14th ICBEN
2023
18 - 22 JUNE
BELGRADE

14th ICBEN Congress on
Noise as a Public Health
Problem

Active control of road noise caused by tire cavity-resonance in passenger car based on optimized weights-FxLMS algorithm.

[1]Sang-Kwon Lee[1], Kanghyun An[1]

[1] 1Inha University, Incheon City, South Korea

Corresponding author's e-mail address: sangkwon@inha.ac.kr

ABSTRACT

This study proposes a new method for active noise cancellation (ANC) of cavity noise of a tire. A general method for ANC of road noise is to use several accelerometers for acquirement of reference signals. Cavity noise of tire is caused by the resonance of tire cavity mode. Resonance frequencies of tire cavity are determined by the cavity structure of tire. Therefore, harmonic sinusoidal signals related to resonance frequencies can be used for reference signals. However, resonance frequencies could be varied due to small change of tire cavity during driving of a car. For the overcome of this variation, adaptive filter of ANC system was designed and applied to the ANC of a cavity noise. It is called optimized weights filtered-x LMS algorithm (OW-FxLMS). The proposed method did not need accelerometers for the ANC of cavity noise and practically was applied to the ANC of cavity noise of a tire in a car. Tire cavity noise of a test car was attenuated to 3-5 dBA.

Keywords (3-6): Tire cavity noise, Resonance frequency, Active noise cancellation, Adaptive filter, Noise accentuation

INTRODUCTION

Since pneumatic tires have excellent riding comfort, they are applied to most commercial vehicles. However, since tire resonance occurs in an annular cavity formed between a tire and a wheel, resonance vibration noise may be transmitted to the interior of the vehicle. In conventional internal combustion engine vehicles, engine noise masked tire resonance, but as the driving method of vehicles changed to motor-based, reduction of tire resonance became more important [1]. Tire resonance noise is a tone noise corresponding to a tire resonance frequency generated when a tire cavity is excited from a road surface, and since tone noise is easily recognizable inside a vehicle, it can cause discomfort. T. Sakata found that the resonance frequency of automobile tires exists between 230Hz and 300Hz [2]. At these two frequencies, resonance noise caused by road excitation is generated inside the vehicle. In general, when no load is applied to the tire, if the tire's resonant frequency is f_b, when a load is applied to the tire, resonance noise is generated around the resonant frequency f_b, at a frequency f_l lower than the resonant frequency f_b and at a frequency f_h higher than the resonant frequency f_b [3]. In order to reduce tire resonance, it is necessary to control the resonance generated at two frequencies. Various studies have been conducted to reduce tire resonance. A typical method is to attach a sound-absorbing material to the inside of a tire, and recently, a study on attaching a metamaterial has been introduced [4-5]. In addition, research on reducing resonance transmitted to the room by installing a resonator in a tire has been conducted [6-8]. These methods require weight gain in a passive manner. The technology of reducing the resonance without increasing or decreasing the weight is an active method. The active method is a technique of electronically controlling the phase of noise. Tire resonance is a part of road noise, and recently, a technology to reduce resonance using road noise active noise control technology has been commercialized [9]. For active noise control of road noise, it is necessary to attach an accelerometer sensor to the chassis of the vehicle. The acceleration sensor plays a role in finding the resonance frequency of the chassis parts, which is the transmission path of road noise generation. In the road noise active noise control technology, the signal measured by the acceleration sensor is used as a reference signal for active noise control. Resonant frequencies of chassis components are largely classified into three types. These are the booming frequency in the low frequencies, the tire resonant frequency in the middle frequencies, and the rumbling frequency in the high frequencies. In order to find all these frequencies, multiple acceleration sensors are required, and the optimal attachment location must also be selected. By finding three main frequencies and reducing them all, the noise reduction effect is great, but many acceleration sensors are required. In this study, we present an indoor active control technology for tire resonance noise that does not require an acceleration sensor. In general, the tire resonance frequency can be obtained through a simple transfer function experiment. During driving, the resonance frequency fluctuates due to a change in the resonance shape of the tire. For active noise control of tire resonance noise, the tire resonance frequency was used as a reference signal, and a new adaptive filter was designed and applied to the active noise control algorithm for the influence of resonance frequency variation during driving. The new adaptive filter is an order filter [10]. When the reference signal fluctuates, the active noise control effect using order filter is excellent. The resonance sound of test tire in this study fluctuates in a frequency band of 200 Hz to 230 Hz. In general, the FxLMS algorithm has used for active noise control and the notch filter has been used as adaptive filter. In this study, an order filter is applied to the active noise control of tire noise. Although the frequency of tire resonance is determined by the shape of the tire, it is not a completely single frequency component, so a notch filter used for active noise control of a single frequency is not suitable for active control of tire resonance. Under these conditions, the order filter can be applied even if there is a slight frequency difference between the frequency of the reference signal and the actual noise signal. In this study, we discuss the difference in mutual noise reduction effect between the case of applying the active noise control technique and the case of reducing the tire resonance by installing the existing resonator, and suggest the applicability of the proposed tire active noise control technology.

