AUTOMOBILE BRAKE SQUEAL NOISE SUPPRESSION USING PIEZOELECTRIC-BASED DEVICES

Jaehan Park[1], Tae Ho Jung[2], Jeong Kyu Kim[2], Gyuhae Park[1*]

[1] School of Mechanical Engineering, Chonnam National University, Gwangju 500-757, South Korea, gpark@chonnam.ac.kr
[2] Hyndai Motor company, 135-9, Hyundaiyeonguso-ro, Jangdeok-ri, Namyang-eup, Hwaseong-si, Gyeonggi-do, South Korea, taeho.jung@hyundai.com

Keywords: Vibration, Piezoelectric, Brake Squeal, Dither control, Shunt damping

ABSTRACT

Automobile brake squeal noise, which is a friction-induced vibration in the frequency range of 1 kHz to 20kHz, still remains a major problem for the automotive industry. This paper presents experimental investigations into the application of piezoelectric-based devices to suppress automobile brake squeal noises. Two techniques are employed, including dither control and shunt damping. Dither is a concept of active noise control by introducing high-frequency vibrations into a system to suppress lower-frequency disturbances. Shunt damping is a passive technique which dissipates the vibration energy of the system with piezoelectric devices. Several experimental investigations are carried out to validate the performance of the proposed techniques. The results indicate that the proposed device could effectively suppress the brake squeal noise.

1 INTRODUCTION

Disk brake squeal noise is an ongoing problem for the automotive industry [1]. In most cases, the brake noise has little effect on the performance of the brake system. However, this type of noise is perceived as annoying sound for customers and seriously affects the satisfaction ratings as well as warranty costs. For this reason, considerable efforts have been directed to the reduction of the disc brake noise. Among many types of brake noises, brake squeal noise, which is a friction-induced vibration in the frequency range of 1 kHz to 20 kHz, is considered to be the most sensitive noise to customers [2].

In order to suppress the brake squeal, piezoelectric based noise reduction techniques have attracted many researcher because piezoelectric devices can be used in both active and passive ways. Dither control refers to the use of a high-frequency and low amplitude signal to change the characteristics of nonlinear system [3]. Dither has been employed to many applications such as optics, image processing, controls and communications to improve the performance [4]. In a brake system, dither reduces the unstable vibration by turning Coulumb-type friction into viscous-like damping [5-6]. The practical application of dither control for the brake system was first demonstrated by Cunefare et al. [7]. A piezoelectric stack was installed inside the caliper piston to reduce brake squeals. The results showed that the dithering with normal direction force in the frequency range of 7.5 kHz to 20 kHz could reduce the brake squeal. The suppression of brake squeal using dither control was also demonstrated by Pervozvanski [8]. Michaux et al. [9] compared the performances of normal force dither and friction force dither in terms of brake squeal reduction. It was found that the normal force dither was not as effective as the friction force dither due to control force limitation caused by braking pressure. Since squeal noise generally occurs in low-speed just before a complete stop, Teoh et al. [10] conducted experimental investigation on the friction transit from the kinetic to the static condition. The results showed that the torsional mode of the leading brake shoe was unstably excited in the normal direction during the squeal noise generation.

Several active control techniques were also applied to reduce brake vibrations. The requirement of complex sensing devices and amplifiers, however, makes these techniques difficult to be adapted by the automobile industry. As an alternative approach, piezoelectric shunt damping was used to reduce the vibrations of mechanical structures as a passive control [11-13]. In order to optimize the damping effect, the design of the electrical shunt aims at maximizing the energy dissipation at the target frequency.

Forward [14] studied inductance-frequency networks for the damping effect on the vibration of optical systems. Hagood and Von Flotow [11] investigate the relationship between the performance and tuning of the LR-networks. Neubauer and Oleskiewicz [15] developed the efficient mechanical model of a brake with embedded piezoelectric transducers and discussed shunt control strategies. The validation was then conducted with the measurement on a brake test rig. Neubauer et al. [17] introduced two technical applications, a squealing disc brake and a bladed disc, using piezoelectric shunt damping. In their study, synchronized switch damping on inductor and negative capacitance were combined to maximize the damping of the target modes on the two structures. In both cases, it was possible to control the vibrations and squeals.

