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NON-DESTRUCTIVE ULTRASONIC METHODS FOR QUALITY ASSURANCE OF BRAKE PADS

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ABSTRACT

Brake noise, a major source of warranty cost, is a complex problem involving a myriad of design and processing variables that include friction material properties, rotor design, caliper design, and vehicle suspension. Although noise is minimized through proper brake design and appropriate choice of the friction material formulation, the realization of noise-free brakes in commercial vehicles requires that critical friction material properties are maintained in production. Process variations can significantly alter friction material properties which can adversely influence noise performance.

In this paper, we explore ultrasonic methods to measure uniformity and consistency of brake pads non-destructively. These studies explore how ultrasonic measurement can be implemented as both part of a control scheme to improve the manufacture of friction materials and/or as a quality assurance method to ensure that noise-prone components do not enter the marketplace. Over 300 brake pads of 7 different configurations from 5 different manufacturers were non-destructively measured. Measurements on production pads demonstrated significant variations in both the average value and spatial uniformity of friction materials from various manufacturers. Process specific studies related measured ultrasonic characteristics to variations in manufacturing. To enable rapid, automated, testing with this method, a series of laboratory experiments was performed to identify optimal ultrasonic coupling methods, signal processing schemes and analysis methods. A mechanically scanned prototype system was assembled and used to test brake pads. Comparison of automated test results with those obtained using manual test methods established the feasibility of the automated testing scheme and the applicability of the ultrasonic method.

INTRODUCTION

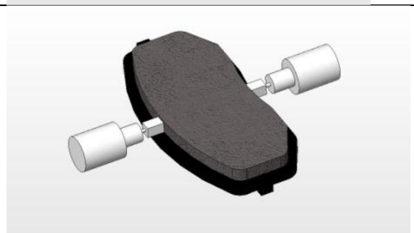
Friction material manufacturing is subject to intra-material as well as inter-batch inconsistency that existing methods are unable to adequately quantify at the point of manufacture. These inconsistencies adversely affect customer satisfaction, contribute to lost business and consume engineering and testing resources. Both material formulation and process variations significantly alter friction material characteristics and adversely influence noise performance. Because mechanical properties of friction materials are thought to play an important role in braking system noise performance (1-4), test methods sensitive to these mechanical properties are desirable. Methods based on ultrasonic propagation offer the promise for a non-destructive method that can be implemented as both part of a control scheme to improve the manufacture of friction materials and/or as a quality assurance method to ensure that noise-prone components do not enter the marketplace.

Several previous studies have reported on the use of ultrasound to measure the engineering constants of friction materials (5-7). The use of ultrasound to determine the mechanical properties of materials is based on the fundamental relationship between the ultrasonic velocity and the material elastic constants (8). This method, described in detail in SAE specification J2725 (5), is the only technique capable of measuring all 5 of the independent engineering constants for the transversely isotropic friction materials. These results are used primarily to provide input data for the modelling and simulation of brake noise. As currently applied to friction materials, this method is destructive. It requires removing the friction material from the steel backing as well as making special cuts in order to measure off-diagonal elastic constants. However, the ultrasonic technique in intrinsically non-destructive and can be applied to as-manufactured components to obtain relevant characterization data.

EXPERIMENTAL METHODS

In this study ultrasonic methods are applied to intact, as-manufactured pads where 4 of the 5 independent velocities can be measured. The measurement technique has been described previously and is identical to that used to measure elastic constants in processed samples (5-8). For intact pads, measurements can be made of two in-plane modes, the longitudinal mode V_{22} and the shear mode V_{21} and two thickness modes, the longitudinal mode V_{33}, and the shear mode V_{32}. The in-plane modes entail propagating ultrasound in the plane of the pad. The measured velocity is related to the flexural and torsional modes of the pad. For the thickness modes, the ultrasound is propagated through the pad and steel backing. The resultant velocities are inversely related to the pad compressibility and shear modulus. Table 1 shows the 4 velocity modes that can be readily measured on as-manufactured brake pads, the measurement geometry, the related elastic constants, and related methods.

