e., a power factor, a pleasant factor and a booming factor can be considered as representative sound quality attributes. For an engineering purpose, it is convenient if these three can be quantified using psycho-acoustical parameters for the further sound quality design of the products. Here the desirable parameters that represent three attributes are discussed.

The quantitative psycho-acoustical parameters that represent the power factor

are A weighted sound pressure level and loudness level defined as ISO532B and the relation between subjective impression on the power factor and dBA and loudness level are shown in Figs 3 and 4 respectively.
Fig

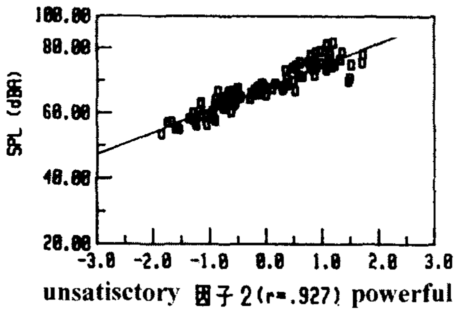

Fig.3 power factor and dBA

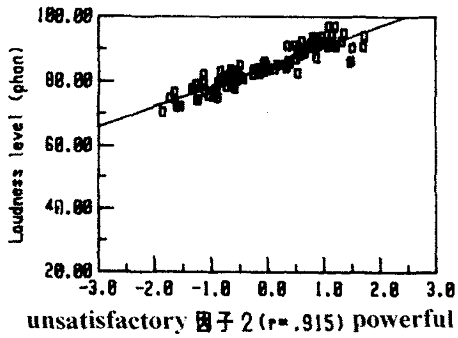

Fig.4 power factor and loudness level

The most important factor that relates to the sound quality treatment of the industrial products is a pleasant factor. The sensation of unpleasantness and pleasantness caused by sound is related to various factors, i.e., the envelope fluctuation of sound signal, strength of high frequency contents of sound and impulsiveness of sound etc.

In the first place relation between the pleasant factor and the time envelope fluctuation of sound is discussed. Unpleasantness caused by envelope fluctuation of sound is related well with the roughness of the sound and this sensation is strongly related with psycho-acoustical parameters called roughness level developed by the authors(1) and roughness(2) for high frequency modulation. The relation between the subjective unpleasantness and roughness level and that with roughness are shown in Figs.5 and 6 respectively.

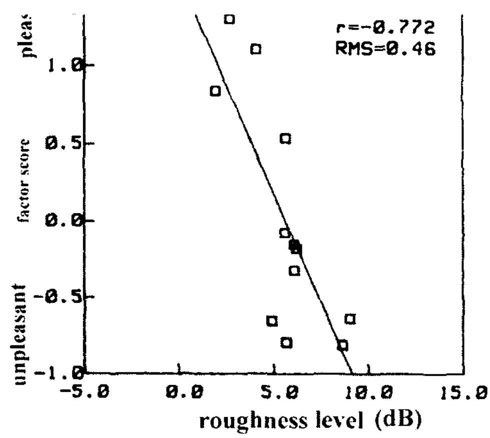

Fig.5 pleasant factor and roughness level

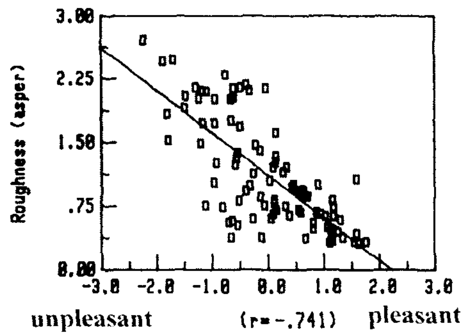

Fig.6 pleasant factor and roughness

As is judged from the figures, the pleasant factor has high correlation coefficients with the roughness level (r=-0.772) and roughness(r=0.741).

For low frequency modulation of sound, our sensation on the pleasant factor is related well with the fluctuation srength(2) and this relation is shown in Fig.7. The correlation coefficient between the pleasant factor and fluctuation strength is r=-0.838 in this case.