ACTIVE NOISE CONTROL ALGORITHM

The tire's internal resonance frequency is excited by the contact force between the tire and the road surface. The resonant sound generated at the frequency excited by the road surface is amplified to a level of noise that can be recognized inside the vehicle through the transmission path of air and structure. Since the tire cavity noise frequency generated inside the vehicle has a correlation with the two tire resonance frequencies, a sinusoidal harmonic signal formed by the two frequencies was used as a reference signal. The tire resonance sound was applied to the active noise control algorithm in the same way as in Fig. 1.

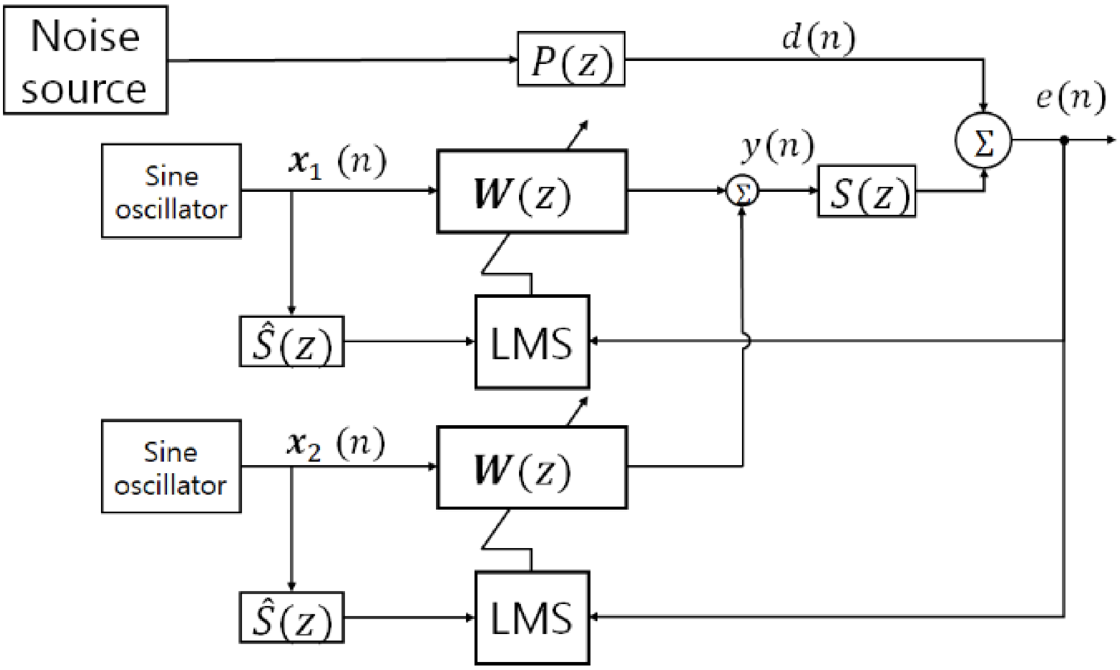


Fig. 1 Diagram of the FxLMS algorithm using in ANC system

Fig. 1 shows flow chart of the FxLMS algorithm which is similar the algorithm used for engine active noise control technology, except for the commonly used reference signal. The control signal y(n) is generated using the reference signals x_1 and x_2, the secondary propagation path S (z) and the LMS filter coefficient W(z), and y(n) destructively interferes with the tire resonance sound d(n) By doing so, the indoor noise, e(n), is minimized. The difference between the active noise control technology used in this study and the existing technology is the selection of the reference signal. The existing active noise control technology for road noise uses the signal measured by the acceleration sensor as the reference signal. In this paper, the reference signal is generated considering resonance frequency of test tire. The effect of slight fluctuations in the tire resonance frequency was solved by using order filter. The order filter is a band pass filter with a frequency band width that tracks fluctuating frequencies. The FxLMS algorithm is mathematically given by