Table 1: Velocity Modes Measured on Intact Pads

Mode	Geometry	Related Elastic Constant	Related Methods
V_{33}		$C_{33} = \rho V_{33}^2$ Thickness Longitudinal Modulus	Compressibility
V_{32}		$C_{32} = \rho V_{32}^2$ Thickness shear Modulus	Compressibility
V_{22}		$C_{22} = \rho V_{22}^2$ In-plane Longitudinal Modulus	Modal (Flexural)
V_{21}		$C_{21} = \rho V_{21}^2$ In-plane shear Modulus	Modal (Torsional)

As with the destructive measurement method (SAE J2725), all modes are measured using "pitch-catch" geometry. The velocities are determined by dividing the length of the propagation path by the measured time-of-flight, ToF. For the in-plane modes, V_{22} and V_{21}, the propagation path is simply the separation between the two sensors. For as-manufactured brakes, the ultrasound must be coupled into and out of the curved surfaces of the friction material which may require some sensor modification such as reducing aperture size or implementation of an ultrasonic lens. For the thickness modes, V_{33} and V_{32}, the ultrasound must propagate through both the friction material and the steel backing plate. It is a relatively easy process to correct for the steel backing contribution to the ToF. This imparts less than a

0.2% measurement error. For the velocity results presented in this study the contribution from the steel backing has been removed from the data. Velocity data are the result of the properties of only the friction material/underlayer combination.

The measurement process begins by generating a scanning template which is illustrated in Figure 1. In this example, we show the measurement of eight locations as indicated by the numbered circles. The location and number of the thickness direction sampling points will vary from one pad type to the next as it is not possible to measure in zones where there are chamfers or spigot holes. Each measurement area is 1.25 centimeters in diameter. The in-plane mode propagation trajectory is illustrated by the dashed lines. In the example shown in Figure 1, four in-plane trajectories are depicted. As with the thickness modes, the number and location of the in-plane propagation paths are dependent upon the brake pad geometry.

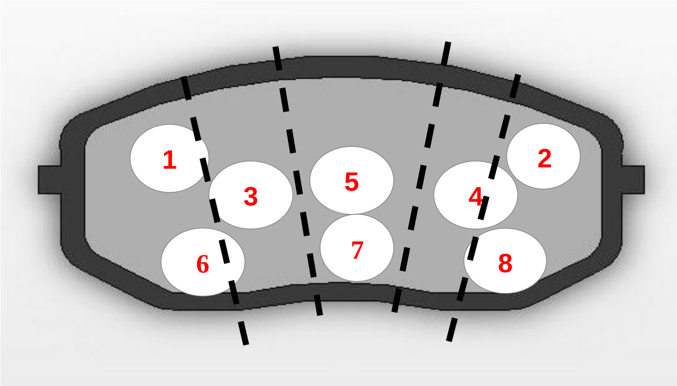


Figure 1: Example measurement template for thickness direction measurements on a brake pad (the numbered circles indicate the measurement locations)

It is of interest to determine the measurement error (repeatability) when applied to as-manufactured brake pads. This was accomplished for the various modes by making repeat measurements on 10 production pads. Figure 2 shows the results obtained for 2 modes, the through-the-thickness mode, V_{33} (Figure 2a), and the in-plane mode, V_{22} (Figure 2b). For the V_{33} mode, the mean value for the 6 repeat measurements along with the standard deviation (error bars) are plotted for each of the 10 pads labelled "6-1" to "6-10". Similar results for the 6 repeat measurements for the V_{22} mode are shown in 2b. These results quantify the measurement error for our test method which varies from +/- 0.2% to 0.5% for the through-the-thickness modes and +/- 0.3% to 0.7% for the in-plane modes. Essentially identical results are obtained on the shear modes V_{32} & V_{21}.