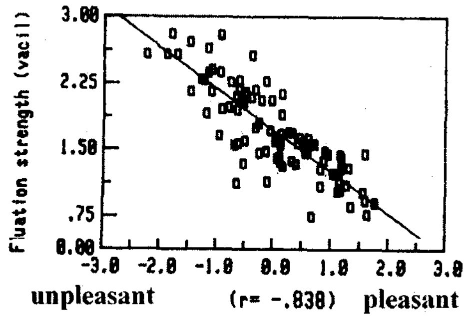

Fig.7 pleasant factor and fluctuation strength

The high frequency contents of sound is also related well with the unpleasantness of sound as the proportion of high frequency contents of sound increases. The relation between the pleasant factor and sharpness of sound(2) is shown in Fig. 8.

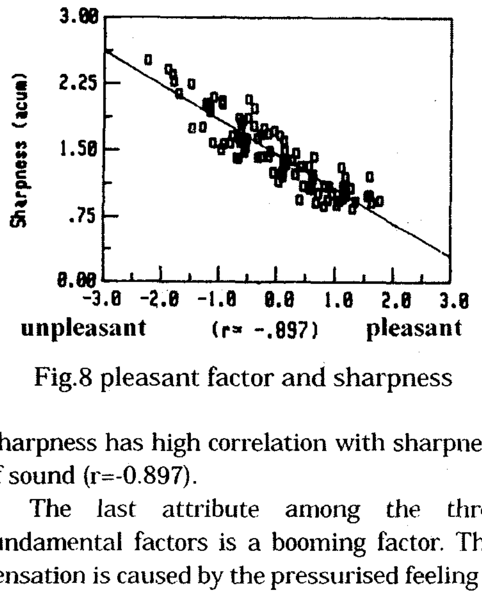

Fig.8 pleasant factor and sharpness

Sharpness has high correlation with sharpness of sound (r=-0.897).

The last attribute among the three fundamental factors is a booming factor. This sensation is caused by the pressurised feeling of ear drums due to the existence of standing wave at the ear position and this sansetion makes subjects feel annoyed. The booming sensation is correlated well with the booming level proposed by Hatano and Hashimoto(3) -(5) and this is shown in Fig.9 for stationary booming noise.

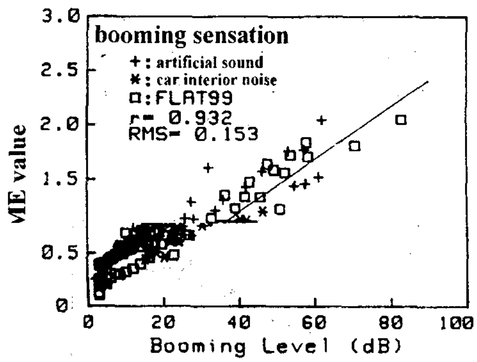

Fig.9 booming sensation and booming level

4. Development of IMPULSE as an metric for impulsiveness

Our sensation on unpleasantness of the sound is also related with the impulsiveness of the sound. This is the case when we hear the noise at idle of a diesel engine truck for example. In order to quantify the sensation caused by the impulsiveness of noise emitted from the diesel powerplant, we have developed the new metric called IMPULSE. This metric is calculated from the absolute noise signal subdivided into short time segment of 200ms. In the first place, rms value of each time segment is calculated. Then, fine time segments that excess the rms value of each 200ms time interval are chosen with their time length. After selecting these fine time segments, the time average value of the selected fine time segments that excess the rms value is calculated in each 200ms time interval. Finally, the IMPULSE is calculated from the average value of the time averages of this value in each 200ms time segment (Fig.10).

The relation between IMPULSE and the subjective evaluation on impulsiveness of the diesel powrplant noise at idle with varying the impulsive frequency contents from 800Hz up to 4kHz in its level ±3dB, ±6dB, ±9dB are shown in Fig.11. The similar figure with the relation in impulsiveness provided by Head Acoustics, GmbH is shown in Fig.12. From Fig.11, a good correlation is found between the subjective evaluation on impulsiveness and IMPULSE proposed by the author. Concerning the impulsiveness proposed by the Head

Acoustics,GmbH, and a good correlation is also found between this metric and subjective evaluation although there exists a little disagreement for one sound (No.11).

