Friction Material Elastic Property Round Robin Study

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ABSTRACT

A method for ultrasonic measurement of friction material elastic constants was evaluated through a round-robin process. The purpose of the study was two-fold: 1) to formulate and evaluate a standard test method (SAE J2725) for measuring elastic constants using ultrasound and 2) to quantify the measurement variability when the testing method is applied by multiple operators and instrumentation. The study involved measurement of 6 different friction materials by multiple operators at 5 different laboratories. All participants measured the same 6 samples. The friction material sample set ranged in density from 2.3 gm/cc to 3.2 gm/cc, the in-plane modulus varied from 11 GPa to 25 GPa, and the through-the-thickness modulus varied from 3 GPa to 7 GPa. All measurements were carried out at ambient temperature in accordance with procedures outlined in the draft SAE test specification (J2725).

INTRODUCTION

New braking systems are tailored to the particular requirements of the vehicle. Brake customer satisfaction is critically dependent on fully-competitive noise, vibration, and harshness (NVH) performance. In an effort to understand the origin of friction-induced vibrations, proper characterization of the individual brake system components is required.

To speed the development of new friction material formulations and to design quiet brake systems, sophisticated models and simulations have been developed. The predictive capability of these models is dependent on accurate material property data such as elastic constants. The elastic properties of friction materials are important design parameters because they may affect the propensity of the brake system to generate noise. Accurate lining material property data such as the Young's modulus, shear modulus, and Poisson's ratio are essential input to brake NVH models. Ultrasonic measurement techniques offer one of the few methods capable of adequately treating the anisotropic properties of friction materials. A complete set of elastic properties can be determined using ultrasonic measurements of wave propagation speed, but a detailed understanding of the material, physics, and measurement method are required to get useful results.

The use of ultrasound to determine the mechanical properties of materials is based on the fundamental physics between ultrasonic velocities and material elastic constants. These methods were originally applied to crystals more than 50 years ago and have been described in a number of books and review articles [1-6]. Extensive compilations of ultrasonic elastic constants of crystals and their variation with temperature and pressure are available [e.g. 7]. The draft of SAE 2725 utilizes methods taken from physical acoustics and applies them to automotive friction materials.

ULTRASONIC METHODS

Plane wave transmission methods are the most widely used ultrasonic approach for determining the elastic stiffness constants of anisotropic solids and the variation of these constants with temperature and pressure. This family of techniques involves the transmission of acoustic plane waves in various (usually high symmetry) directions through the solid, and the determination of the elastic stiffness constants from the measured phase velocities of these waves. Ultrasonic methods to determine the elastic moduli and Poisson's ratios in friction materials involve an adaptation of these commonly used methods.

Although the ultrasonic velocity measurement process is relatively straight forward, it is complicated by the fact that the modulus and Poisson's ratios must be calculated using all the relevant velocities. It is imperative that the relationship between the friction material symmetry and wave propagation directions be understood. To a good approximation, all automotive friction materials belong to a symmetry group that is transversely isotropic [8]. Specifically, with reference to the coordinate system shown in Fig. 1, the mechanical properties of the brake lining are isotropic in the 1-2 plane with the unique axis in the 3 direction (thickness). Before describing the measurement process, the nomenclature for the variables, constants, and the coordinate system will be established. The governing relationships between velocities and elastic constants will be discusses, and then the limitations and assumptions inherent in the ultrasonic method will be noted.

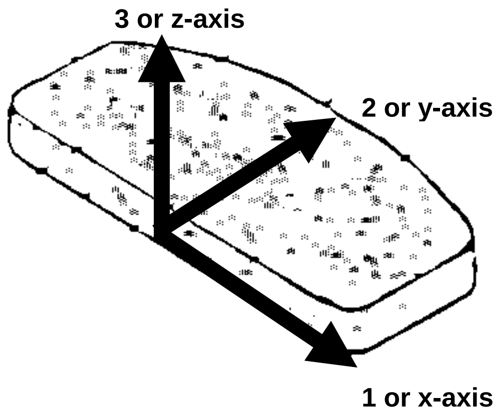


Figure 1. Coordinate definition with respect to brake lining.

Ultrasonic testing methods are analogous to the familiar testing methods of radar and sonar. The basic concept of ultrasonic testing is illustrated in Fig. 2. A short burst of high frequency sound (typically 1 to 3 MHz) is generated at the transmitting transducer and propagates through the sample to the receiving transducer. By measuring the sample thickness and pulse transit time the wave velocities can be calculated. After measurement of shear and longitudinal velocities for different sample orientations, the material elastic constants can be calculated. Sound waves in the megahertz frequency range do not propagate in air, so a coupling fluid is used to promote ultrasonic transmission into and out of the sample.