This paper focused on the practical applications of piezoelectric based dithering and resonance shunt damping to a real brake system. An automobile, K7 (YG), is selected as a target system. A piezoelectric module was designed for both dither control and shunt damping. The module is installed inside a cylinder in the brake. For the experiment, both a built-in device (Pin-on-disc) and a brake dynamometer were built. Several experimental investigations were performed to demonstrate the noise suppression performance of dithering and resonance shunt damping. The details of this study are presented in following sections.

2 SQUEAL NOISE SUPPRESSION USING DITEHR CONTROL

2.1 Theory

Dithering is injection of an external signal to a linear or nonlinear system to obtain several possible objectives. The dithering can be utilized to affect the dynamic behaviour of the system, to stop undesired chaotic behaviour or undesired limit cycle oscillations in the system, and/or to alleviate the resonance jump phenomenon in sliding mode control applications.

The dithering signal may be analogue or digital, and can have any statistical and spectral characteristics. It can be a random or a deterministic signal and can be correlated or uncorrelated to the input signal. Being a random signal, its value at each moment can be dependent or independent of its previous values in time.

2.2 Proof of concept experiment

2.2.1 Experimental procedure

The pin-on-disk system used in the present study is shown in Figure 1. A pin of a bolt is welded to the end of the piezoelectric stack module. The disc is 17 inch brake disk of K7 (YG). The speed of the disc rotation was varied with a variable speed DC motor with a gear speed reducer connected. Squeal noise was generated by the pin in direct contact with the disk.

The dither signal was introduced into the pin-on-disk system in the normal direction with a stack module. The stack module consists of a piezoelectric(PZT) stack, Pin and housing. The stack module has one end is welded in the mount which is fixed on a vibration isolation table and the other end is in contact with pin.

Figure 2 shows the sound pressure level (SPL) of squeal noise at the pin-on-disk system measured at a distance of 30 cm from the pin-on-disk during squealing. There are three recorded peaks at 8 kHz, 16 kHz and 24 kHz with sound pressure level of 97.5 dB, 81 dB and 54.1 dB, respectively..

2.2.2 Squeal suppression experiments in the pin-on-disk system

The applied dither frequency was set higher than the audible human range of 20 kHz. In the experiment, the disk rotates at the speed of 20 rpm when the pin is in direct contact with the disk.

Figure 3 shows the measured SPL of the pin-on-disk system when the different dither signal frequencies are applied. As shown in Figure 3(a), the results show that the squeal amplitude has been reduce to 93.5 dB when the dither signal is set to 22.5 kHz (4 dB reduction). As depicted in Figure 3(b), The 23.5 kHz dither control signal also reduced the squeal noise to 49 dB and has shifted to a lower frequency of 7.8 kHz. Figure 3(c) is the result with the dither applied at 21.5 kHz. The squeal noise at 8 kHz is further suppressed to 35 dB but other noise generated at 10.7 kHz. The completed suppression of the brake squeal is noticed when the dither is applied at 20.5kHz. The squeal noise and its sidebands disappear completely, as shown in Figure 3(d).

As shown, the performance of dither control is dependent on the selected dither frequency. The optimal selection of the frequency is important for effective squeal noise reduction.

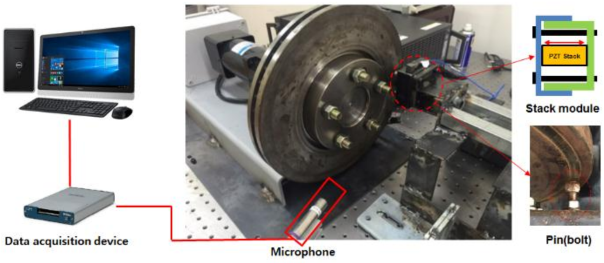

Figure 1: Proof-of-concept experiment setup.