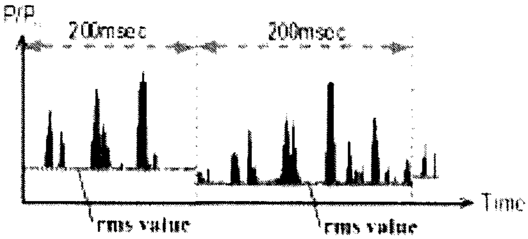

Fig.10 Absolute wave form of impulsive noise signal with 200ms fine time segments

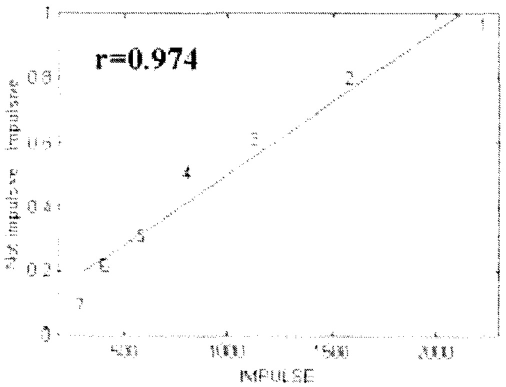

Fig.11 subjective impulsiveness and IMPULSE

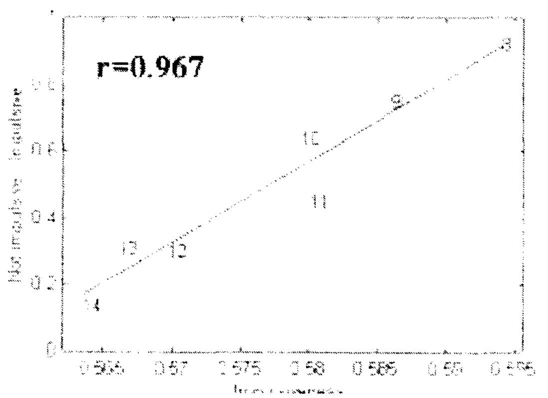

Fig.12 subjective impulsiveness and impulsiveness (Head Acoustics.GmbH)

5. Development of booming index

Concerning the steady state sound, booming sensation is related well with the booming level. But for the tranjent noise at acceleration for example, booming sensation is not correlated well with the booming level. So, booming level must be modified for better correlation. The booming sensation during acceleration is quantified by booming index. The into ten equal time segments in the first place. For each time segment, weighted sensation level on booming (WSL) which is equivalent with booming level is calculated utilizing the weighting function for booming sensation obtained from the subjective evaluation shown in Fig.13 by weighing the 1/3 octave band sensation level (the SPL at the threshold in quiet is extracted from the original 1/3octave band level) and this WSL is weighted by the loudness ratio (L-H)/(L+H) calculated from the partial loudness of the noise below 300Hz [L] and that above 300Hz[H] shown in Fig. 14. After calculating this value for the each subdivision, the booming index is obtained by the power average of this value at each time segment. The relation between the booming level and the subjective evaluation on booming for the car interior noise at acceleration in case of four-cylinder engine is shown in Fig.15 and the similar result with booming index is shown in Fig.16. From these figures, it can be judged that booming index is a better metric for quantifying booming sensation while the vehicle under consideration is in acceleration.

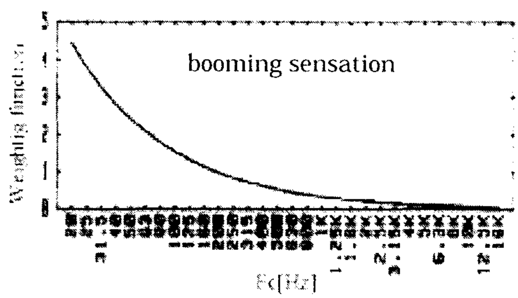

Fig. 13 weighting function for booming level

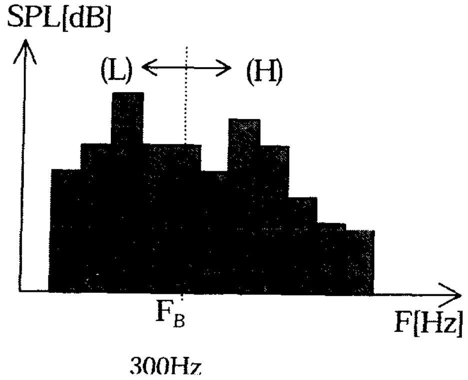

Fig.14 1/3octave band spectrum of the sound and the partial loudnesses below and above 300 Hz

