Ultrasonic Evaluation of Young's Modulus for Reduction of Brake Squeal Noise

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Abstract. Elastic properties of friction materials in brake linings are important design parameters because modulus variations may lead to noise generation of braking systems. This paper is to describe about ultrasonic estimation of Young's modulus of brake linings concerned with squeal noise problem for commercial trucks. Phase velocity of ultrasound propagating through brake lining was measured to calculate Young's modulus based on elastic relations of acoustic waves with material properties. Two kinds of brake lining samples were produced with the same composition by different manufacturing process, one of which is a traditional product and the other is an advanced one developed for brake noise reduction. Five rectangular samples were cut out from each type of brake linings and machined for ultrasonic test. Acoustic pulse of 500KHz was applied to each sample to calculate the time-of-flight(TOF) for the measurement of wave velocity and Young's modulus. The results of ultrasonic test indicate that the low noise brake samples have a less deviation of Young’s modulus than the traditional brake samples. This agrees with previous researches and FEM analysis that Young's modulus variation of brake linings affects the squeal propensity and the instability of brake system.

1. Introduction
The braking system of a vehicle is one of the most fundamental safety-critical components used to decelerate a moving body. Due to the braking operation, the brake system generates an unwanted high frequency sound known as brake squeal that makes the driver uncomfortable. Among the different types of brake noise, squeal noise, because of its higher frequency contents between 1 kHz and 16 kHz, is the most troublesome and irritant one to drivers and the environment, and is expensive to the brakes and car manufacturers in terms of warranty costs [1-3]. There are six mechanisms of squeal formation namely: stick–slip, sprag–slip, negative friction velocity slope, hammering excitation, splitting the doublet modes and mode coupling of structures [4]. It is commonly accepted by researchers that squeal noise in a brake system may be generated by either one of the above mechanisms, or the combined depending on the brake design and operational conditions. From numerous papers on both linear and non-linear stability analyses of dynamical systems with friction-induced vibrations, it is obvious that the effect of the friction material stiffness on squeal noise is indispensable for the design of a quiet brake system. Brake linings or pads are a composite material bonded with various synthetic substances comprised of more than 10 different substances including metals, rubber and organic materials to improve friction property, increase strength, prolong life, and reduce noise. Thus, despite of the same composition, it can have a variation in density and Young’s modulus depending on the manufacturing method. This local heterogeneity in material property, especially Young’s modulus, may increase the propensity of squeal noise caused by friction-induced instability of vibration associated with mode coupling.
This paper investigates the variation of Young’s modulus in brake linings responsible for squeal noise using ultrasonic method. Two kinds of brake lining samples for commercial trucks were prepared to measure and compare its Young’s modulus. It is concluded from acoustic experiment that the variation of Young’s modulus of low noise brake lining is half of the traditional linings, and is estimated effectively by ultrasonic method in non-destructive and quantitative way for the quality control of brake linings.

2. Fabrication of brake lining samples

The Brake system of trucks has a set of linings which is pressed against a rotating drum when it brakes and heated due to friction at the drum-lining interface in a short period of time. Due to these severe working conditions during operation, macro-cracks and friction-induced vibration with noise might develop on the disc surface in the radial direction. Brake lining is generally a combination of a steel back plate and a friction material fixed on the steel back plate as shown in Fig. 1. Heavy duty brake linings are currently manufactured by powder metallurgy (PM) method to compact and sinter the metal powder mixture containing about 20–30% non-metallic constituents [5, 6]. In this process, the friction materials should be formed as uniform as possible even if the flowability of the powdered raw friction material is insufficient. However, conventional brakes have a problem of making brake noises caused by friction-induced vibration partly because of non-uniform distribution of friction materials. Therefore, it is necessary to evaluate local Young’s modulus of brake pads/linings for the quality control of squeal noise. In this work, the variation of Young’s modulus was investigated for an actual drum brake linings used for heavy-duty trucks as shown in Fig. 1(a) and Fig. 1(b) using ultrasonic nondestructive method.