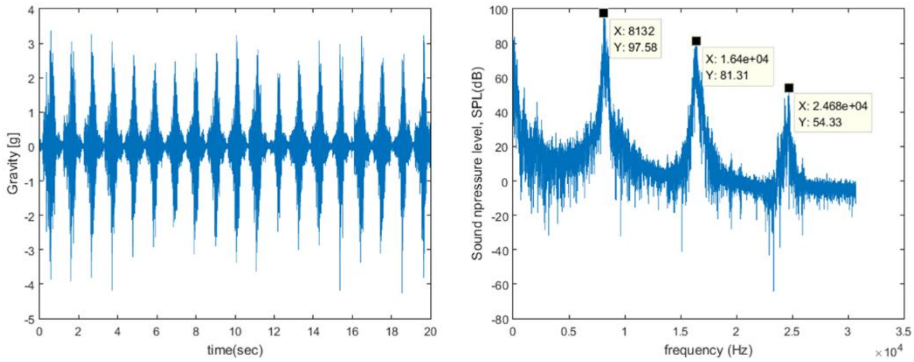

Figure 2: Squeal noise at the Pin-on-disk system

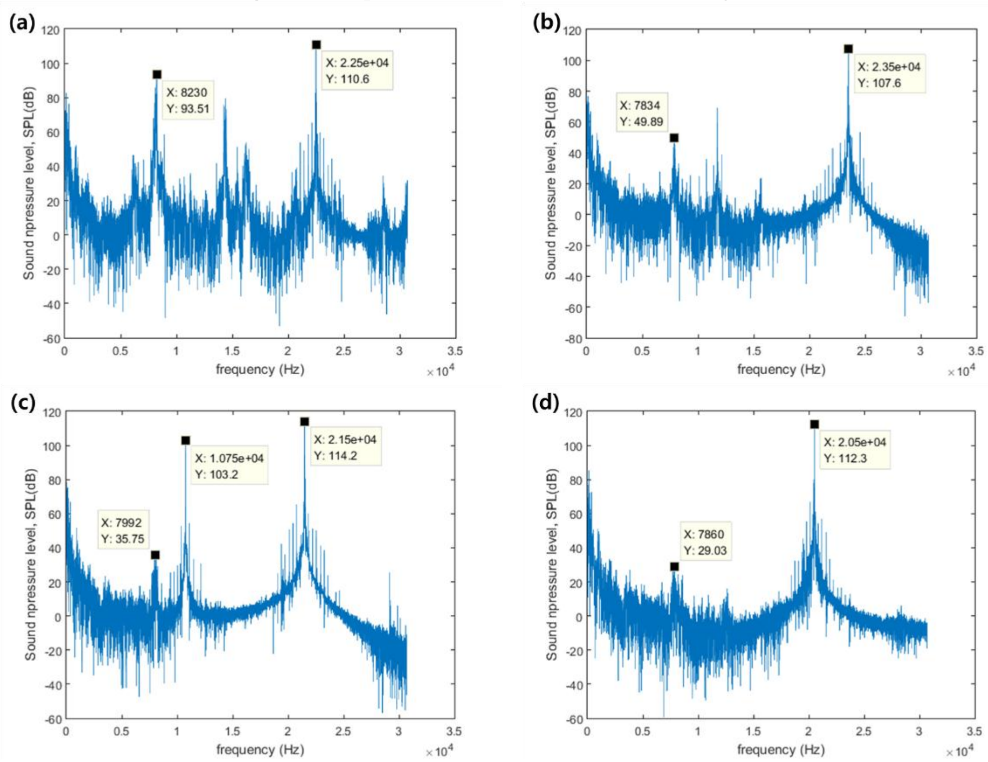

Figure 3: Dither experiment result in the pin-on-disk system at different dither frequency:
(a) 22.5kHz, (b) 23.5kHz, (c) 21.5kHz (d) 20.5kHz

2.3 Brake dynamometer

2.3.1 Experimental procedure

A brake dynamometer is built, as shown in Figure 4. The dynamometer system had the capability to maintain a fixed rotation speed of the rotor, as well as to control the brake line hydraulic pressure.

Two applications were employed. The first application used the PZT stack module, shown in Figure 5(a), as a dither control device. The dither control module was integrated into the piston caliper, as depicted in Figure 5(b). The module was positioned inside the piston with one end in contact with the inboard brake pad and the other end to the closed end of the caliper piston. In the second application, the location of the module is moved to a caliper carrier, as shown in Figure 5(c). During the experiment, the sound pressure level from the system was measured with a microphone. The microphone was positioned approximately 0.3 m apart from the front of the rotor.