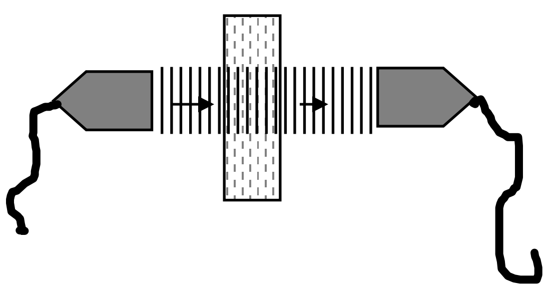


Figure 2. Through-transmission ultrasonic measurement geometry

An ultrasonic wave is a mechanical disturbance that can be characterized by a propagation direction and a polarization. The polarization refers to the direction of microscopic displacement associated with the wave. Each wave type is identified with reference to the coordinate system shown in Fig. 1 using tensor notation, V_{ij}, where the i index refers to the propagation direction and the j index refers to the polarization. With reference to Fig. 1, V_{33} propagates in the through-thickness or 3-direction with polarization in the same 3-direction, i.e. it is a longitudinal wave. V_{32} also propagates in the 3-direction, but its polarization is in the 2-direction making V_{32} a shear wave.

SAE J2725 SPECIFICATION - Briefly, the method [9] involves measuring ultrasonic velocities along principle symmetry directions, i.e. V_{11}, V_{22}, V_{33}, V_{31}, V_{32}, V_{21}, and V_{45}. The V_{45} mode represents a departure from the standard nomenclature and will be described in more detail below.

Equipment Requirements - The test equipment includes:

- Ultrasonic pulser-receiver unit (50 MHz bandwidth)
- Waveform digitizer and display (50 MHz minimum)
- Coupling load test fixture (100 kg capacity)
- 2 longitudinal wave ultrasonic sensors (1-5 MHz)
- 2 shear wave ultrasonic sensors (1-5 MHz)
- Micrometer (0.0025 cm resolution)
- Balance (0.01 g resolution)
- Ultrasonic couplant
- Propagation timing standard (steel reference)

Sample Selection & Preparation - For friction materials, the material symmetry is transversely isotropic with the "unique" axis along the materials thickness (3-direction in Fig. 1). A minimum of one rectangular sample oriented along the principle axes of the pad and one sample which has been sliced at a 45 degree angle relative to the “unique” pad axis must be cut from the brake lining (Fig. 3).

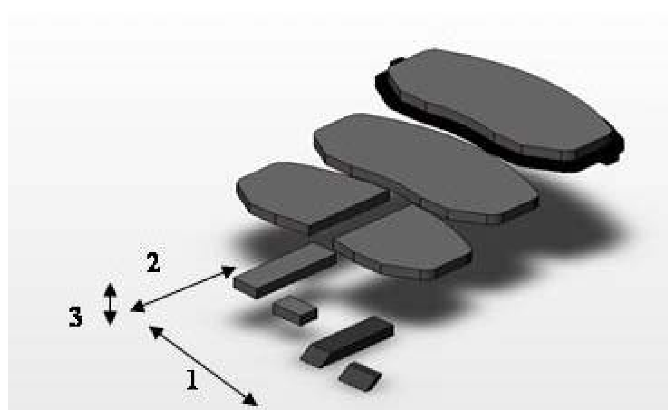


Figure 3. Typical cutting diagram for disc brake pad

The brake lining is removed from the steel backing using a band saw. From these segments, small, 15 mm by 20 mm by ~8 mm rectangular test specimens are cut. Saw cut marks are removed using a belt-sander and efforts are made to produce rectangular test pieces with parallel surfaces. In order to simplify orientation of the cut piece for the measurement, the longest sample dimension, (20 mm), corresponds to the longest dimension of the original pad (1-direction in Fig. 1). The smallest dimension (~ 8mm) always corresponds to the thickness direction (3 in Fig. 1).

For larger truck blocks it may be desirable to proportionally increase the sample dimensions by a factor of up to 3 times. The thickness direction is the limiting factor. For drum brake segments, the same rectangular pieces are cut from the segment, however in this case the slight curvature of the surface must be removed by sanding. This is particularly important on the concave surface.

A second sample type, a cut 45° relative to the unique, 3-direction, is used to obtain the off-diagonal elements of the elastic constant matrix. This geometry is dictated by the symmetry of the material and the chosen analysis methods. The 45-degree sample must be thinner than the thickness (3-direction) of the brake lining to insure proper transit time measurement. A typical thickness is approximately 6 millimeters. Measurements are made by propagating ultrasonic waves parallel to the normal of the 45-degree cut surface. This sample must be cut such that the 45-degree faces are parallel to one another and the ultrasound can propagate perpendicular to this cut surface and reach the other side before being reflected and refracted by a sidewall.

For all samples the parallelism should be accurate to +/- 25 microns. The surface finish as obtained with 200 grit sandpaper. For the 45-degree sample, the angular uncertainty is controlled primarily by the cutting fixture. It should be better than +/- 5 degrees.

Elastic Constants Calculations - Conversion of the measured ultrasonic velocities to elastic constants and engineering constants requires use of equations developed from linear elastic theory. The equations are given in the Appendix to this publication.

