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Sound Quality Evaluation for the Axle Gear Noise in the vehicle

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.A gear whine sound due to the axle system is one of the most important sound qualities in a sport utility vehicle (SUV). In the previous works about the gear whine sound, it was known that it is difficult to evaluate the gear whine sound objectively by using the only A-weighted sound pressure level because of the masking effect. In this paper, for the objective evaluation of the axle-gear whine sound, the characteristics of the axle-gear whine sound is at the first investigated based on the synthetic sound technology and the new objective evaluation method for the axle-gear whine sound is developed by using the sound metrics, which is the psychoacoustic parameters, and the artificial neural network (ANN) used for the modeling of the correlation between objective evaluation and subjective evaluation. This model is successfully applied the objective evaluation of the axle gear whine sound for real sport utility vehicles and the output of the model are compared with subjective evaluation. The results have a good correlation over 90 per cent.

1 Introduction

There are many different sound qualities inside of a car, such as those of the engine, road, wind, exhaust and other sounds, as shown in Fig. 1 [1-4].

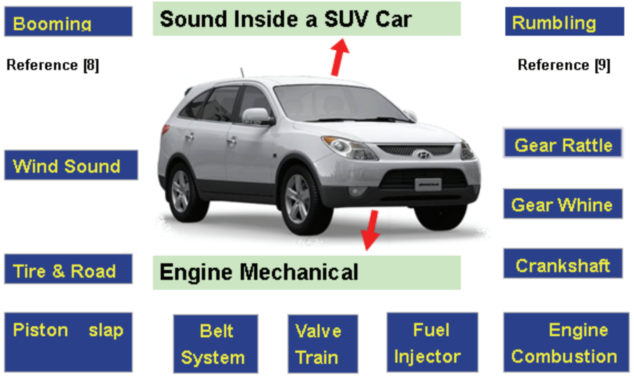


Fig. 1 Sound quality in the compartment of a passenger car.

In particular, the axle-gear whine sound in a sport utility vehicle (SUV) becomes one of the dominant sound sources as the number of SUVs increases worldwide [5]. It is sometimes difficult to evaluate the axle-gear whine sound objectively from the viewpoint of sound quality since it is embedded in the background sounds [6]. In this paper, considering this masking effect, new metric is developed and it is used for the objective evaluation of the axle-gear whine sound. This metric is based on the difference between the background sound and gear order sound. This new metric is called SNR (signal to noise ration) index. In addition, it was found that the loudness is also correlated with the gear-gear whine noise. These two sound metrics are used for the input of the ANN model, which is a tool to identify the correlation between the axle-gear whine index and the subjective evaluation for the axle-gear whine sound of an SUV. The multiple regressions have been used for modeling of sound quality of gear whine noise [7]. Recently, the ANN has been used for the sound quality analysis in automotive engineering [8-9].

2 Artificial Neural Network Theory

The deadline of paper submission is May the 7th. Manuscripts sent via email are not accepted.

The ANN very loosely simulates a biological neural system (there is an extensive literature on ANN [10]); a multi-layer feed-forward network is used throughout this paper. The training algorithm used with this network is back-propagation [11], which is mostly used in the analysis of mechanics problems. The main goal of back-propagation neural networks is the mapping of input, vector $x \in R^N$, into output, vector $y \in R^M$. This can be written in short as

$$x_{N\times 1} \rightarrow y_{M\times 1}\ , \tag{1a}$$

and in general

$$x^{(p)} \rightarrow y^{(p)}\ , \text{ for } p = 1, 2,\ldots,P, \tag{1b}$$

where p is the number of patterns. The mapping is performed by a network composed of processing units (neurons) and connections between them. Input signals x_j are accumulated in the neuron summing block Σ and activated by function F to have only output y_i:

$$y_i = F(z_i), z_i = \sum_{j=1}^{N} w_{ij} x_j + b_i\ , \tag{2}$$

where z_i – active potential, $w_{i,j}$ –weights of connection, b_i – threshold parameter. Among various activation functions, sigmoid functions are commonly used:

$$F(z) = \frac{1}{1+e^{-\mu z}} \in (0,1) \quad \text{for } \mu > 0, \tag{3}$$

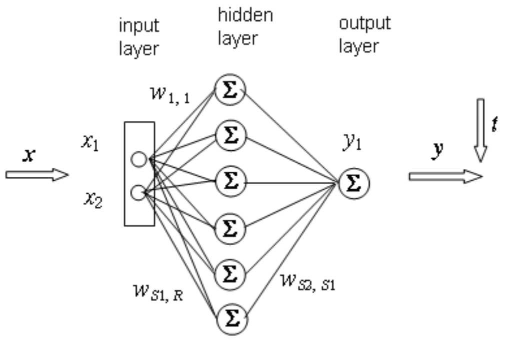


Fig. 2. Structure of artificial neural network for rumbling index: (a) three-layer, back-propagation network

3 Synthetic axle-gear whine sound Page layout

To apply ANN to sound quality analysis, the optimal weights $w_{i,j}$ of connection of neurons in ANN., as shown in Fig. 2(b), should be obtained through a training procedure of ANN. For training of ANN, the various subjective rates for the axle-gear whine sound quality of the interior sounds of SUVs should be selected as the target of ANN. Thus, the mean-square-error for the difference between the subjective rate evaluated by a passenger and the objective rate, which is the output of ANN, should be minimized to obtain the optimal weights of the connections of neurons of ANN. As a result, a large number of interior sounds with the axle-gear sound quality of various subjective rates are required. It is difficult to obtain these kinds of interior sounds from mass-produced passenger cars, however, because most cars do not have a significant axle-gear whine noise problem due to development. Therefore, in this paper, those sounds are synthesized by using the information introduced in the many papers researched for enhancing the axle-gear whine sound quality. Basically, the interior sound of a car consists of very complex frequency spectrum since it has many excitation sources, resonance systems and parts of sound radiation [1-4].

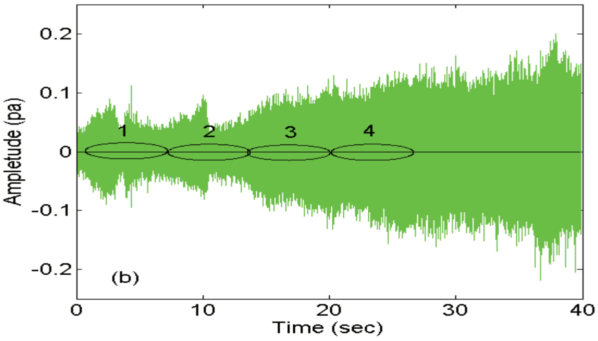
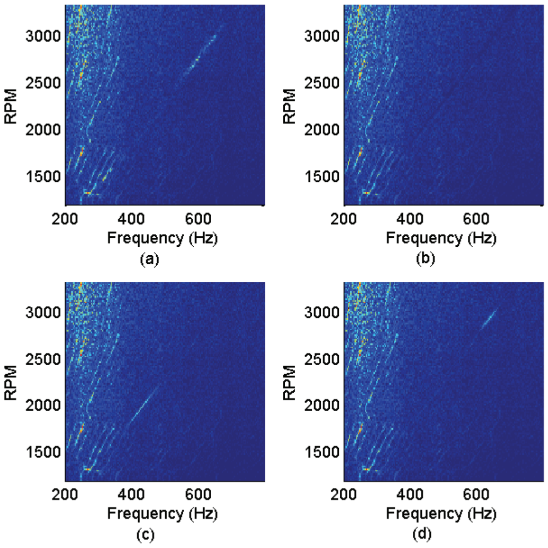


Fig. 3 Time history for the interior sound of a reference SUV car used for the production of the 80 synthetic axle-gear whine sounds: 1, 2, 3 and 4 mean the different speed steps.

However, it is known that the meshing frequency of the gear in the axle system influences the axle-gear whine sound quality [5-7]. Other frequency components play roles of background noise. Fig.3 shows the time history for interior sound and meshing frequency component of the axle-gear. The horizontal axis designates time and the vertical axis shows the sound pressure level inside of the car. The car is accelerated with stationary speed. The speed is divided by four different speed steps.The signal is measured inside a reference SUV used for the production of 80 synthetic axle-gear sounds.