$$\boldsymbol{w}_k(\boldsymbol{n}+\boldsymbol{1}) = \boldsymbol{w}_k(\boldsymbol{n}) + \mu\, e(n)\hat{\boldsymbol{x}}_k(n) \tag{1}$$

Here, $\hat{\boldsymbol{x}}_k(n)$ is the value obtained by convolving the transfer function of the secondary propagation path with $\mathbf{x}_k$(n) which is the reference signal. If you want to control tire resonance using an existing algorithm, you must either measure $\mathbf{x}_k$ using a sensor or know the exact frequency. On the other hand, the order filter can reduce the effect of frequency mismatch between the reference signal and the noise signal by securing an appropriate filter bandwidth. The transfer function of the secondary transfer path is measured and used experimentally in an experimental vehicle. $\mathbf{w}_k$(n) is the order filter. μ and e are the step size and error value, respectively. The step size is a constant required to update the adaptive filter, and the error is the difference between the secondary sound source provided through the audio speaker and the vehicle interior noise in order to cancel the tire resonance in the room. The secondary sound source y(n) is a signal that is reproduced through the speaker and offset with the resonant sound. It is obtained through the convolution of the reference signal **x**(n) and the adaptive filter **w**(n) and is expressed as in Equation (2).

$$y_k = \sum_{l=0}^{L-1} w_{l,k}(n)\, x_k(n), \;\; k = 1{,}2 \qquad (2)$$

In order to cancel the tire resonance, the filter coefficient $w_k(n)$ must be updated at every step. The adaptive filter is updated using Eq. (2). At this time, the step size μ is a value specifying how quickly the filter coefficients are updated, and the following condition must be satisfied.

$$0 < \mu < \frac{2}{L_o P_x} \qquad (3)$$

Here, L_o is the size of the adaptive filter, and the value of L_o must satisfy the following condition to secure the frequency bandwidth [10].

$$0 < L_o < \frac{2\times f_s}{f_{OB}} \qquad (4)$$

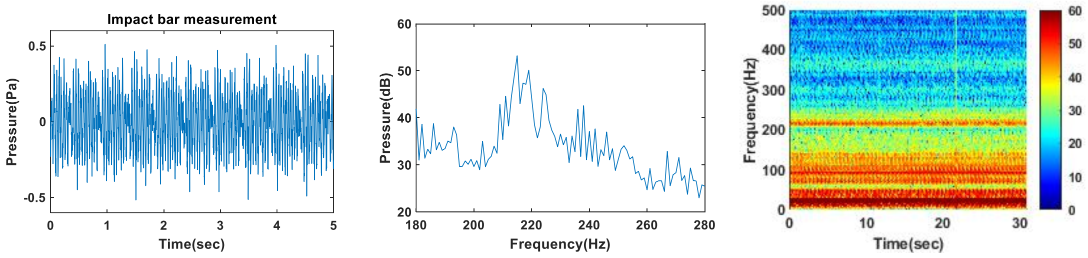
ACTIVE NOISE CONTROL OF TIRE CAVITY NOISE

In order to proceed with active noise control for the vehicle resonance sound, first, the cavity resonance sound for the experimental vehicle is analyzed, the secondary transmission path is measured, and the active noise control effect during driving using the proposed method is verified. Finally, the noise reduction effect of the method using a resonator and the proposed method was compared.