ASSUMPTIONS AND APPROXIMATIONS - As noted previously, the ultrasonic methods applied to measurement of the modulus of complex friction materials represents an adaptation of a measurement methodology previously developed for monolithic materials. As the intent of the measurement process is to generate material properties useful for modeling, it is important for the user to understand the underlying assumptions that form the basis in converting ultrasonic velocity data to elastic constant data. These are listed below:

"Effective" Property Assumption - Friction materials are composites comprised of numerous constituent materials with widely varying size, modulus, density, and shape. The physical properties of the combined composite material are related to those of the constituents. In order to apply ultrasonic methods to measure the macroscopic or "effective" elastic constants, it is essential that the wavelength of the sound be greater than the size of the constituents. Our measurements are carried out in the frequency range from 1 MHz to 2 MHz, which corresponds to ultrasonic wavelengths in the 1 to 2 mm range. Generally, the constituent materials are less than 0.3 mm in scale. When the probing wavelength approaches that of the microstructure, the effective modulus approach breaks down. This is often evidenced by pronounced dispersion in wave velocities and a loss of coherency of the ultrasonic pulse. Generally, the "effective" property condition is satisfied for all but the most coarse-grained materials.

Geometrical Optics - The analysis assumes that the ultrasonic wave propagates in a straight line and that the ultrasonic pulses are short such that interference from multiple reverberations can be neglected. This requires that the ultrasonic sensors have wide bandwidth and that the ultrasonic wavelength be small relative to the sample dimensions (propagation path). When the wavelength becomes large compared to the sample size, the method morphs into a modal technique where resonance phenomena dominate. The propagation path ranges from 6 mm to 20 mm.

Linear Materials - The analysis of ultrasonic data, or the conversion of this data into elastic constants, relies on equations extracted from linear elasticity theory. This theory predicts that the measured ultrasonic velocity is independent of load. For some friction materials, this is not the case. Specifically, in the through-the-thickness propagation direction the measured velocity can change significantly with load. Thus, even though the load does not appear explicitly in the inversion algorithms that convert velocity to modulus, it is essential to record and report the load at which the velocity was measured. Some friction materials are highly non-linear and load dependent, and this departure from linearity is monitored by measuring the velocity at specific loads.

Transverse Isotropy - The equations used to convert the measured velocities to the elastic constants and engineering constants assume that the friction material is isotropic in the plane of the pad. With reference to Fig. 1, the modulus in the 1-direction is the same as that along 2-direction. In fact, because of the redundancy built into the measurement process, this assumption can be validated for each sample measured. Specifically, both the V_{22} and V_{11} longitudinal modes and the V_{31} and V_{32} shear modes can be measured and compared. Under the transverse isotropy condition, these velocities should be equal. All friction materials analyzed satisfy this condition with the differences being less than a few percent.

Non-Viscoelastic Behavior - The goal of the elastic property measurement of friction materials is to provide friction material property data that can be used to in NVH simulation and modeling. Because the data are obtained under high strain rate conditions (frequency 1 MHz to 2 MHz) the question arises as to the applicability of data obtained at megahertz frequency to vibration problems in the kilohertz frequency domain. This of course depends on the visco-elastic properties of the friction materials which is largely unknown. The importance of the visco-elastic properties has yet to be resolved.

Uniformity - The goal of elastic constant measurements on friction materials is to develop mechanical property data that are representative of a specific friction material formulation. It must be kept in mind that measurements are made on relatively small samples. Thus, we are estimating the properties of a pad and a material based on the analysis of a small sample. It is known that the spatial variation in the ultrasonic velocity within a single disc pad can be several percent [8].

Furthermore, the current testing method requires two samples (described in the previous section) to obtain a complete set of elastic constants. Because data from these measurements must be combined to calculate the elastic constants, material non-uniformity can be a problem. The recommended measurement process is to analyze a minimum of 3 samples taken from different pads in order to mitigate the sampling errors. Also in sample preparation and selection care must be taken to extract samples away from the "cut-outs" in the steel backing plate. The symmetry and values of the velocity in these regions are known to differ from those backed by the steel in zone away from the "cut-outs".

EXPERIMENTAL

The SAE Linings Committee initiated a round robin study to measure the elastic constants in friction materials using ultrasonic methods. The goals were to formulate a consistent measurement protocol and to evaluate the method by comparing measurement results and variability obtained by several operators and instruments. As the result of this effort, a preliminary testing specification for the measurement of elastic properties of friction materials was drafted [9] and a study was initiated in March 2006.

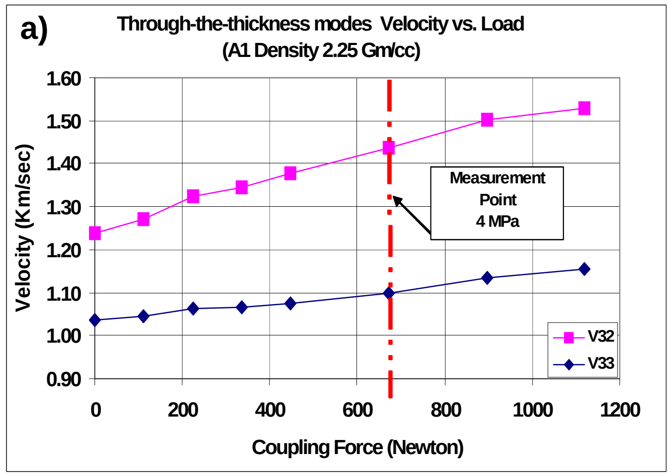
TEST SAMPLES - The study involved the analysis of 6 different friction material types. Each analysis included measurements on 2 pieces extracted from a single brake lining: a rectangular piece and a "45-degree" piece (Fig. 3). The sample properties were selected to be representative of the range of available friction materials (Table I). Density varied from 2.24 to 3.17 g/cm^3.