(a)

(b)

(c)

(d)

Fig. 4. Image plot for the interior sound of an SUV car

Fig.4 (a) shows the image plot for STFT (Short Time Fourier Transform) of the interior sound measured inside a reference SUV. The speed of the drive shaft increases from 1000 rpm to 3500rpm. The acceleration duration is 40 seconds. In the figure, the horizontal axis designates the frequency and the vertical axis shows the rpm. From this figure, we can see that the pressure level of the sound at the meshing frequency of the axle-gear is dominant at high frequency and the meshing frequency is related to the rotating speed of the drive shaft (i.e., rpm). At a low frequency, the dominant sounds are due to the engine sound and other background noise [1]. So if we change the amplitude of this meshing frequency component, the axle-gear sound quality for the interior sound of this car will also be influenced. Mathematically, the time history of this component can be expressed as an analytic signal [12] with the amplitude and frequency modulated signal as follows:

$$x(t) = a(t)e^{j\phi(t)} \tag{4}$$

where $a(t)$ is the function associated with amplitude modulation (i.e., it is the envelope of the signal $x(t)$), and $\phi(t)$ is the function associated with frequency modulation. Fig. 5(a) represents the time history of the meshing frequency component sound. It is obtained by filtering the interior sound as shown in Fig. 4(a) with a Kalman order adaptive filter [13]. Fig. 4(b) shows the image plot for STFT of the interior sound obtained by removing the meshing frequency component of the original interior sound. The signal of the sound with only meshing frequency component is expressed as a form of the analytic signal explained in equation (4). The instantaneous frequency for the analytic signal [12] is given by

$$f_i(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt} \tag{5}$$

Therefore, if the speed of the drive shaft is constant with meshing frequency f_0, the function $\phi(t)$ is given by

$$\phi(t) = 2\pi f_0 t \tag{6}$$

If the speed of the drive shaft is changed with the meshing frequency $f_0 + f(t)$, then the function $\phi(t)$ is written by

$$\phi(t) = 2\pi(f_0 t + f(t)) \tag{7}$$

We can produce interior sounds with the axle-gear sound qualities of various subjective rates by modifying the envelope of the signal as shown in Fig. 5(a) and adding it to the background noise as shown in Fig. 4(b) because the background noise influences the axle-gear sound quality. In this paper, the envelope of the analytic signal is modified as follows: (8)

$$\begin{cases} \mathscr{A}(t) = \left[A_j \sin\Omega_k (t - t_i) + A_j + 1\right] \cdot a(t), & t_i - \frac{1}{2\Omega_k} \le t \le t_i + \frac{1}{2\Omega_k}, i = 1,..5, j = 1..4, k = 1..4 \\ \mathscr{A}(t) = 1 \cdot a(t), & \text{otherwise} \end{cases} \tag{8}$$

where $a(t)$ is the envelope of the firing frequency component of the analytic signal; t_i is the i-th time where the amplitude modulation takes place; A_j is the j-th magnitude for presenting the magnitude of amplitude modulation; and Ω_k represents the k-th frequency for determining the duration of amplitude modulations.

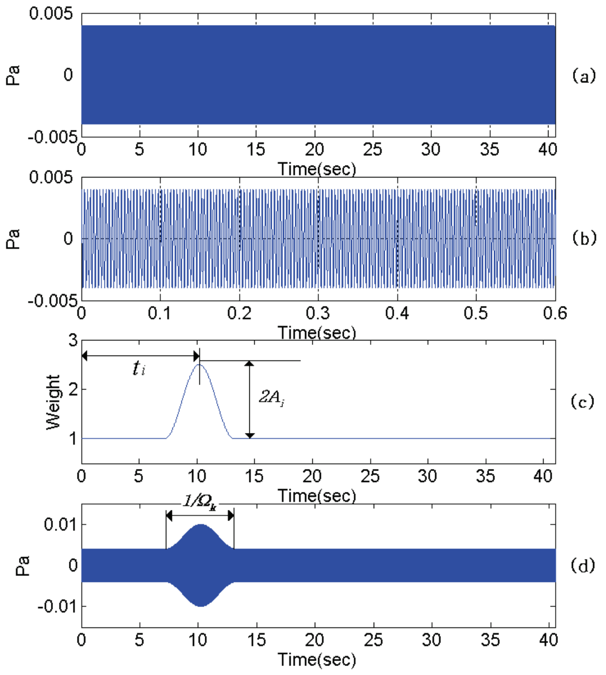


Fig. 5 Modification of meshing frequency component sound for production of the 80 interior sounds