Tire resonance sound analysis and resonance frequency

In order to apply the ANC algorithm, the resonance frequency of the tire cavity was measured experimentally. To conduct the experiment, as shown in Fig. 2, the experimental vehicle was installed on the vehicle chassis dynamometer, the impact bar was attached to the tire driving roller, and the vehicle interior noise was measured while driving the dynamometer. The tire continuously receives an impact force by the impact bar, and a resonance sound is generated from the tire cavity, and the resonance vibration is transmitted to the inside of the vehicle through a transmission system. Fig. 3 (a), (b), and (c) show time-series data, frequency analysis, and time-frequency (spectrogram) respectively measured in the test vehicle.

Fig.2 Test car excited by impact bar on roller of chassis dynamometer.



(a) (b). (c)

Fig.3 Time and frequency component of measured signal (a) time history (b) FFT of time data (c) spectrogram of time data

According to the frequency analysis result as shown in Fig. 3 (b), the two frequencies at which the measured resonant sound is maximum are 215Hz and 225Hz. 220 Hz is the side effect of 215 Hz. This effect means that frequency fluctuations occur around the two frequencies analysis. In the paper, active noise control technology was applied with the goal of reducing noise in these two frequency bands.

Active control of tire resonance

An active noise reduction device for reducing resonance was installed in the test vehicle and driving was conducted. The experimental equipment and peripheral equipment used in the experiment are as shown in Fig.4. The test vehicle was driven at a constant speed of 50 km/h on the public road. As shown in Fig. 4(a), error microphones were installed on the left and right sides of the driver's seat head to measure indoor noise before and after active noise control. The secondary sound reproduction speaker was installed in the seat behind the driver's seat.

(a) (b)

Fig.4 Equipment for active noise cancellation of cavity noise (a) error microphone and speaker for 2nd sound source (b) Auto box controller, lowpass filter and speaker amplifier.

In order to prevent the aliasing phenomenon in the data processing process of the noise signal measured by the error microphone, a low pass filter was applied to the microphone measurement signal to block components of 500Hz or higher. As a controller for active noise control, Micro Autobox (dSPACE Co.) was used. The low-pass filter and controller used in the experiment are shown in Fig.4(b). The FxLMS algorithm was fabricated using Matlab Simulink (MathWorks Co.) and then embedded in the controller to perform active noise control. In order to apply the FxLMS algorithm, it is necessary to measure the secondary transmission path as shown in Fig.1. The random excitation method was used to measure the secondary transmission path between the secondary sound source speaker and the microphone. Fig.5 shows the flow chart of the equipment used for measuring the secondary transfer path.