The samples were also qualitatively characterized by the load-dependent behavior of their through-the-thickness velocities. Severe load dependence is a known source of variability. Including materials with load-dependent properties provides a more realistic evaluation of the test method. Figure 4(a) illustrates severe load-dependence for friction material A1, while Fig. 4(b) shows slight load dependence for friction material A7. In each case both longitudinal (V_{33}) and shear (V_{32}) through-the-thickness modes are shown. The vertical line indicates the coupling pressure (measurement point (4 MPa) per draft SAE J2725 specification.

TEST PLAN - Five companies participated in the study, including Bosch Braking Systems, Federal Mogul, Ford Research & Advanced, Industrial Measurement Systems, and TRW (Table II). All participants measured the same set of 6 friction material samples (Table I) in accordance with draft test specification J2725. Each friction material was cut from the steel backing plate and the bonding interlayer removed by grinding. All measuring surfaces were ground parallel to +/- 0.003 cm. Ultrasonic signals were digitized using 50 MHz sampling frequency. The sample density was determined by measuring the weight (0.01 g precision) and dividing by the volume of the rectangular pieces.

Table I. Inventory of Round Robin Test Materials

Sampl	Density	Load
A1	2.25	Severe
A2	2.51	Moderate
A3	2.65	Slight
A4	2.24	Moderate
A5	2.82	Severe
A7	3.17	Slight



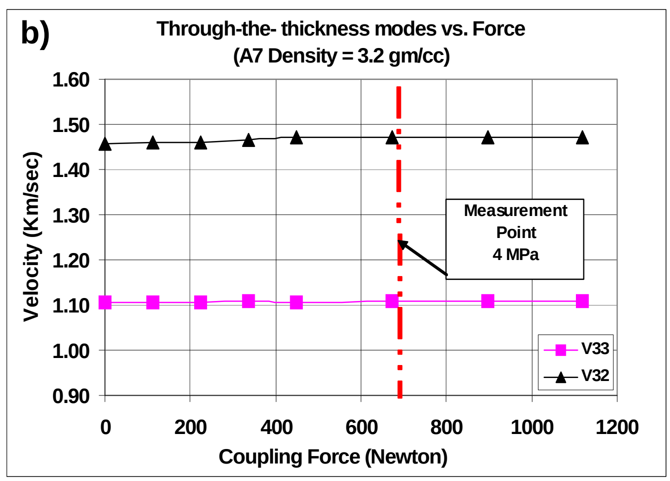


Figure 4. Examples of severe (a) and slight (b) load-dependent velocities.

To facilitate quantitative statistical analysis, each group was to conduct 3 trials for each of the six materials over the course of 4 months. Furthermore, it is desirable to have multiple operators from each site measure the samples. The current draft specification requires measuring of all mode velocities at a fixed coupling pressure of 4.0 MPa. Some participants measured the sample set using a coupling pressure of 2.0 MPa.

Table II Round Robin Data Inventory

Instrument	40 bar	20 bar
I	2 operator @ 3 trials	1 operator @ 3 trials
2	2 operator @ 3 trials	none
3	1 operator @ 3 trials	1 operator @ 3 trials
4	1 operator @ 1 trial	1 operator @ 1 trial
5	2 operator @ 3 trials	1 operator @ 3 trials

RESULTS AND DISCUSSION

The goal of this paper is to provide a concise and quantitative summary of the round robin study. The experimental data depicts the reproducibility and repeatability of ultrasonic methods applied to "real" friction materials by multiple users and instruments. First, velocity data is summarized form all participants on the representative sample set. Then, the results of the gage repeatability and reproducibility (R & R) analysis are presented. Finally, a detailed error propagation analysis shows the origins of the observed variability. Approaches to improving the measurement procedure and the testing methodology are suggested.

The measurement process and variability can be separated into three levels: 1) core parameters; 2) first level computed parameters; and 3) second level computed parameters. The core parameters include basic measurements such as dimensions, weight, transit times, and force. The precision is determined by the properties of the gages used to make the measurements and sample geometry. For this study, precision was 0.0025 cm for dimensions, 0.01 g for weight, 0.02 µs for time, and 100 g for force.

The first level computed parameters include density and ultrasonic velocities. The density is the weight divided by the volume calculated from the measured sample dimensions. Density variation results from variation in sample geometry, specifically the parallelism. The velocity for each mode is the sample thickness divided by the measured transit time. Variation in velocity is dependent upon the thickness accuracy/parallelism and the ultrasonic pulse integrity, e.g., signal to noise and pulse shape. The load (coupling pressure) also contributes to variability because in some materials the velocity is load-dependent.

The second level computed parameters include the elastic constants, engineering moduli, and Poisson's ratios. In this case, the variability is controlled by the propagation of error from the uncertainty in density and ultrasonic velocities, as well as the validity of the friction materials assumptions and approximations (see Experimental).

Although each individual measurement of ultrasonic velocity is relatively simple, it is necessary to track both the ultrasonic wave mode (shear or longitudinal) and the direction of propagation relative to the pad coordinate system defined in Fig. 1. The specification calls for measuring 7 velocities on each sample, which are then pooled to form the five independent velocities used for calculations. When combined with the density, the elastic constant matrix (6 parameters), the engineering moduli (4 parameters), and the Poisson's ratios (3 parameters) can be calculated.