Fig. 5(c) shows one example of the modified envelopes $\mathscr{A}(t)$ and illustrates the roles of the parameters. Fig. 5(d) displays the analytic signal $x(t)$ modified by using the modified envelopes $\mathscr{A}(t)$. The modified analytic signal is given by

$$x(t) = \mathscr{A}(t)\exp(j\phi(t)) \qquad (9)$$

4 Subjective Evaluation

For the target of the ANN, the 80 synthetic interior sounds were subjectively evaluated by 21 NVH engineers (17 males and 4 females). In addition to the synthetic interior sounds, the interior sounds of five mass-produced SUVs were also used. The subjective evaluation therefore consists of a total of 85 interior sounds. A playback system and headphone of Head Acoustics Company were used for the subjective evaluation.

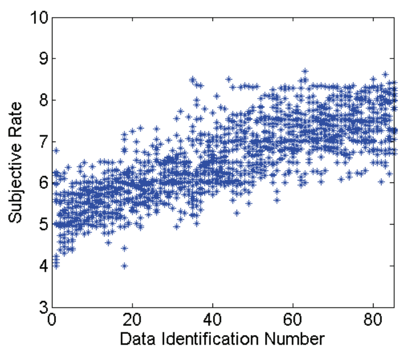


Fig. 6 Subjective rates for the 85 interior sounds of passenger cars

The 85 interior sounds were randomly evaluated; the subjective rate was evaluated for point 4 to point 9. Fig. 6 (a) shows the results of the subjective evaluation for the 85 signals. The averaged subjective rates for 85 synthetic interior sounds are plotted from the left side of the graphic from low rate to high rate.

5 Sound metrics

The sound metrics for the 85 interior sounds were calculated for the input data of ANN. According to psychoacoustic theory [13], there are four major sound metrics: loudness, sharpness, roughness, and fluctuation strength. These metrics have been confirmed by psychoacoustic scientists. Many other sound metrics are developed for application to automotive engineering, such as SNR(signal to noise ratio) tonality, kurtosis and sound pressure (dBA) depending on their application. In this paper, four major sound metrics – loudness, sharpness, and roughness and fluctuation strength and two more extended sound metrics, SNR index and tonality – were calculated.

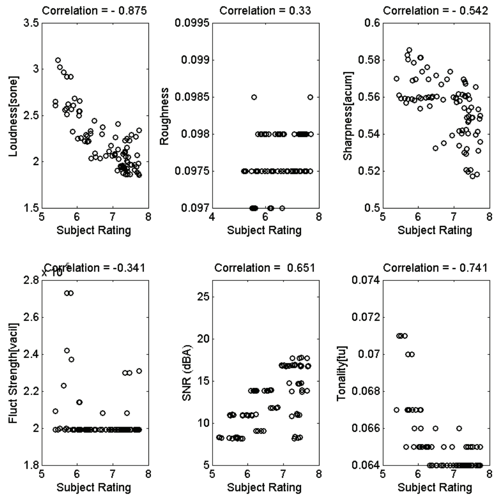


Fig. 7 Sound metric for the 85 interior sounds

These sound metrics for 85 interior sounds are shown in Fig. 7 (a) to Fig.7 (f). Among these metrics, the high correlated metrics with subjective rate are used for the input of the ANN to be used as the axle-gear whine index.

5.1 Loudness

Loudness represents the auditory perception character related to the magnitude of sounds [13]. In this paper, the Zwicker model [13] is used to calculate the loudness for the 85 interior sounds. Loudness is measured in phones or sones; one sone is the loudness for a pure tone sound with amplitude of 40dB at 1kHz. Here, loudness is calculated for 85 interior sounds. In Fig. 7 (a), loudness is plotted versus the subjective rating for 85 interior sounds. According to these results, the maximum loudness is about 3.2 sones. At this level, the average subjective rating is about 5.5. From the graphic, it is concluded that the subjective ratio is proportional to 1/loudness.