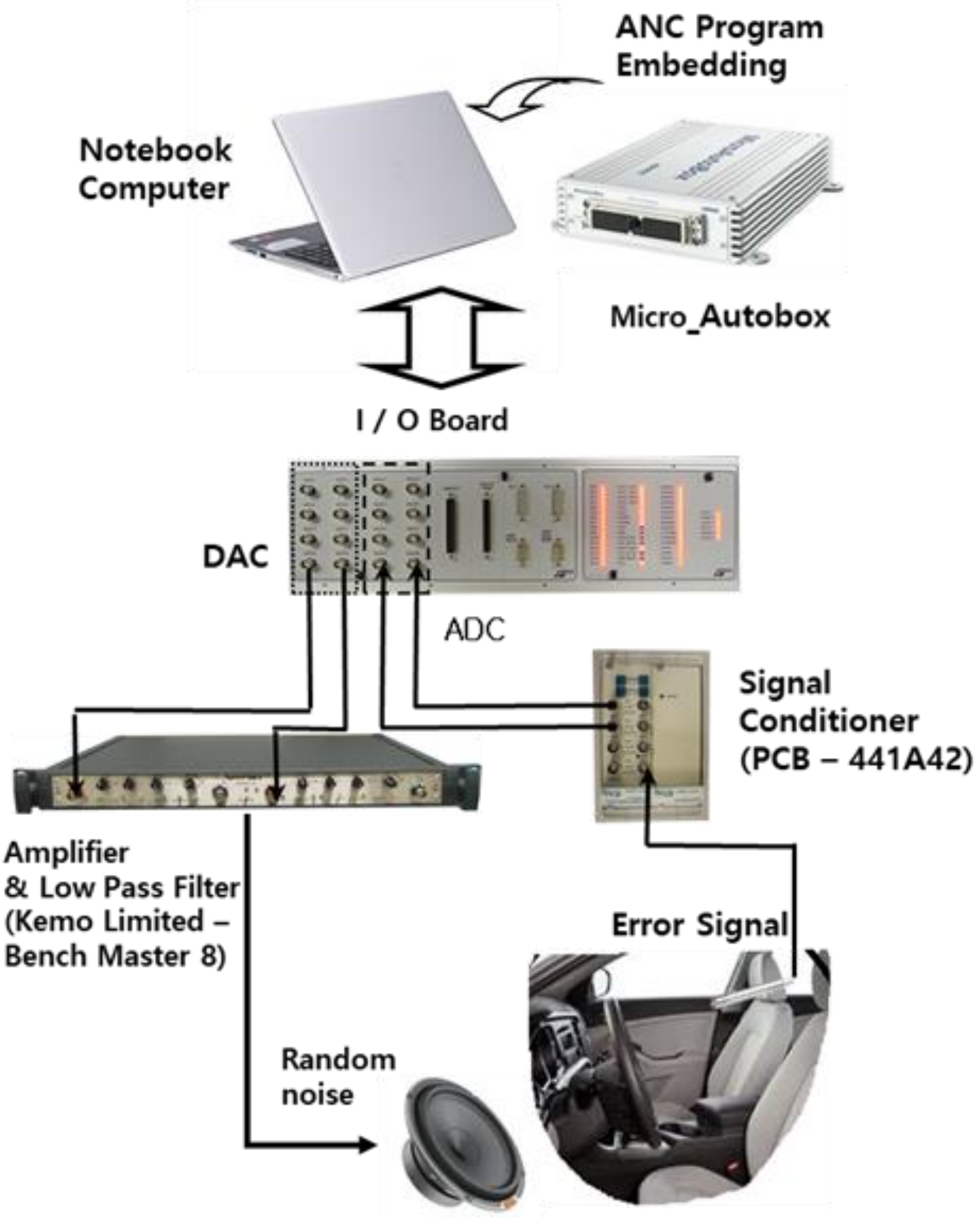
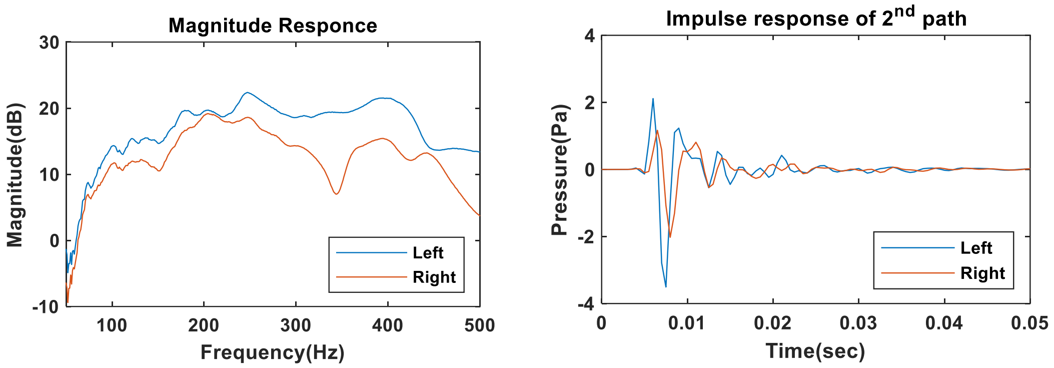


Fig. 5 Equipment and data flow used for transfer function of secondary path.

The transfer function and impulse response of the secondary transfer path measured using the white signal excitation method are shown in Fig. 6 (a) and (b) respectively. According to these results, a main resonance frequency exists between 200 and 300 Hz. The resonance of the secondary path affects the active noise control of tire noise. The adaptive filter executes the real time control of the amplitude influenced by the secondary path. Specially in the resonance frequency, adaptive filter should be band stop filter of noise amplified by secondary path.



(a) (b)

Fig. 6. Transfer function of secondary path for active noise cancellation of tire cavity noise (a) transfer function (b) impulse response.