FIRST LEVEL PARAMETERS - In this section the complete set of velocity and density data for 2 samples is presented in Figure 5 and 6. Sample A7 (Fig.5) exhibits linear properties and no load dependence, while sample A1 (Fig 6) shows the highest level of load dependence for the through-the-thickness velocity modes. Data were obtained using five different instruments and eight different operators (O-1 to O-8).

The measurements are arranged chronologically from left to right. The measurement portion of this study took approximately 3 months to complete. The six samples initially measured by operator 1 on machine 1 were re-measured by operator 8 on machine 5 after 3 months. The fact that there are no systematic variations in the values from left to right suggests little or no property variation can be attributed to aging, repeat measurements or material handling. The ordinate shows the percent deviation from the mean of all the measurements and the abscissa identifies the instruments 1 through 5. The clustering of points indicates repeat measurements by the same operator. For instruments 1, 2, and 5 two different operators participated in this study.

For linear sample A7 (Fig. 5), it is evident that all modes were measured within a few percent. It is likely that operator error played a role in the isolated cases where there was a larger excursion from the average. In comparison, load-dependent sample A1 (Fig. 6) showed considerably more variability in the V_{33} mode, illustrating the difficulty in measuring load-dependent materials.

It is believed that the origin of this increased variability lies in the inability of the various operators to consistently identify the appropriate measurement point. Transit time measurements require identification of the ultrasonic pulse phase as it propagates through the sample. Distortion of the pulse shape with load can lead to ambiguity in determining the appropriate measurement point. This is apparent in the data shown in Figure 6a where there is clustering of points at -10% and + 10% with additional points around 0% and one point at +20%.

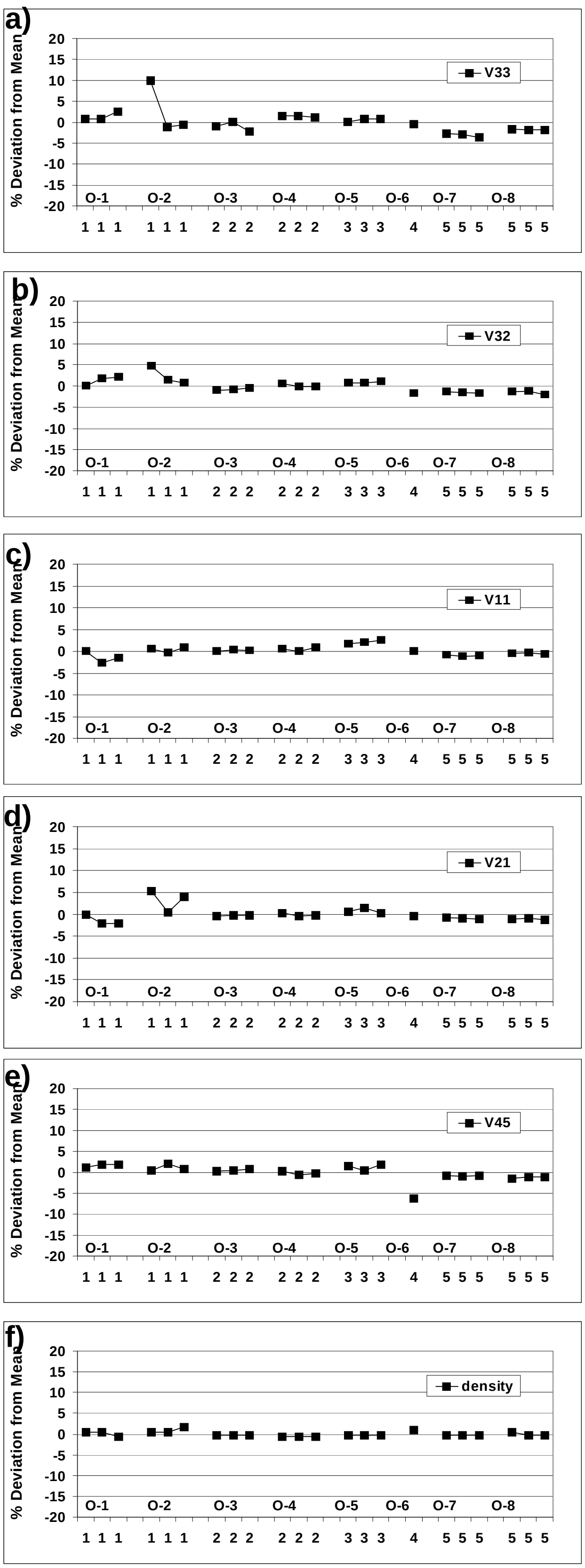


Figure 5. First level parameters for sample A7 a) V_{33}; b) V_{32}; c) V_{11}; d) V_{21}; e) V_{45}; and f) density.