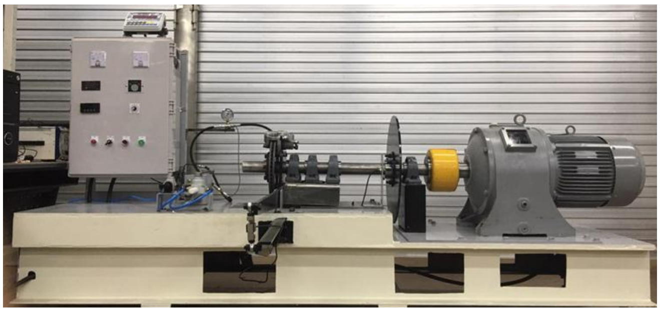

Figure 4: Brake dynamometer .

2.3.1 Squeal suppression experiments in the brake dynamometer

The experiment was performed with the brake dynamometer. In the experiment, the disk was allowed to rotate at the sliding speed of 32 rpm when the brake operates.

Figure 6 shows the measured SPL of the brake dynamometer when two application dither control is applied. Figure 6(a) shows the SPL of the squeal noise at the brake dynamometer. There is a recorded peaks at 4.6kHz with sound pressure level of 32dB. As shown in Figure 6(b), the results show that the squeal amplitude has been reduced to 24 dB (8 dB down) with the application of dither control at 19kHZ. Figure 6(c) shows the result with second application dither control applied to the brake dynamometer. As the result, the squeal was reduced by 8 dB by the dither control applied at 20 kHz.

Figure 7 show the time-frequency response of the system. The dither signal was applied at 9-20 s. As can be seen, the 19kHz dither signal is effective in reducing the squeal noises. It should be noted that the applied dither control is higher than the audible ranges.

.

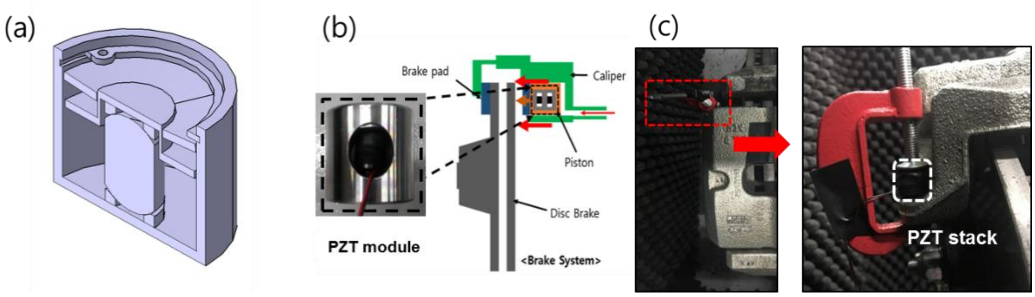

Figure 5: PZT stack module (a) module cross section (b) module inside caliper piston.
(c) PZT stack put on the carrier

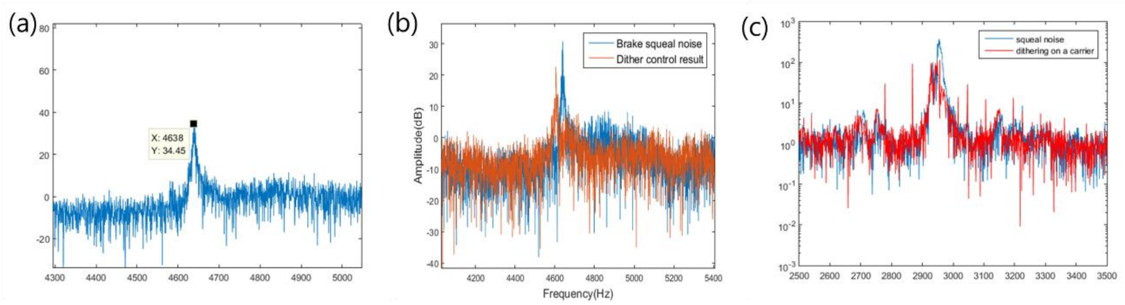

Figure 6: (a)Squeal noise (b) First application result (c) second application result