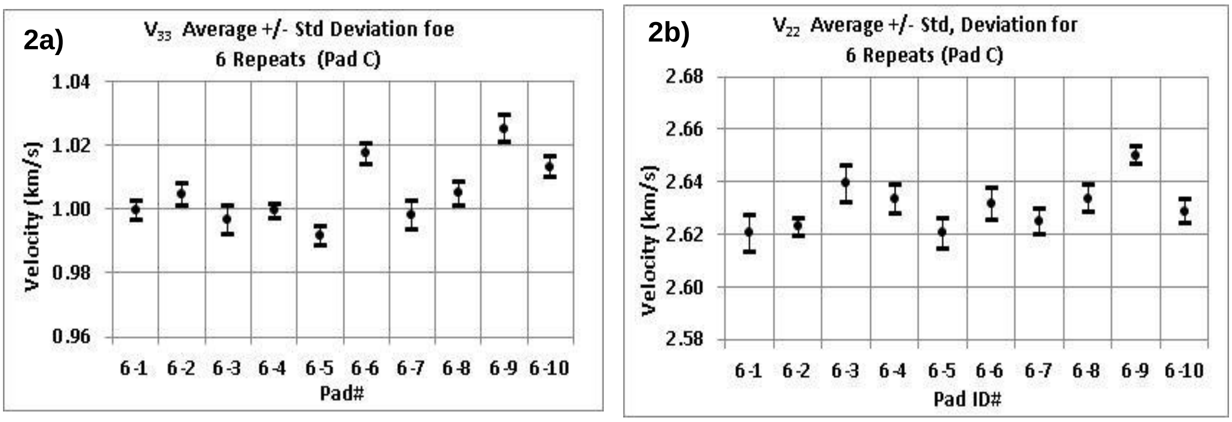


Figure 2: Average and standard deviation for 6 repeats on the 10 pads for V_{33} and V_{22} modes

TYPICAL DATA

Ultrasonic velocity data obtained on several different production pads produced by several different vendors has been presented in a previous study (9). In this paper, we summarize several of these findings, report on additional observations, and present test data directed at formulating ways to automate the measurement process.

One production study was directed at measuring the long term uniformity of production pads. In this study we measured a total of 140 pads (Pad type C) consisting of 20 pads from seven different months of production over a time span of 18 months. Figure 3a shows the average velocity data for all modes obtained on all production brake pads. For the through-the-thickness modes, V_{33} & V_{32}, five regions were measured on each pad, while for the in-plane velocity, V_{22} & V_{21} only 3 zones were measured. These brake pads were among the best production pads measured in terms of consistency and uniformity. The anisotropy of these pads is 2.7 (ratio of in-plane to out-of-plane velocity) which is typical for brake pads. It is apparent that the first batch of 20 samples show slightly elevated in-plane values, V_{22} = 2.705+/-.016 km/s and V_{21} = 1.637+/-.010 km/s versus 2.627+/- .022 km/s and 1.601+/-.012 km/s for the remaining six batches. Although these differences are small, they are significant relative to the measurement error (+/- 0.5%, see Figure 2). For the through-the-thickness modes there appears to be no significant measurable difference between the batch 1 average and the remaining six sample batches.