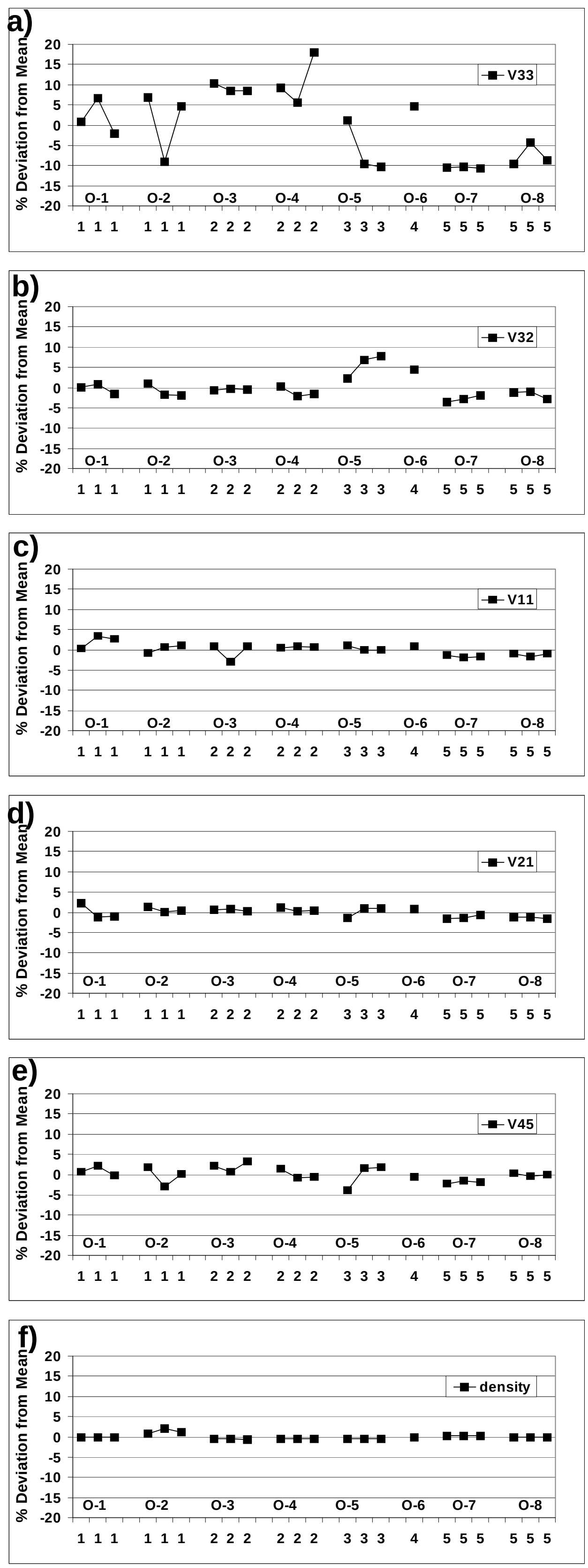


Figure 6. First level parameters for sample A1 a) V_{33}; b) V_{32}; c) V_{11}; d) V_{21}; e) V_{45}; and f) density.

The measured V_{33} velocities do not varyrandomly but "jump" in discreet steps indicating different measurement points. Improvements in measurement technique may be needed to insure more consistent measurements. Even the one data point measured by operator 2, machine 1 shows a 10% jump, suggesting misidentification of the proper measurement point

Aside from obvious difficulties related to measuring V_{33}, the measurement variations found in all other modes are comparable for the linear sample A7 and the non-linear sample A1. This includes all shear wave measurements in which the ultrasonic wave is propagating in the plane the pad.

GAGE R&R ANALYSIS - The complete gage R&R results are summarized in Tables III, IV, and V. The repeatability and reproducibility percent contribution should be less than 1% for an excellent gage, and less than 9% for an acceptable gage [10]. Metrics with unacceptable gage R&R's are noted in the table by underlining.

The gage R&R % contributions for all of the measured velocities (Table III) are all in the range of a few percent except for the V_{33} mode. Variability in V_{33} is strongly affected by the load-dependent samples. Elastic constants that do not depend on V_{33} have excellent gage R&R, while those that depend on V_{33} do not pass the gaga R&R (Table IV). The gage R&R for the engineering constants (Table V), such as Young's moduli (E_1, E_3), shear moduli (G_{13}, G_{12}) and the Poisson's ratios (ν_{12}, ν_{13}, ν_{23}) show the same trend as the elastic constants. The gage R&R results reflect the fact that the Poisson's ratios are strongly dependent on V_{33}, while the Young's and shear moduli are not.

Table III. Velocities Gage R&R (Percent Contributions)

	V_{11}	V_{22}	V_{33}	V_{31}	V_{32}	V_{21}	V_{45}
R&R	1.6	1.7	21.1	5.2	3.8	1.6	2.9
Repeat.	0.8	0.8	8.6	2.9	1.1	0.8	1.8
Reprod	0.8	0.9	12.4	2.3	2.7	0.7	1.1
Part	98.4	98.3	79.0	94.8	96.2	98.5	97.1

Table IV. Elastic Constants Gage R&R (Percent Contributions)

	C_{11}	C_{33}	C_{44}	C_{66}	C_{12}	C_{13}
R&R	0.8	11.5	2.6	1.3	11.9	16.4
Repeat.	0.2	5.3	0.7	0.5	8.3	10.9
Reprod	0.6	6.2	1.9	0.8	3.6	5.5
Part	99.2	88.5	97.4	98.7	88.1	83.6