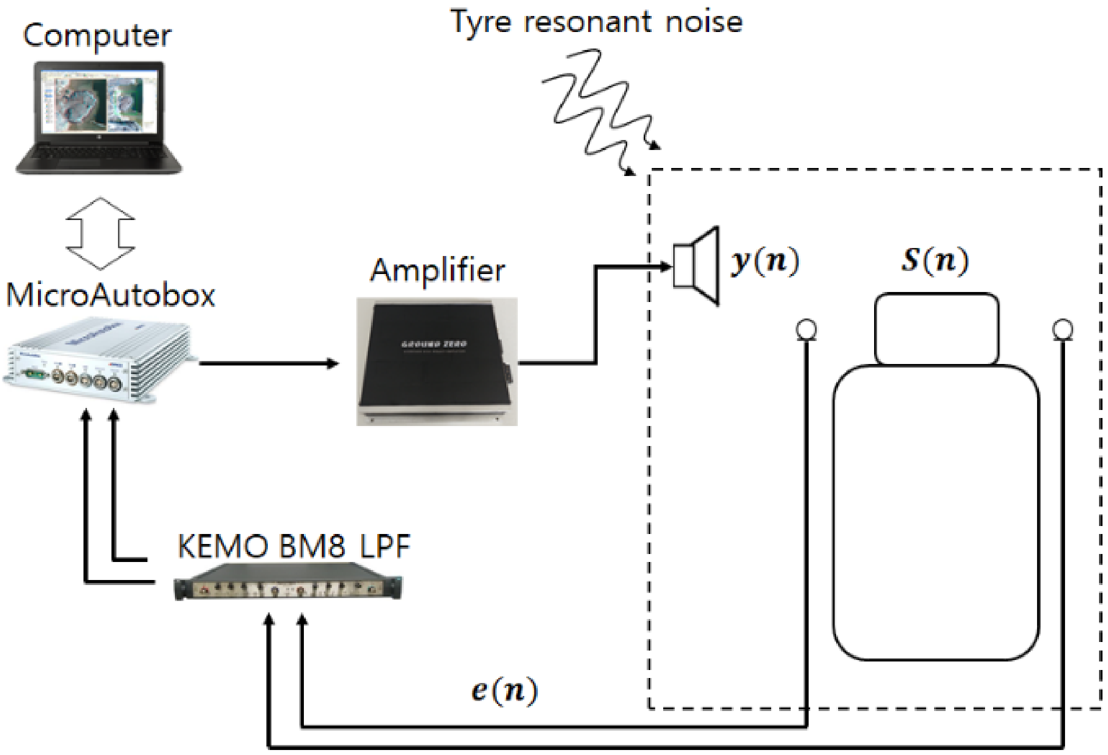
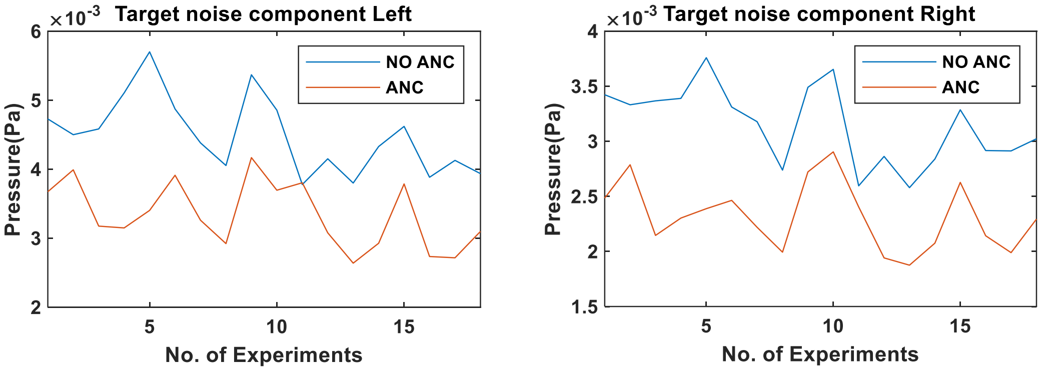


Fig.7 System for the active noise cancellation of tire cavity noise

Fig. 7 is a schematic flow chart of the equipment used in the active noise control system for active noise control of tire resonance used in this study. The tire resonance noise control procedure generates a sine wave harmonic signal corresponding to the measured tire resonance frequency in real time using signal processing technology in a control computer. The generated sinusoidal signal is used to create a reference signal for the FxLMS algorithm. This sinusoidal signal is used as a reference signal by convolutional multiplication with the measured secondary path impulse response function. This reference signal is used to update the order filter of the FxLMS algorithm shown in Equation (1). The secondary sound source was amplified by convolutional multiplication of the sine wave signal and the updated order filter, and then the secondary sound source transmitted to the speaker was created. In order to cancel the resonant noise reproduced through the rear seat speakers, the phase and amplitude are adjusted by the controller in real time.