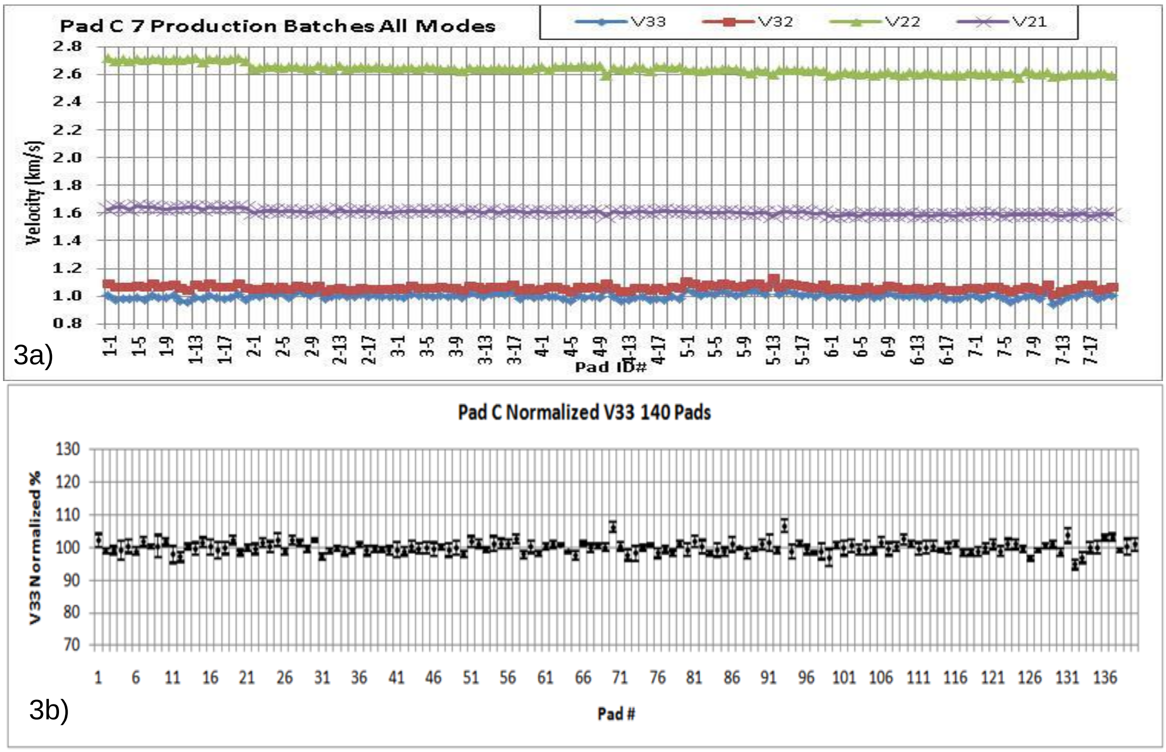


Figure 3: a) All 4 velocities measured on 140 production pads manufactured from August 2008 to March 2010; 3b) Mean and standard deviation for V_{33} on all 7 batches of the 140 Pad C production pads

Although not highlighted in Figure 3a, the through-the-thickness modes V_{33} & V_{32} are highly correlated with each other as are the 2 in-plane modes, V_{22} & V_{21}. Figure 3b shows a measurement of the V_{33} mode normalized to the group average (average = 100%). In this plot, the normalized value for each pad is plotted along with the +/- standard deviation of the 5 measurements made on each pad. Most of the values fall within a few % of the mean indicating the long term stability of both the measurement process and the pad manufacture. There are a few “outlier pads” with excursions from the mean as high as 8%. Because our test is non-destructive, there is a potential that "outlier" pads can be identified and removed from the population so that additional tests, including noise studies could be carried out in subsequent investigations.

Figure 4 shows thickness direction V_{33} data obtained on a different pad material (pad type X). This Figure shows data from 5 pads where 8 measurements were made on each pad (see Figure 1 for position location). The data is plotted in two ways: 4a) shows the average velocity measured on each pad (eight positions) along with the standard deviation of the measurement; 4b) shows the variation by position in each pad. These results indicate that both the pad-to-pad variation (mean value in 4a) and the variation within each pad (standard deviation in 4a) are quite high for this material. Figure 4b indicates that there is a systematic spatial variation in the velocity distribution. Positions 3, 4, and 5 exhibit systematically lower velocity relative to the other five positions. This systematic spatial variation in the measured velocity is probably related to the manufacturing process.

The influence of the friction material underlayer on the measured velocities is shown in Figure 5. In this study, the thickness of the underlayer was deliberately varied while the friction material formulation remained constant. Four different underlayer thicknesses were investigated ranging from 0 mm to 6 mm in thickness. For each underlayer thickness, 64 pads were fabricated and tested (32 "in-board" pads and 32 "out-board" pads). Figure 5 shows the ultrasonic data for the thickness direction modes, V_{33} and V_{32}, for the 64 pads. The results show both measured velocities decrease with increasing underlayer thickness. This data also shows the longitudinal measurement, V_{33}, and the shear measurement, V_{32}, are highly correlated. Only the average velocities are shown in Figure 5. For each pad, 8 independent measurements are made for each mode. The average variation within each pad is 7% for the V_{33} mode and 6% for the V_{32} mode. Conventional compressibility tests were made on these pads and correlated with this velocity data which yielded correlation coefficients of R^2=0.94 for both velocity modes (9).