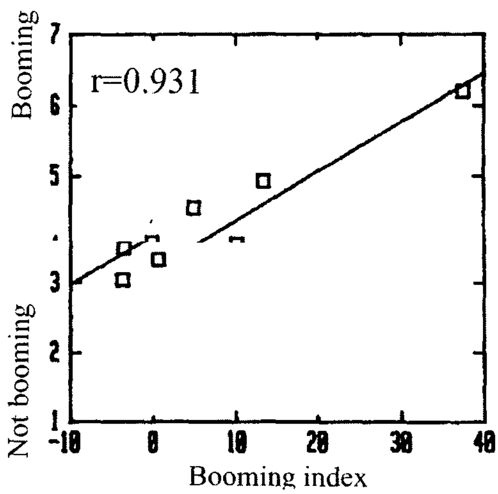

Fig.16 Evaluation on booming sensation and booming index

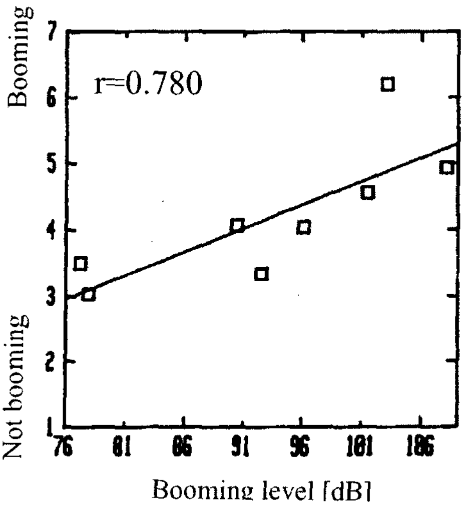

Fig.15 Evaluation on booming sensation and booming level

In order to get good result, the original diesel idle noise was modified its frequency components in low, medium and high frequencies to check the effect of increase and decrease of their level. As a result, the reduction of high frequency components above 2kHz affected most to reduce annoyance (Fig.17). For the practical realization of this effect, an engine compartment enclosure made by compressed felt like material was fixed to the truck body. The effect of the improvement was checked by the pair comparison method and this effect was quantitatively examined using roughness level (Fig.18), roughness (Fig.19), fluctuation strength (Fig.20) and sharpness (Fig.21).

Improvement of exterior noise at idle

In an urban area, in front of a convenience store (a small size super market) sometimes a delivery truck stays without stopping its diesel engine for a while for delivering goods. Especially during night time this causes annoyance to the inhabitants dwelling near by. In order to minimize this negative effect, sound quality of exterior noise of diesel truck at idle was studied.