![Figure 1](image1.png)

Figure 1. Drum brake lining of heavy-duty trucks, (a) side view, (b) top view.

Two kinds of brake linings were prepared with the same composition for this study, one of which is a product manufactured by conventional PM method, and the other made by an advanced PM method developed for noise reduction. From each brake lining, five rectangular samples (5mm in thickness and 30mm x 30mm in width) were cut out from different locations respectively as shown in Fig. 2(a) and machined for ultrasonic test. Total 10 specimens fabricated from a conventional brake lining and a newly developed brake lining are displayed all together in Fig 2(b) and numbered consecutively to identify where it comes from in each lining. In Fig. 2(b), five samples on the top ( #1 ~ #5) were from a conventional brake lining, and the next five ones ( #6 ~ #10) from a low-noise brake lining.

![Figure 2](image2.png)

Figure 2. Fabrication of test specimens, (a) sampling method, (b) test specimens
Measurement of Young’s modulus using ultrasonic method

Measurement of ultrasonic wave velocity was conducted to estimate the elastic modulus of brake lining specimens using the pulse-echo method and the time-of-flight (TOF) measurement. In the TOF method, an acoustic transducer generates a pulse signal of ultrasound that propagates and reflects back from the back surface of samples, being detected after a delay. This duration of wave propagation depends on the thickness of the brake specimen as well as the elastic properties of the traveling medium (brake specimen). The configuration of experiment is illustrated in Fig. 3 to measure the TOF of ultrasonic pulse. At the start of a measurement, a pulse generator (JSR Ultrasonics, DPR300) excites an electric pulse, which is converted into a ultrasonic transducer (Technisonics, C0008GP) to ultrasonic pulse of 500kHz propagating through the specimen at a velocity \( c \). When it travels in the specimen, the pulse reflects multiple times at the boundaries of brake specimen and returns to the transducer repeating this round-trip travel as shown in Fig. 3(a). After these echoes were recorded in digital oscilloscope (Lecroy wave runner 530), the time interval between two maximum peaks of consecutive echoes was measured. Fig. 3(b) shows the pulse-echo measurement equipment of the TOF for brake lining samples, where an echo signal from the back surface is captured and used to calculate the TOF of the ultrasonic wave. The acoustic phase velocity \( c \) is expressed through the TOF and the thickness of the plate \( d \) by the simple relation of equation (1).

\[
c = \frac{2d}{TOF}
\]

The TOF method is very easy and simple to use and works well unless it suffers from low signal-to-noise ratio (SNR) or signal shape distortion due to high attenuation and nonlinearity. For an isotropic material, the elastic modulus is related to the ultrasonic wave velocity (compression mode) \( c \) as the following [5,6].

\[
E = \rho c^2
\]

where \( E \) is the Young’s modulus, \( \rho \) is the density of material. The assumption made in equation (2) is not correct in a strict sense, but is reasonable if the friction materials of highly irregular shape and size are mixed well like poly-crystalline structure and relatively small compared with the wave length of ultrasound. On each sample, five different points were selected for ultrasonic measurements including the center of the specimen and other four points around the center at 0, 90, 180, and 270 degrees. One hundred acoustic signals were collected at each point and averaged over the five measurement locations of the sample to obtain more reliable and accurate TOFs.

![Figure 3. Measurement of ultrasonic wave speed, (a) pulse-echo test in sample, (b) acoustic equipment - ultrasonic transducer, pulser/receiver and oscilloscope.](image)
4. Experimental results

Once the TOF from reflection signals for brake lining specimen was obtained in ultrasonic test, the Young’s modulus was calculated from the acousto-elastic relation of equation (2). Acoustic velocity and Young’s modulus of five specimens of the conventional brake lining are listed in Table 1 along with basic geometric and physical properties. Maximum Young’s modulus was 60.8Gpa and minimum was 57.1Gpa. Percentage standard deviation of five measurement values of Young’s modulus was 2.5%. As for the low-noise brake lining samples, the maximum Young’s modulus was found in Table 2 to be 60.8Gpa and the minimum 59.1Gpa. Percentage standard deviation of five measurement values of Young’s modulus was 1.1%. It was found from experimental results that the low-noise specimens revealed a less deviation in Young’s modulus than the traditional ones as it was reported in previous experimental and theoretical researches [2-4, 7].