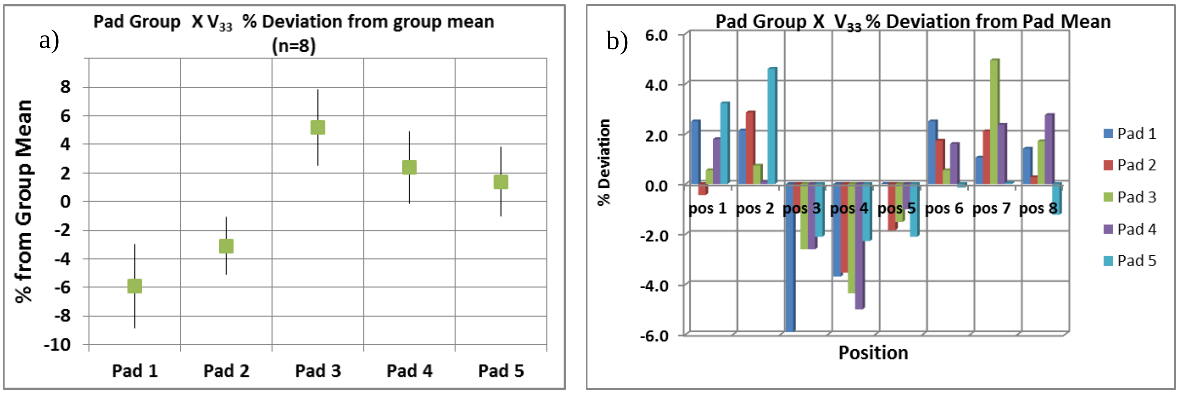


Figure 4: Typical thickness direction V_{33} data obtained on a series of 5 pads where 8 measurements were made on each pad

RELATION TO NVH PERFORMANCE

Ultimately, the use of ultrasonic velocity as an important quality assurance tool will depend upon its effectiveness as a predictor of noise performance. It is recognized that the modulus and specifically the compressibility of the brake is one of many factors controlling noise performance (4, 6, 10). It is also recognized that the velocity is fundamentally related to relevant elastic properties. Direct correlations between ultrasonic data and subsequent noise analysis are desirable. A limited amount of work has been done to establish this relationship.

Eight of the brake pads (4 "in-board" and 4 "out-board") characterized ultrasonically as part of the "underlayer process" study described in the previous section were subjected to dynamometer noise measurement (SAE J2521). These tests included one pair with 0 mm underlayer, two pairs with 2 mm underlayer, and one pair with 6 mm underlayer. With reference to the data in Figure 5 these represent pads with high velocity, intermediate, and low ultrasonic velocity respectively. This dynamometer test consists of more than 450 stops with airborne noise amplitude recorded in the frequency range from 2 kHz to 17 kHz. A small snapshot of the results of the noise test are shown in Figure 6 where the average value of the V_{33} velocity for the pair of pads is correlated with the % of noisy stops >70 dB. The pads exhibiting the lower through-the-thickness velocity (thicker underlayer) yield the larger % of noisy stops above 70 dB. The R^2 correlation coefficient for the 4 data points is 0.97. The limited amount of data and the bi-modal nature makes any definitive conclusions from Figure 6 somewhat questionable. The results are certainly limited to this pad configuration, platform, and friction material formulation. However, these results do illustrate the potential of the non-destructive method to measure and select pads with specific characteristics prior to noise evaluation.

