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EVALUATION OF ENHANCEMENT OF SOUND QUALITY OF AXLE GEAR BASED ON ARTIFICIAL NEURAL NETWORK

Tae-Gyu Kim[1] ,Sang Kwon Lee[1]and Sung-Jong Kim[1]

[1]School of Mechanical and Manufacturing Engineering, Inha University
Inchon, 402-751, Korea
sangkwon@inha.ac.kr

Abstract

There are various sounds in the car as much as cars have many mechanical parts. These sounds make various sound qualities. The international competition in car markets has continuously required the research about the sound quality of a car. The domestic carmakers have also invested a lot of money for the research and development of sound quality. Car axle plays an important role in a vehicle and its NVH development is also important. By this time, NVH development of car axle is mainly based on the reduction of sound pressure level (dBA), which cannot gives, the satisfaction to the customers in view of the sound quality of a vehicle. Therefore, in this project, a sound quality index evaluating the sound quality of axle noise based on human sensibility is developed and applied to the development of the sound quality of axle noise.

1. INTRODUCTION

There are many different sound qualities inside a car such as those of the engine, road, wind, exhaust and other sounds [1-4]. These sounds are the dominant sound sources that need to be reduced to a reasonable level since the sound pressure level due to them is considerably higher than that due to the other sounds and overrules the interior sound pressure level. Therefore, NVH (noise, vibration and harshness) engineers in the automotive companies try to reduce the sound pressure level due to these sound sources and reduce their sound pressure to as close to a marketable level as possible. Unfortunately, the other sounds, which are masked by these major sound sources, then become important [5]. 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. It is sometimes difficult to evaluate the axle-gear whine sound objectively from the viewpoint of sound quality since it has a high energy level in a narrow bandwidth and is affected by the masking effect of background sounds [6]. Considering this masking effect, new metrics are developed and they are used for the objective evaluation of the axle-gear whine sound. These metrics are based on the difference between the background sound and gear order sound. The least square method is used for the modeling of the correlation between objective and subjective evaluation. This model was applied to a few real cars and the results have a good correlation [7]. However, the metrics used for this method are not based on psychoacoustic theory but only on the masking effect. Therefore, this method is practical but has limited application. Recently, objective evaluation methods for automotive sound have been developed with sound metrics based on psychoacoustic theory and synthetic sound technology, and these methods are applied to the sound quality analysis of automotive sounds [8-9]. This paper investigates the characteristics of the gear whine sound based on synthetic sound technology and developes an objective evaluation method by using the sound metrics based on psychoacoustic theory and artificial neural network (ANN), which has been used for the modeling of the correlation between objective evaluation and subjective evaluation. Throughout this research, it was found that the loudness and articulation index are 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. For the training process of ANN, 80 interior sounds with the axle-gear whine sound quality of various subjective ratings were synthesized by using the signal characteristics of the gear-gear whine sound, which are well known in many research papers [5-7]. Another five interior sounds of SUVs were obtained by measurement, and the axle-gear whine sound qualities for these interior sounds were subjectively evaluated by 21 persons for the target of ANN.

2. ARTIFICIAL NEURAL NETWORK

The ANN very loosely simulates a biological neural system; a multi-layer feed-forward network is used throughout this paper. The training algorithm used with this network is back-propagation, which is mostly used in the analysis of mechanics problems.

3. SYNTHETIC TECHENOLOGY FOR AXLE-GEAR WHINE NOISE

To apply ANN to sound quality analysis, the optimal weights $w_{i,j}$ of connection of neurons in ANN, 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]. 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 signal is measured inside a reference SUV used for the production of 80 synthetic axle-gear sounds. Fig.1 (a) shows the image plot for STFT (short time frequency) 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 sound pressure level inside of the car. 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 with the amplitude and frequency modulated signal as follows:

$$x(t) = a(t)e^{j\phi(t)} \tag{1}$$

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. 2(a) represents the time history of the meshing frequency component sound. It is obtained by filtering the interior sound as shown in Fig. 1(a) with a Kalman order adaptive filter. Fig. 1(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 (1). The envelope and frequency modulation functions are $a(t)$ and $\phi(t)$, respectively. The instantaneous frequency for the analytic signal is given by