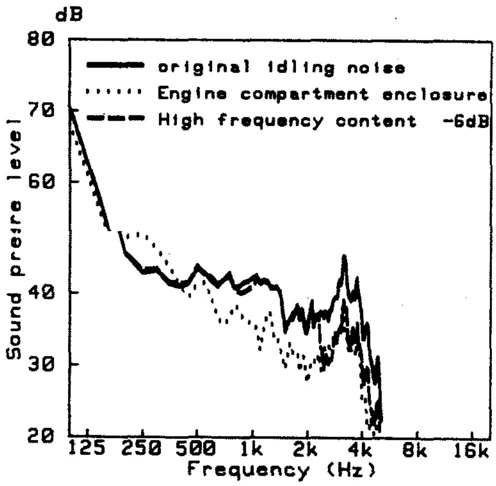

Fig.17 power spectrum of diesel exterior noise at idle

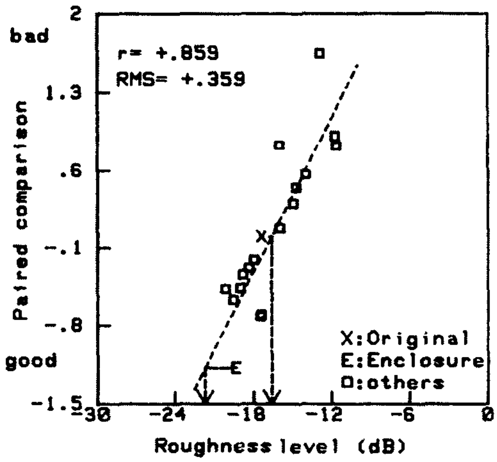

Fig.18 pair comparison and roughness level

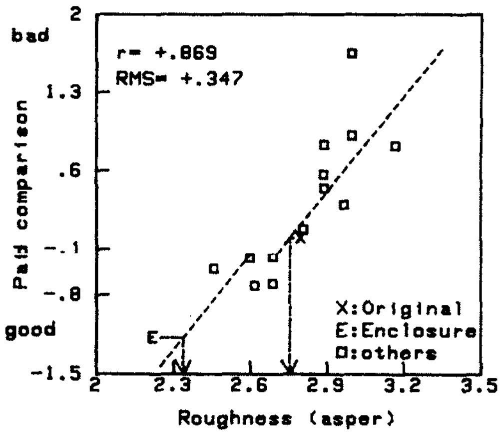

Fig.19 pair comparison and roughness

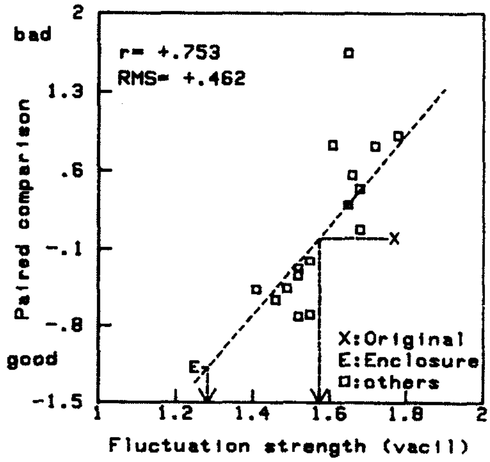

Fig.20 pair comparison and fluctuation strength

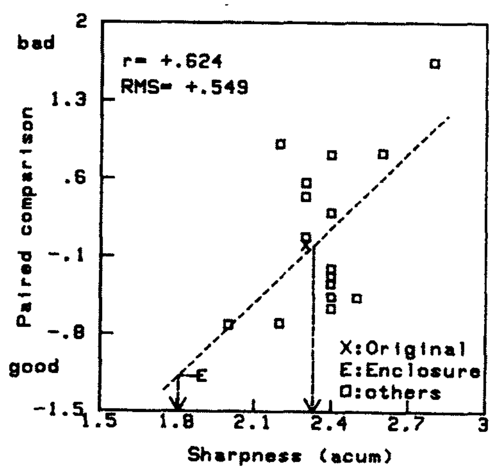

Fig.21 pair comparison and sharpness

7. Conclusions

(1) The numbers of sound quality attributes that have to be considered for improvement are three, i.e., power factor, pleasant factor and booming factor.

(2) Power factor is quantified by dBA and loudness level.

(3) Pleasant factor is quantified by roughness for the envelope fluctuation of sound and by sharpness for high frequency contents of sound.

(4) Booming factor is quantified by booming level for steady state sound.

(5) Booming sensation during acceleration is quantified by booming index that takes the transient variation of time signal into account.

(6) Impulsiveness of the sound is quantified by IMPULSE proposed by the authors and impulsiveness proposed by Head Acoustics, GmbH.

Literature

[1] Hashimoto T., Hatano S., Modification of roughness level for higher correlation with unpleasantness; weighted roughness level due to modulation frequencies, Trans. JSAE Vol.28, No.2, pp.79-84, 1997 (in Japanese with English summary)

[2] Zwicker E., Fastl H., Psychoacoustics: Facts and Models, Second updated edition , Springer 1999

[3] Hatano, S., Hashimoto T.,Evaluaion of booming factor of car interior noise under running condition:evaluation of artificial noise and the location of subjective impression of real car noise. transaction of the Society of Automobile Engineers of Japan, Vol.26, No.3,98-103 (1994) (in Japanese with English summary).

[4] Hatano, S.,Hashimoto, T.,Quantification of booming factor .Transaction of the Society of Automobile Engineers of Japan, Vol.27, No.1,94-97 (1996)(in Japanese with English summary).

[5] Hatano, S.,Hashimoto, T.,Quantification of booming factor , modified measure taking the effects of specrum pattern and the loudness of the sound into consideration,Transaction of the Society of Automobile Engineers of Japan, Vol.27, No.2,85-89 (1997)(in Japanese with English summary).

[6] Hashimoto, T., Hatano, S.,Improvement of sound quality of exterior noise at idle of Society of Automobile Engineers of Japan, Vol.27, No.2,80-84 (1997)(in Japanese with English summary).

[7] Hashimoto T., Sound quality approach on vehicle interior and exterior noise: Quantification of frequency related attributes and impulsiveness, Fostschritteder Akustik, DAGA 2000, pp.92-93 (2000)