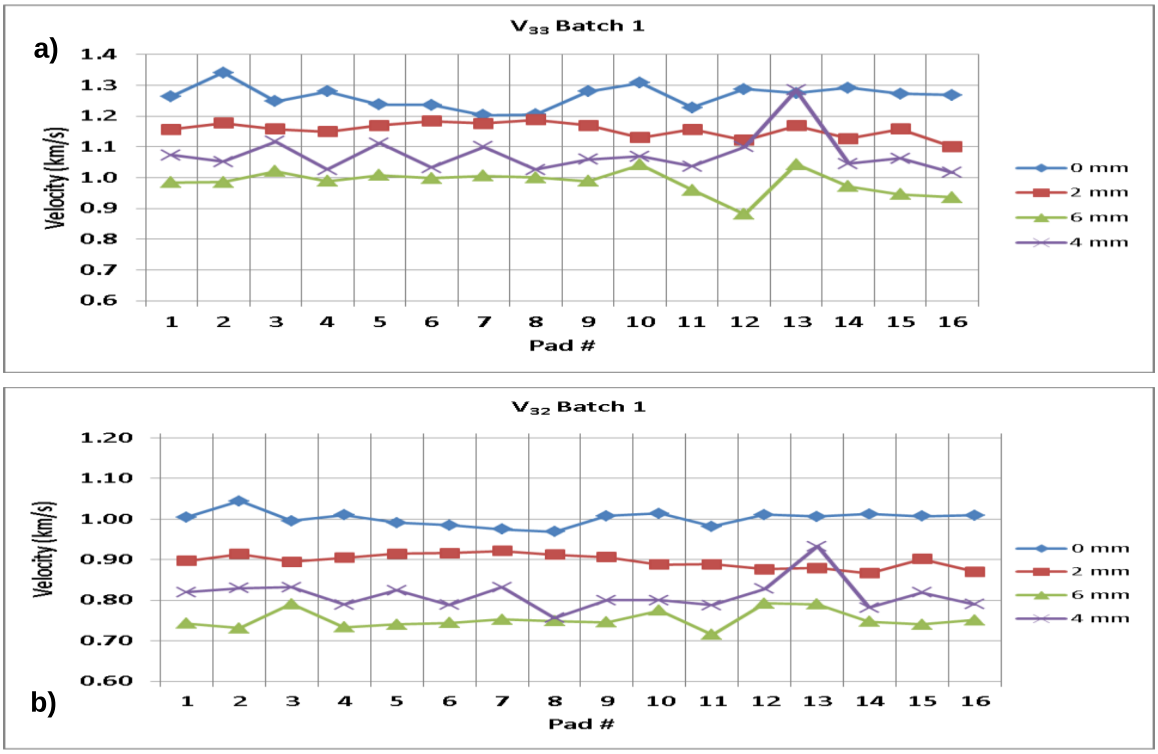


Figure 5: a) Average V_{33} measured on individual samples manufactured with varying thickness of underlayer; b) V_{32} data. Each data point is the average value of 8 measurement positions

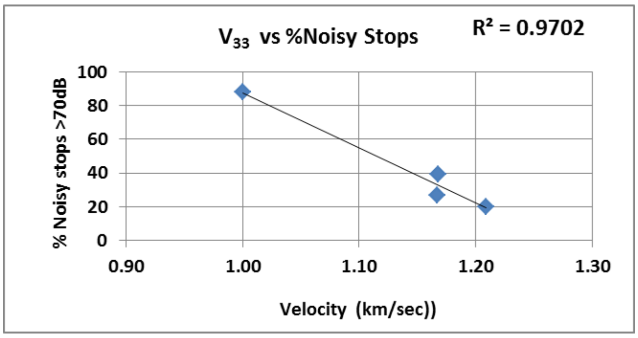


Figure 6: Correlation between the % noisy stops > 70 dB and the measured V_{33}.

PROTOTYPE SYSTEM

All results presented in the previous section used the same instrumentation and methods as those used for laboratory analysis of friction materials. In order to evaluate the potential for automating the ultrasonic measurement process, a prototype measurement system was developed. The parts handling system consists of an open frame x-y mechanical stage and a single vertical axis stage to hold the ultrasonic sensors. One sensor is instrumented with a load cell to measure the coupling force. A spring-loaded brake pad holding fixture was constructed and attached to the stage and configured such that the pad could be scanned to allow measurement of multiple positions. These various components are illustrated in Figure 7.

The instrumentation components of the system are illustrated in Figure 8. The system is designed such that there is a contact force feedback loop that can be used to acquire ultrasonic data at one or more user specified loads. With the sensors retracted, the brake pad is moved to a position predetermined by the user, the sensors are then coupled at a user-defined load and the ultrasound pulse recorded and processed to measure the time-of-flight (ToF).

The system consists of ultrasonic hardware used to generate and receive the ultrasonic pulse, a high speed analog to digital convertor (100 MHz) to capture and process waveforms, and signal processing to determine the ToF. The data collection and ToF measurement can be made extremely rapidly with processing time of a fraction of a millisecond. Raw data is recorded as a rate of 100 Megasamples/sec. Inspection speed is limited primarily by the parts handling hardware.