Table V. Engineering Constants Gage R&R (Percent Contributions)

	E_1	E_3	G_{13}	G_{12}	ν_{12}	ν_{13}	ν_{23}
R&R	1.0	3.9	2.6	1.3	31.9	17.8	20.4
Repeat.	0.4	1.9	0.7	0.5	17.1	9.6	14.3
Reprod	0.6	2.0	1.9	0.8	14.8	8.2	6.1
Part	99.0	96.1	97.4	98.7	68.2	82.2	79.7

Figures 7 through 13 illustrate the details of the gage R&R round robin results [MINITAB14]. This subset was chosen to highlight various aspects of the study. The figures are laid out in the same format. The Components of Variation graph (top left) summarizes the contributions to the observed variation, which includes repeatability, reproducibility, and part-to-part variation. The percent contribution is derived from the variance, so the bars sum to 100%, while the percent study variation is standard deviation based and therefore does not sum to 100%. A properly conducted gage R&R should have representative part-to-part variation, as the measurement variation is evaluated in relative to the overall variation.

The R-Chart by Operator (middle left) depicts the measurement range for each sample and operator. Ideally the ranges should be small and below the upper control limit (UCL). The X-Bar Chart by Operator (bottom left) show the sample averages and control limits. Data points outside the control limits indicates that the part-to-part variation is greater the measurement uncertainty.

The density gage R & R (Fig. 7) had a low contribution of 1.8%. However, operators 1 and 2 had poor repeatability (middle left, range above UCL). Operators 1 and 2 calculated a different density for sample 4 (lower right), perhaps due to a systematic error in measuring the sample weight or dimensions.

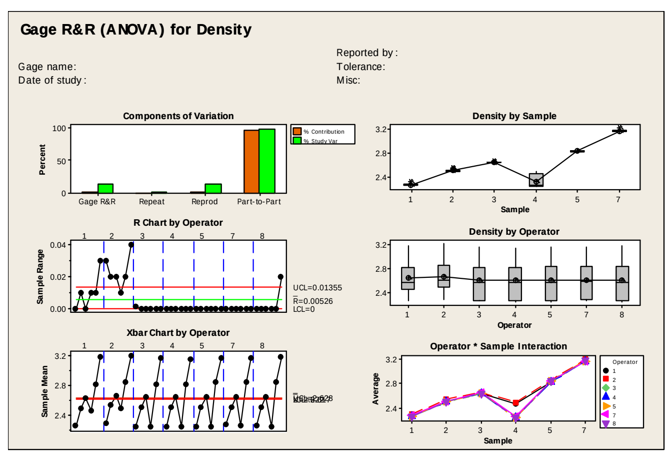


Figure 7. Density Gage R & R.

The V_{11} gage R & R (Fig. 8) was 1.6% contribution at a coupling load of 4 MPa. Operators 1, 2, 3, and 4 each had 1 sample measurement above the UCL (middle left). V_{11} by sample indicates consistent measurement of each sample, while V_{11} by operator shows little variation between operators and instruments.

The V_{33} gage R & R (Fig. 9) had a 21% contribution, which is greater that 9% acceptability limit. The V_{33} by sample plot clearly shows that highly load dependent samples A1 and A5 were difficult to measure consistently. This result is consistent with the large variation in V_{33} presented previously in Fig. 5. Operator 4 generally measured high, especially on the load dependent samples (lower right).

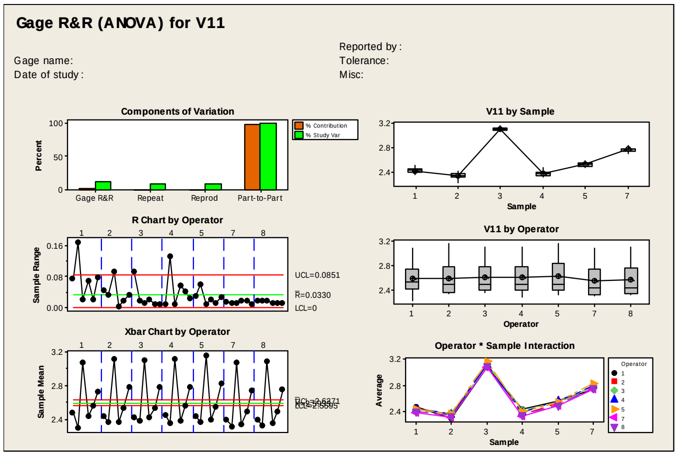


Figure 8. V_{11} Gage R & R.

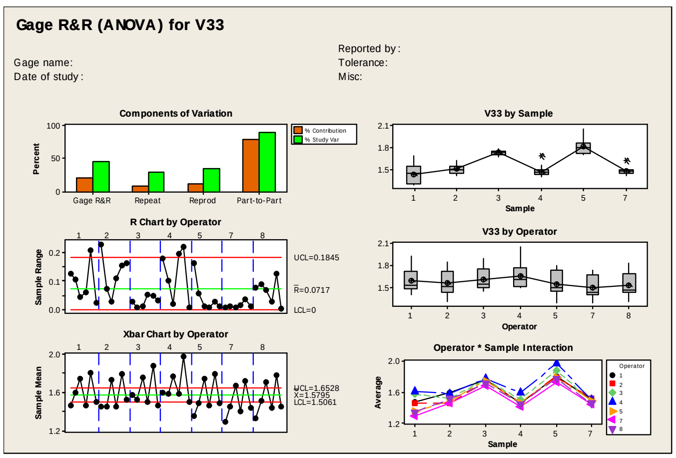


Figure 9 V_{33} Gage R&R.