5.2 Signal to Noise Ratio (SNR) Index

Signal to noise ratio index is a quantitative measure of the signal with respect to background. Therefore, signal to noise rate is important for the identification of the pure tone sound is embedded background noise (7). At constant speed of the drive shaft, the meshing frequency component of the gear tooth generates the whine noise inside a car. In general, this meshing frequency component is embedded in the background noise such as engine noise, tire noise, wind noise and other component noises inside a car. According to previous work, it is known that if signal to noise ratio is over17dB, then whine noise is clearly identified. During accelerating of the car, the meshing frequency component of the gear tooth is changed. Therefore, the minimum value of SNR_m for all synthetic sounds is calculated during acceleration of a car. The minimum value of SNR for each signal is selected as the sound metrics. The correlation between subjective ratio and SNR_min is calculated and plotted as shown in Fig. 7 (e). However, the correlation is not high level. The reason for this low correlation is due to the change of the meshing frequency because the rotating speed of gearbox shaft increases during acceleration. The value of SNR for the identification of the whine noise depends on the frequency or rpm. Therefore in order to improve the correction the weight function is developed. The flow chart for the development of weight function for this improvement is shown in Fig. 8. In the Fig.8,

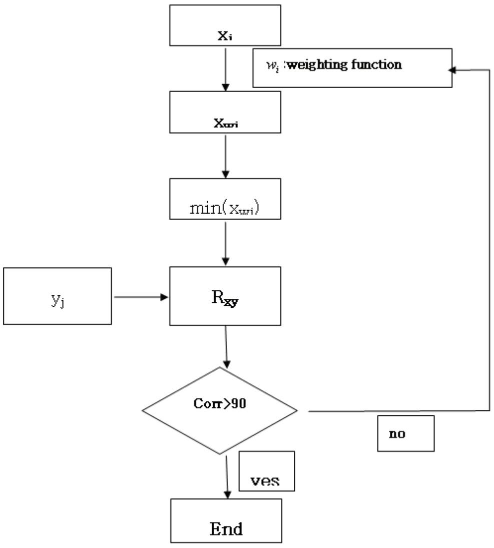


Fig. 8 The flow chart for the development of weight function for this improvement;

x_i is the original value of SNR_m at the i^{th} rotating speed of the propeller shaft in axle gearbox. x_{wi} is the value of weighted at the i^{th} rotating speed of the propeller shaft in axle gearbox which is calculated by multiplying the original of SNR_m by weight function w_i (i.e. $x_{wi} = x_i \times w_i$). The value of correlation, R_{xy}, between subjective ratio y_j for j^{th} synthetic sound and minimum value x_{wi} of the weighted SNR_m is calculated. The calculation is repeated until the correlation become 0.9.It's mathematic expressed given by,

$$w_i = 0.0047 \times \exp(-0.45t + 10) + 1 \qquad (11)$$

The minimum value x_{wi} of the weighted SNR is used the new metric. The new calculated correlation between weighted minimum SNR_wm and subjective rating are calculated. The correlation is improved from 0.657 to 0.918 as shown in Fig. 10. This new SNR is used for the sound metric as the input of ANN.

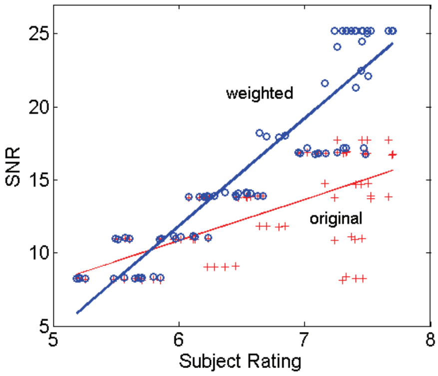


Fig. 9. Comparison between original correlation and improved correlation (x = the minimum value of original SNR, o = the minimum value of weighted SNR)