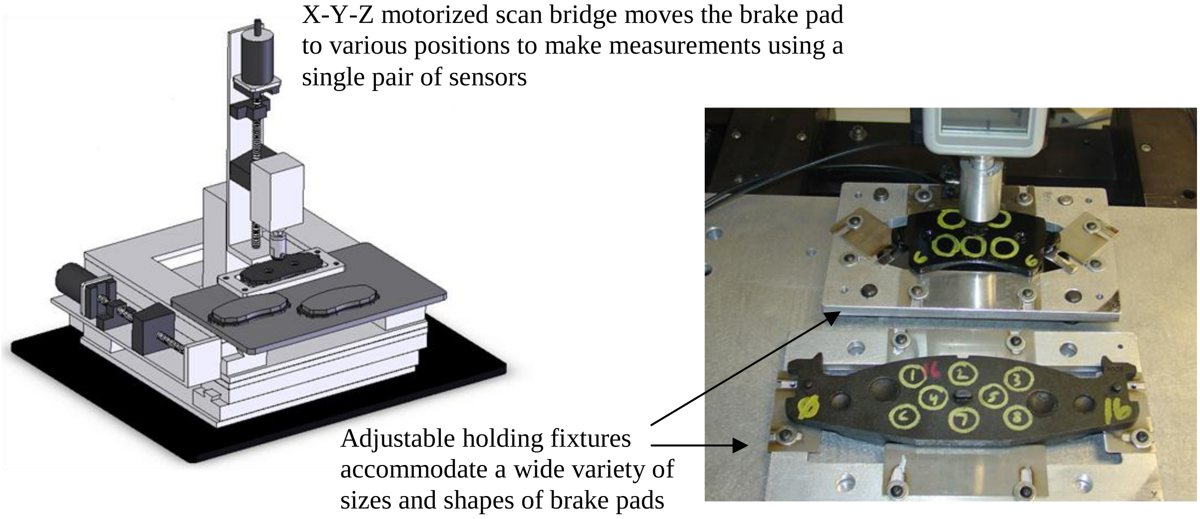


Figure 7: Prototype ultrasonic system for automated measurement of V_{33} and V_{32} in brake pads

For the automated system, it is desirable to integrate the measurement of coupling pressure into the measurement process in order to both improve the repeatability of the measurement as well as enable measurements at different coupling loads. The automated system benefits from automatic gain control (AGC). The dynamic range of the ultrasonic system is on the order of 100 dB, thus implementation of an automatic gain control scheme offers the potential to compensate for any variations in coupling efficiency. In addition, in certain configurations, the signal loss may be an important parameter that can be monitored when AGC capability is in place.

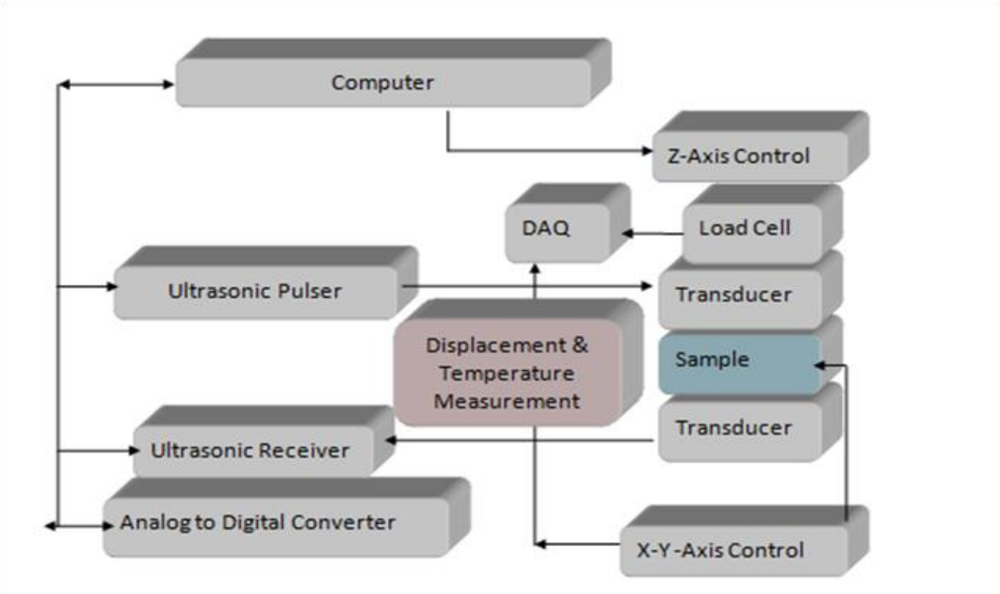


Figure 8: Block diagram of the automated system

For this implementation, system flexibility takes priority over inspection speed. It is essential that the system is capable of generating data on a wide variety of pad geometries with minimal set-up time. The prototype system uses simple peak detection for ultrasonic velocity measurement which isolates the highest amplitude sample point within a window. The operator selects a window in which to search and the software selects from within this window the highest amplitude peak. This method is subject to instrument noise when not using averaging or filtering but operates independent of frequency, phase and pulse shape, making it ideal for velocity measurements in significantly differing anisotropic materials such as brake pads.