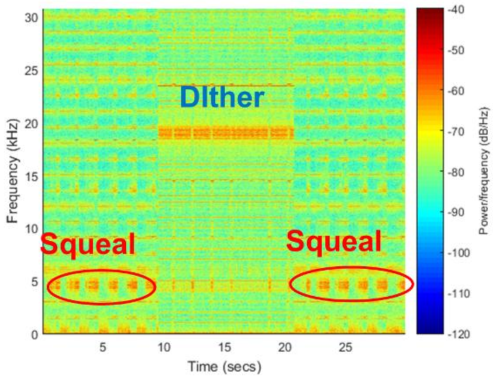

Figure 7: result of first application dither at time-frequency domain

3 SQUEAL NOISE SUPPRESSION USING SHUNT DAMPING

3.1 Experimental procedure

The experimental setup is shown in Figure 8. The shunt damping is applied to the pin-on-disk system using a patch type PZT. We used the same experimental setup as the dither experiment. Figure 9(a) shows the SPL of the squeal noise at the pin-on-disk system measured. There are also three recorded peaks at 8kHz with sound pressure level of 45dB. The target frequency of the shunt was set at 8.5 kHz.

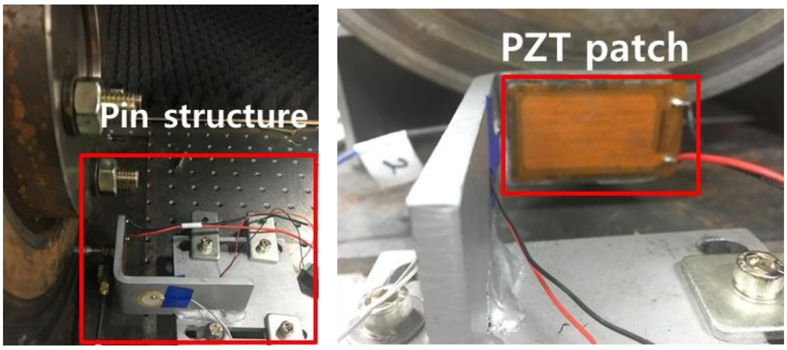

Figure 8: The pin-on-disk system for shunt damping

3.2 Squeal suppression experiments

The experimental results are shown in figure 9. The shunt damping is originally on when the system generate the squeal noises. At 5 second, the shunt is set off, and it is clearly shown that the squeal noise increased by 5 dB as shown in figure 9(b). Our current effort focuses on i) the optimization of shunt parameters, and ii) the use of the same piezo-stack module for both dither control and shunt damping.

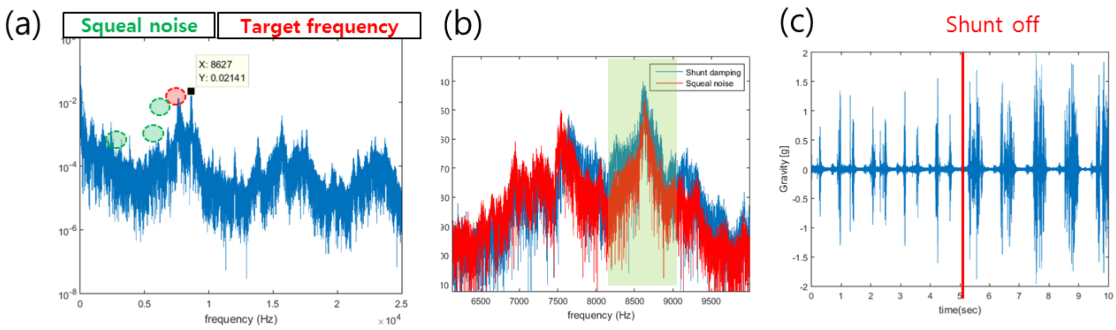

Figure 9: (a) squeal noise, result of shunt damping (a) frequency domain (c) time domain

4 CONCLUSIONS

The paper presents the performance of piezoelectric-based devices for automobile squeal noise suppression. Two techniques are employed, including dither control and shunt damping. Dither is a concept of active noise control by introducing high-frequency vibrations into a system to suppress lower-frequency disturbances. Shunt damping is a passive technique, which dissipates the systems' vibration energy with piezoelectric devices. Several experimental investigation are performed to the built-in break systems. The results indicate that the proposed device could effectively suppress the brake squeal noise. It was found that the dither could reduce the squeal noise by 8 dB, while the shunt damping still requires further optimization to suppress the squeal noise.