6 Axle-gear whine Index Using Artificial Neural Network

ANN has been applied to developing a booming index and rumbling index for sound quality analysis of automotive sound quality analysis [8, 9]. In this paper, ANN is applied to the development of the axle-gear index of an SUV. Previous sections discussed the input and target for ANN; as shown in Fig.2 (a) the type of ANN used in the paper is the multiple-layer network. In this section the main work is to find the optimal weights $w_{i,j}$ of connections. The averaged subjective ratings and sound metrics for the 85 synthetic interior sounds were used for the optimization of the weights $w_{i,j}$ of connections of the ANN. Loudness and the SNR_m index of sixty synthetic sounds were used as the input for training of the ANN. Another twenty synthetic sounds were used for testing of the ANN. The ANN used as the axle-gear whine index consists of 2-6-1 structure, *i.e.,* $N = 2$, $H_1 = 6$ and $M = 1$. The number of weights of connects in the one hidden layer is six. Optimal weights are obtained by training of the ANN. Mathematically, the axle-gear whine index using these optimal weights of connect and threshold is written by

$$\text{whine index} = F^2(\mathbf{LW}^2 F^1(\mathbf{IW}^1\mathbf{x}+\mathbf{b}^1)+\mathbf{b}^2) \qquad (12)$$

where the function F follows the form of equation (3), IW^1 is the weight matrix in the input layer, LW^2 is the weight matrix of the first hidden layer. The axle-gear whine index is the output of the trained ANN. Fig. 10 shows the correlation of the output of the ANN and the averaged subjective ratings of the sixty synthetic sounds used for the training of the ANN. In Fig. 10, the horizontal axis "T" means subjctive rating and the vertical axis "A" means the output of the ANN. They very much correspond and have a good correlation of 98.7%. These results are very well correlated. The axle-gear whine index by using the trained ANN is applied to the estimation of the subjective rating for another twenty synthetic interior sounds for a test of the trained ANN. These estimated subjective ratings are compared with the averaged subjective ratings of the twenty synthetic interior sounds. These results are plotted as shown in Fig. 11. The correlation between the averaged subjective ratings for five mass-produced SUVs and the output of the trained ANN is 96.9 %.

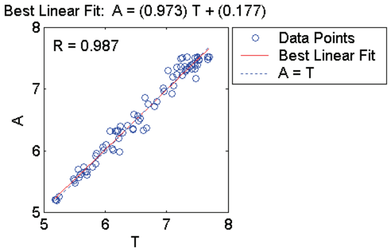


Fig. 10. Correlation between the output of the trained ANN and the averaged subjective ratings for the 60 synthetic interior sounds for the train of the ANN.

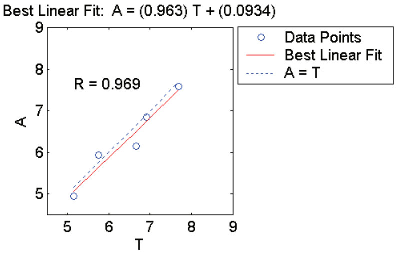


Figure 11. Correlation between the output of the trained ANN and the averaged subjective ratings for the five interior sounds of the mass-produced SUV.

This gear whine index is also appled to the production of sound quality map as shown in Fig. 12. Fig. 12 show the sound quality maps for the gear whine sound. The subjective rates for gear whine sound of 5 passeneger cars are pointed in the sound quality map in Fig. 12. This is a meanful results to find the relationship between sound metrics and sound qulaity level and the contribution of sound metrics to the sound quality pictocally.

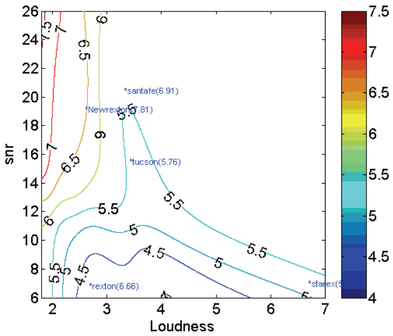


Fig. 12 Sound quality maps for a axle gear whine noise.

7 Conclusions

Loudness, sharpness, roughness, fluctuation strength, articulation index and tonality for those interior sounds were calculated for the input of the ANN. It was found that both loudness and articulation indexes for those sounds have a relationship with the averaged subjective ratings of those sounds. The correlation between the output of the trained ANN and the averaged subjective rating for those sounds is 96.3%. It is concluded that the output of the trained ANN can be used for the axle-gear index for the interior sounds of SUVs. This has been confirmed with the application of the trained ANN to the estimation of the subjective ratings for the axle-gear whine sound qualities of five mass-produced SUVs.

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