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

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

$$\phi(t) = 2\pi f_0 t \tag{3}$$

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

$$\phi(t) = 2\pi(f_0 t + f(t)) \tag{4}$$

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. 1(a) and adding it to the background noise as shown in Fig. 2(b) because the background noise influences the axle-gear sound quality. In this paper, the envelope of the analytic signal is modified as follows:

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

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. 2(c) shows one example of the modified envelopes $\mathscr{A}(t)$ and illustrates the roles of the parameters. Fig. 2(d) displays the analytic signal $x(t)$ modified by using the modified envelopes $\mathscr{A}(t)$. The modified analytic signal is given by

$$x(t) = \mathscr{A}(t)\exp(j\phi(t)) \tag{6}$$

To get the synthetic interior sounds with different axle-gear whine sound quality, these modified analytic signals with various values for the Ω_k, t_i and A_j are added to the background noise as shown in Fig. 1(b). Fig. 1(c) and (d) shows the image plot for STFT of the interior sound for the synthetic interior sound by using a modified analytic signal as shown in Fig. 2. Fig. 1(c) shows the axle-gear whine sound located at low rpm and Fig. 1(d) shows the axle-gear whine sound located at high rpm. With this method, the 80 synthetic interior sounds with the axle-gear sound quality of various subjective rates are completed. The subjective rates of these interior sounds are used for the target of the ANN.

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 for the subjective evaluation. Therefore, the subjective evaluation consists of a total of 85 interior sounds. The playback system and headphone of Head Acoustics Company were used for subjective evaluation. The 85 interior sounds were randomly evaluated; the subjective rate was evaluated for point 4 to point 9. Fig. 3 (a) shows the results of 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. Fig. 3 (b) illustrates the standard deviation with 95% confidence interval. It is calculated from all subjective evaluations of car individual interior sound. The subjective evaluation data within this deviation are used for the target of ANN.

5. 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. 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 articulation 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 eight. 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

$$\text{axle-gear whine index} = F^2(\mathbf{LW}^2 F^1(\mathbf{IW}^1\mathbf{x} + \mathbf{b}^1) + \mathbf{b}^2) \tag{7}$$

where 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. 4(a) shows the correlation of the output of the ANN and the averaged subjective ratings of the sixty synthetic sounds used for the traing of the ANN. In Fig. 4(a), 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 96.3%. 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 the test of the trained ANN. These estimated subjective ratings are compared with the averaged subjective ratings of the twenty synthetic interior sounds. Fig. 4(b) shows their correlation, which is 95.5%. It can be used to estimate objectively the subjective ratings of the axle-gear whine sound qualities of an SUV without subjective evaluation by a skilled engineer. Finally, the trained ANN is applied to the estimation of the axle-gear whine sound quality of the five mass-produced SUVs. These results are plotted as shown in Fig. 4(c). The correlation between the averaged subjective ratings for five mass-produced SUVs and the output of the trained ANN is 97.8 %. Throughout these results, the axle-gear whine sound for an SUV is objectively evaluated by the trained ANN very well. Therefore, in order for an inexperienced engineer to evaluate the axle-gear whine sound using equation (7), the interior sound of an SUV should first be measured with a binaural head system and recorded. Second, the sound metrics of the recorded sound should be calculated by using methods explained in session 5. Finally, two sound metrics -- loughness and articulation index -- are used for the input of equation (7).