One of the practical issues which needs to be addressed for the implementation of a fully automated test system is the coupling of the ultrasound into and out of brake pads. Because of the high ultrasonic frequencies employed, the ultrasound is attenuated by air and the strong acoustic impedance discontinuity between the solid pad and the air leads to significant signal loss. For the semi-automated laboratory tests presented previously, a viscous, water-soluble gel was used to couple the ultrasound. However the use of couplant is undesirable for production testing in that the couplant must be removed (particularly if in contact with the friction material surface) which adds cost to the inspection.

Several alternate non-liquid approaches to coupling ultrasound into the brake pads have been explored. These include various combinations of direct pressure contact, liquid/gel coupling to the steel side, and the use of intermediate compliant layers. We have found that soft, thin, low modulus sheets of material appear to be useful for reliable and repeatable coupling to the brake pads. It is even possible to make measurements on the brake pads using no couplant. In this case one incurs an additional 20 dB signal loss (factor of ten) but does not appear to compromise the integrity of the measured velocity data.

The prototype system depicted in Figure 7 was assembled and tested. To date, this system has been used to measure the V_{33} and V_{32} velocities on two different pad configurations. An IMS produced video demonstration can be found at the IMS website at the following URL: (http://imsysinc.com/products/futureETEK.htm).

Ten brake pads which had been analysed previously in manual tests were used for the initial repeatability studies using the automated prototype system. For each pad the velocity V_{33} was measured in 5 positions with a loading of 4.0 MPa. The samples were removed and remounted and the measurement repeated 5 times (r1 to r5). Figure 9 shows the average pad value for each of the 10 pads. All the data is plotted as the difference from the group average. For example, pad # 1 has a V_{33} value 3% above the group mean while pad #8 has a value 3% below the group mean. All of the repeat scans are plotted and overlapped. The average variation for each repeat scan is less than 0.5%. In all cases the measurements were made with 1 MHz longitudinal transducers, gel couplant on the steel backing side only, and no couplant on the friction material side.

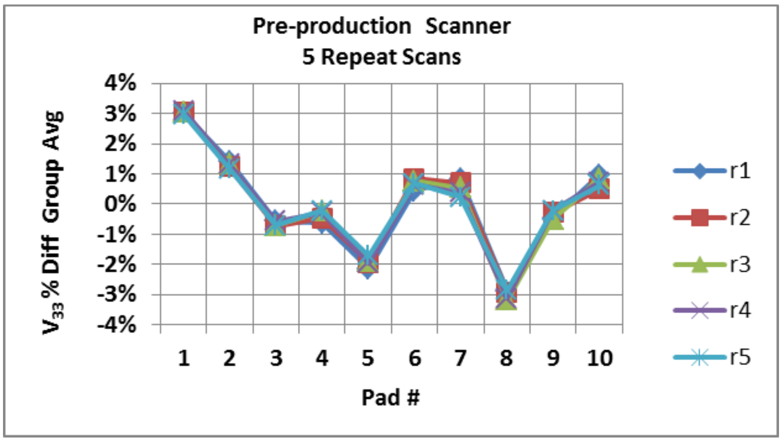


Figure 9: V_{33} measured with the prototype system on 10 pads with 5 repeat scans (r1 to r5)

SUMMARY AND CONCLUSIONS

Ultrasonic characterization data has been generated on a range of intact, as-manufactured brake pads. Through our analysis of over 140 pads taken from production, we have demonstrated that 4 of 5 independent velocities can be measured on as-manufactured pads. Ultrasonic methods are capable of spatial resolution on the order of tens of millimeters and systematic velocity spatial variations on this scale have been observed. Furthermore, for some friction material/underlayer formulations, the underlayer thickness can significantly influence the thickness mode velocity and the pad compressibility. Limited data on correlations between non-destructive velocity data and noise performance show promising results. A prototype system designed to automate the measurement process has also been assembled and tested. These results are encouraging, suggesting that rapid, non-destructive ultrasonic testing of brake pads has potential as a method for quality assurance of friction material at the point of manufacture.

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