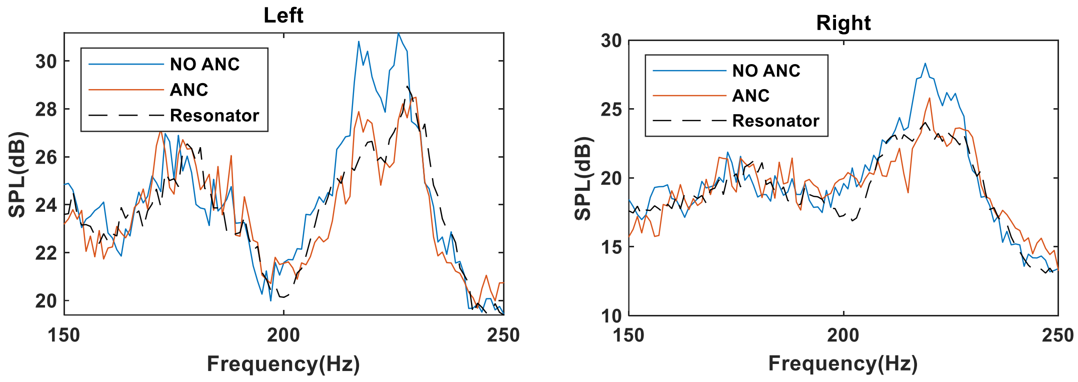
Noise control result

Fig. 8 and Fig. 9 shows the result of controlling the tire resonance noise using the tire resonance active noise control system. Fig. 8 shows the effect of ANC proceed by several experiments while the vehicle is driving on a straight road at constant speed. In order to verify the effect of the active noise control system, the effect of the active noise control system is compared with the case of mounting the resonator on the tire and shown in Fig. 9. Fig. 8 shows the difference in sound pressure between the applied and non-applied ANC in each driving test. It shows the degree to which the sound pressure is reduced between 210 Hz and 230 Hz corresponding to the resonance frequency band. The filter length of the algorithm was 15 and the test run was repeated 18 times. In all trials, when ANC was applied, it was confirmed that noise was reduced in the frequency band corresponding to tire resonance. When the test results were averaged, the reduction effect of 2.79 dB at 218Hz and 3.63dB at 226Hz in the case of the measurement signal of the driver's seat left microphone during ANC, and the noise reduction effect of 4.01 dB and 2.54dB at the right microphone position, respectively, were confirmed. In addition, in order to compare the active noise control performance with the passive method, the resonance noise reduction results using the Helmholtz resonator conducted in the same vehicle and the same driving conditions were compared. Figure 9 compares the noise level before and after ANC and under each experimental condition using a resonator. A resonator was installed on the test tire, and cavity noise was recorded while driving on the same road at 5 km/h. When the resonator is installed, the interior noise is 3.54dB and 3.71dB for the left microphone and 3.65dB and 3.31dB for the right microphone. According to the comparison results, the noise reduction effect of the two methods was similar. To show the effect of ANC in time and frequency, the interior noise is analyzed by short time Fourier transform. Fig. 10 is a spectrogram of interior noise when ANC is activated midway while the vehicle is driving. It can be confirmed that the filter converged quickly after ANC operation. The proposed ANC method is successfully applied to reduce the road noise caused by tire cavity resonance.