Table 1. Young’s modulus and wave velocity of conventional brake linings

| Specimens (conventional lining) | Density [kg/m³] (ρ) | Thickness [mm] (d) | Acoustic wave velocity [mm/sec] (c) | Elastic modulus [GPa] (E) | Standard Deviation [%] (σ) |
|---------------------------------|---------------------|-------------------|-------------------------------------|--------------------------|--------------------------|
| #1                              | 1,790               | 4.98              | 5,651                               | 57.1                     | 2.5 %                    |
| #2                              | 1,800               | 4.98              | 5,816                               | 60.8                     |                          |
| #3                              | 1,800               | 4.97              | 5,754                               | 59.5                     | 2.5 %                    |
| #4                              | 1,810               | 4.91              | 5,697                               | 58.7                     |                          |
| #5                              | 1,810               | 4.98              | 5,644                               | 57.6                     |                          |

Table 2. Young’s modulus and wave velocity of low-noise brake linings

| Specimens (conventional lining) | Density [kg/m³] (ρ) | Thickness [mm] (d) | Acoustic wave velocity [mm/sec] (c) | Elastic modulus [GPa] (E) | Standard Deviation [%] (σ) |
|---------------------------------|---------------------|-------------------|-------------------------------------|--------------------------|--------------------------|
| #6                              | 1,820               | 4.97              | 5,701                               | 59.1                     | 1.1 %                    |
| #7                              | 1,790               | 4.97              | 5,775                               | 59.6                     |                          |
| #8                              | 1,800               | 4.95              | 5,810                               | 60.8                     | 1.1 %                    |
| #9                              | 1,830               | 4.97              | 5,757                               | 60.6                     |                          |
| #10                             | 1,830               | 4.97              | 5,724                               | 59.9                     |                          |

5. Conclusions

Young’s modulus of drum brake linings for heavy-duty truck were estimated by ultrasonic method for the investigation of the variation of elastic constant responsible for squeal noise. Rectangular specimens extracted from two different types of brake linings were fabricated and subject to acoustic pulse excitation of 500 kHz for the measurement of ultrasonic wave velocity of lining samples. The specimens from the traditional brake lining had a variation in Young’s modulus ranging from the maximum 60.8GPa to the minimum 57.1GPa with 2.5% standard variation. On the other hand, the specimens from low noise lining had Young’s modulus from the maximum 60.8GPa to the minimum 59.1GPa with 1.1%
standard variation. From the experimental results, the samples from low noise lining were found to have more even distribution of Young’s modulus than the traditional one, even though they had the same composition. This agrees well with previous researches that the variation of Young’s modulus in brake lining has an effect on squeal noise, i.e., the low deviation of Young’s modulus of brake lining reduces squeal noise. It is also concluded that ultrasonic measurement of Young’s modulus is very effective, fast and economical to evaluate the quality assurance of brake linings for squeal noise reduction.

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**6. References**

[1] Rashid A 2014 *International J. of Vehicle Noise and Vibration* **10**(2014) 257
[2] Belhocine A and Ghazaly N M 2015 *Latin American Journal of Solids Structure* **12** 1432
[3] Nam J and Kang J 2013 *Trans. of the Korean Society of Noise and Vibration Eng.* **23** 717
[4] Ghazaly N M, El-Sharkawy M and Ahmed I 2014 *J. of Mechanical Design and Vibration* **15**
[5] SAE international Surface Vehicle Standard 2009 SAE standard J2725_200901
[6] Kim N and Yang S 2016 *J. of the Korean Soc. for Nondestructive Testing*, **36** 9
[7] Negesh S N, Siddaraju C, Prakash S V and Ramesh M R 2014 *Procedia Mat. Sci.*, **5** 295