6. CONCLUSIONS

The characteristics of axle-gear whine sound were investigated by using synthetic sound technology. The 80 axle-gear whine sounds were synthesized and they were evaluated subjectively by 21 NVH engineers. Throughout these tests, it was concluded that the axle-gear whine sound is affected by the speed of an SUV and the amplitude of the meshing frequency component of the interior sound. An artificial neural network has been applied to the development of the sound quality index of the axle-gear whine sound of an SUV. The averaged subjective ratings for the interior sounds of 80 synthetic interior sounds were used for the development of the axle-gear whine index using the ANN. For the training of the ANN, 60 synthetic sounds were used and 20 synthetic sounds were used for testing of the trained ANN. The ANN used in the present paper is a back-propagation neural network with 2-6-1 structure. 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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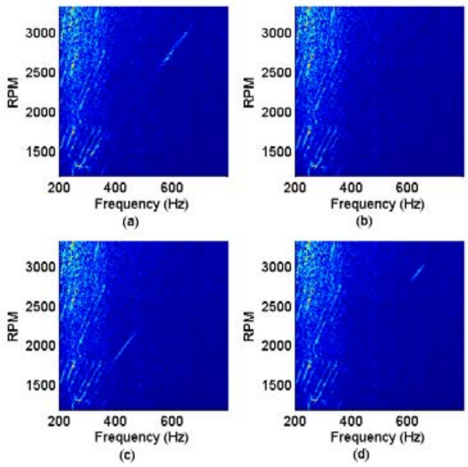


Figure 1. Image plot for the interior sound of an SUV car: (a) base sound (b) background noise without the sound component due to tooth meshing (c) synthesized axle-gear sound located at low rpm (d) synthesized axle-gear sound located at high rpm

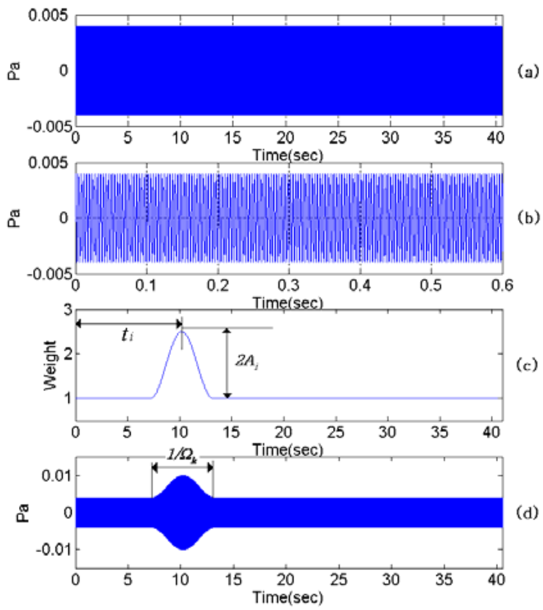


Figure 2. Modification of meshing frequency component sound

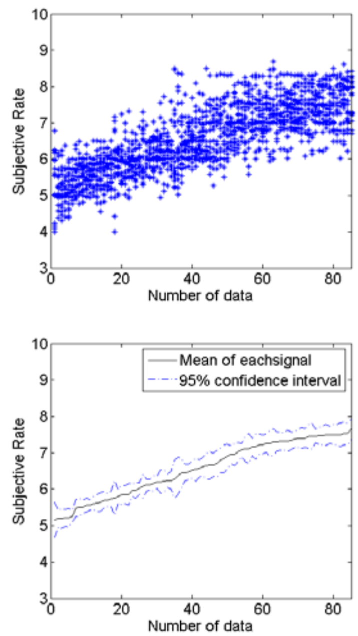
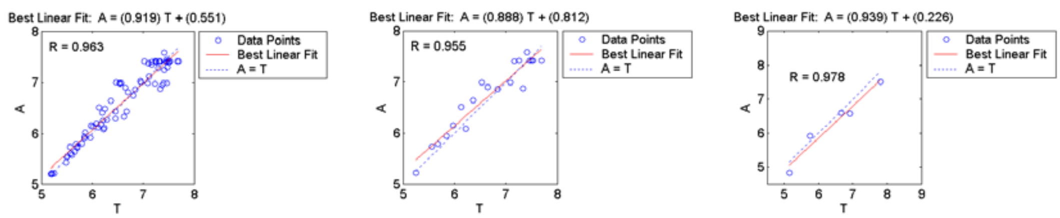


Figure 3. Subjective rates for the 85 interior sounds of passenger cars:



(a) (b) (c)

Figure 4. Correlation between the output of the trained ANN and the averaged subjective ratings. The horizontal axis “T” means subjctive rating and the vertical axis “A” means the output of the ANN.