ACKNOWLEDGEMENTS

This research is supported by Hyundai Motor Company and the Basic Science Research Program (NRF-2015R1D1A1A01059092) and the Leading Foreign Research Institute Recruitment Program (2011-0030065) through the National Research Foundation of Korea (NRF). This research is also partially funded by the Ministry of Science, ICT and Future Planning.

REFERENCES

[1] A. Akay, Acoustics of friction, *Journal of the Acoustical Society of America* 111, 2002, pp. 1525-1548.

[2] Papinniemi, A., Lai, J. C. S., Zhao, J., Loader, L., Brake Squeal: a literature review, *Applied Acoustics*, 63, 2002, pp. 391-400.

[3] O. MORGUG L, On the control of some chaotic systems by using dither, *Physics Letters A*, 262, 1999, pp. 144-151.

[4] Choe-Yung Teoh, Zaidi MohdRipin, Dither effect on drum brake squeal, *Journal of Vibration and Control*, 23, 7, 2015, pp. 1057-1072

[5] Cunefare KA, Graf AJ, Experimental active control of automotive disc brake rotor squeal using dither. *Journal of Sound and Vibration*, 250, 2002b, pp. 579–590.

[6] Thomsen JJ, Some general effects of strong high-frequency excitation: stiffening, biasing and smoothening. *Journal of Sound and Vibration*, 253, 2002, pp. 807–831

[7] Cunefare KA, Graf AJ, Experimental active control of automotive disc brake rotor squeal using dither. *Journal of Sound and Vibration*, 250, 2002b, pp. 579–590.

[8] Pervozvanski AA, Canudas-de-Wit C, Asymptotic analysis of the dither effect in systems with friction. *Automatica*, 38, 2002, pp. 105–113.

[9] Michaux MA, Ferri AA, Cunefare KA Effect of tangential dither signal on friction induced oscillations in an sdof model. *Journal of Computational and Nonlinear Dynamics 2*, 2007,pp. 201–210.

[10] Teoh CY, Ripin ZM, Transient analysis of drum brake squeal with binary flutter and negative friction-velocity instability mechanisms. *Journal of Vibroengineering*, 13, 2011, pp. 275–287.

[11] N.W. Hagood, A. von Flotow, Damping of structural vibrations with piezoelectric materials and passive electrical networks, *Journal of Sound and Vibration*, 146, 1991, pp. 243-268

[12] Lesieutre, G. A., Vibration Damping and Control Using Shunted Piezoelectric Materials, *Shock Vibr. Dig.*, 30(3), 2008, pp. 187–195.

[13] Guyomar, D., Richard, T., and Richard, C., Sound Wave Transmission Reduction Through a Plate Using a Piezoelectric Synchronized Switch Damping Technique, *Journal of Intelligent Material Systems and Structures*, 19(7), 2008, pp. 791–803.

[14] Forward, R. L., Electronic damping of vibrations in optical structures, *Applied Optics*, 18, 1979b, pp. 690–697.

[15] Neubauer, Marcus and Matthias Kroeger, Suppression of brake squeal using piezoceramics. In: Braking 2006, *International Conference on Vehicle Braking Technology*. 2006, pp. 254–263.

[16] Tang, J. and Wang, K. W. Active–passive hybrid piezoelectric networks for vibration control: comparisons and improvement. *Smart Materials and Structures*, 10, 2001, pp. 794–806.

[17] Neubauer, M., Oleskiewicz, R., Popp, K., and Krzyzynski, T. Optimization of damping and absorbing performance of shunted piezoelements utilizing negative capacitance *Journal of Sound and Vibration*., 298, 2006, pp. 84–107