(a) (b)

Fig.8 Comparison of the effect of ANC in each experiment (a) left error microphone (b) right error microphone



(a) (b)

Fig.9 Comparison of tire resonant noise attenuation between passive and active method (a) left error microphone (b) right error microphone

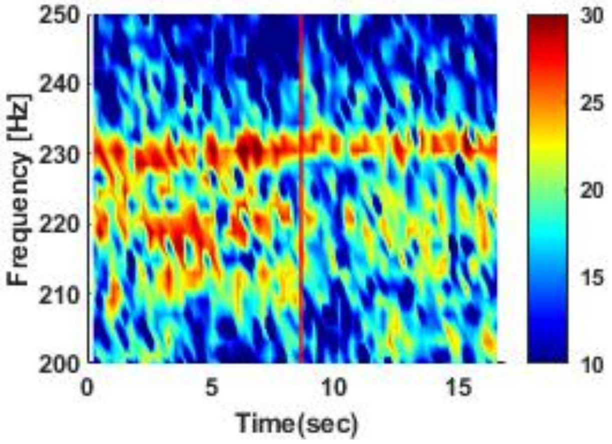


Fig. 10. Spectrogram of Interior noise measurement during the experiment (Active noise control is activated 9 seconds after the beginning of the measurement)

CONCLUSIONS

In this study, a technique ANC technology to reduce road noise generated by tire resonance is proposed during vehicle is driven. Since tire cavity resonance occurs in the cavity inside the tire and has a certain bandwidth. To reduce this kind of road noise using ANC, a sine wave signal is used as a reference signal in this study. There is no need for an acceleration sensor to acquire a reference signal, and the resonance frequency problem that fluctuates during driving is solved by using an order filter. Since tire resonance is determined by the shape of the space inside the tire, it is necessary to apply a different design for each tire shape in order to reduce tire noise using a sound absorbing material or a resonator. Therefore, active noise control technology can be effective for reduction of tire noise providing advantages in time and cost. In addition, ANC method for the reduction of tire cavity noise is possible without measurement of a reference signal such as acceleration. ANC is a new possible method to replace the conventional methods for tire noise reduction**.**

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1F1A1062889). This work was supported by the grant funded by the Korea evaluation institute of industrial technology (KEIT) (No. 20018706).

REFERENCES

1. Cao, Y., Wang, D., Zhao, T., Liu, X. et al., "Electric Vehicle Interior Noise Contribution Analysis," SAE Technical Paper 2016-01-1296, 2016.
2. T. Sakata, H. Morimura and H. Ide, “Effects of Tire Cavity Resonance on Vehicle Road Noise,” Tire Science and Technology, Vol.18, No.2, pp.68-79, 1990.
3. H. Yamauchi and Y. Akiyoshi, “Theoretical analysis of tire acoustic cavity noise and proposal of improvement technique,”JSAE Review, Vol.23, No.1, pp.89-94, 2002.
4. H. heo, M. Sofield, J. Ju and A. Neogi, “Acoustic Metasurface-Aided Broadband Noise Reduction in Automobile Induced by Tire-Pavement Interaction,” , Materials 2021, Vol.14, No.15, 2021.
5. Z. Mohamed and X. Wang, “A study of tyre cavity resonance and noise reduction using inner trim,” Mechanical Systems and Signal Processing, Vol.50-51, pp.498-509, 2015.
6. H. Periyathamby, “Helmholtz resonator for reducing tire cavity resonance and in-vehicle noise,”Canadian Acoustics, Vol.32, No.4, pp.27-31, 2004.
7. W. Zhao, Y. Liu, X. Liu, Y. Shan and X. Hu, “Analysis of Tire Acoustic Cavity Resonance Energy Transmission Characteristics in Wheels Based on Power Flow Method,”, Appl. Sci., Vol.11, No.9, 2021.
8. Y. Min, K. Sim, S. Yang and Y. Kim, “Comparison of Helmholtz resonators noise reduction with tire stiffness,” Proceedings of the KSNVE Annual Autumn Conference 2019, pp.227-227, 2019.
9. N. Zafeiropoulos, J. Zollner, V. Kandade Rajan, “Active Road Noise Cancellation for the Improvement of Sound Quality in the Vehicle”, ATZ worldwide, Vol. 120, No. 3, pp.38-43., 2018.
10. S. Lee, S. Lee, J. Back and T. Shin, “A New Method for Active Cancellation of Engine Order Noise in a Passenger Car,” Appl. Sci., Vol.8, No.8, 2018.