The gage R&R result of the computed elastic constant C_{11} (Fig. 10) had an excellent contribution of only 0.8%. This elastic constant is dependent only on the in-plane longitudinal velocity and is thus not influenced by variability of V_{33}. A couple bad measurements by operators 2 and 4 did not significantly degrade the results.

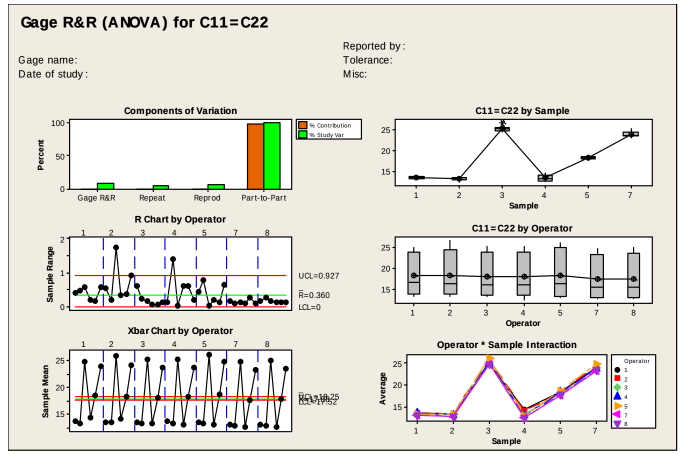


Figure 10. C_{11} Gage R&R.

The gage R&R results for the off-diagonal elastic constant C_{13} (Fig. 11) had an unacceptable contribution of 16.4%. In contrast to C_{11}, this constant is significantly influenced by variability in V_{33}. Operator 2's range was sometimes out of control and operator 4 was systematically higher than the others.

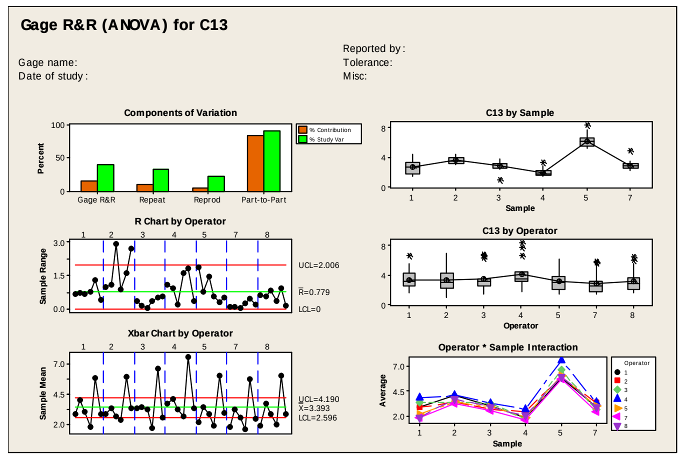


Figure 11. C_{13} Gage R&R.

For E_3, the Young's modulus in the through-the-thickness direction, the gage R&R result was an acceptable 3.9% contribution (Fig. 12). This modulus is also adversely influenced by the variation in V_{33} but not to the extent of the off-diagonal elastic constants. Again operator 1 and 2 exceeded the range control limits.

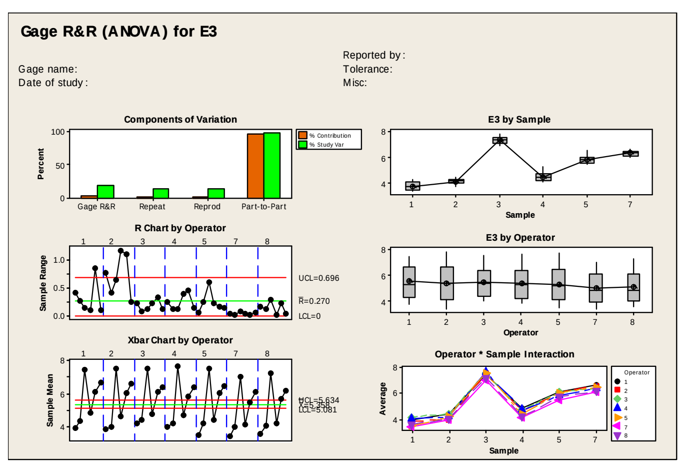


Figure 12. E_3 Gage R&R.

The gage R&R for a calculated Poisson's ratios, P_{23} (Fig13), had an unacceptable 20.4% contribution. All Poisson's ratios are greatly influenced by the variability of V_{33}. Operators 2 and 5 were outside the range control limits. Also samples 1, 5, and 7 have large ranges and/or outliers.

PROPAGATION OF ERROR - The previous section presented the gage R & R results for measured and computed parameters using standard statistical analysis methods [11]. In this section, measurement uncertainties (mass, thicknesses, transit times) are propagated to all calculated parameters to quantitatively assess the impact of measurement uncertainties [12].

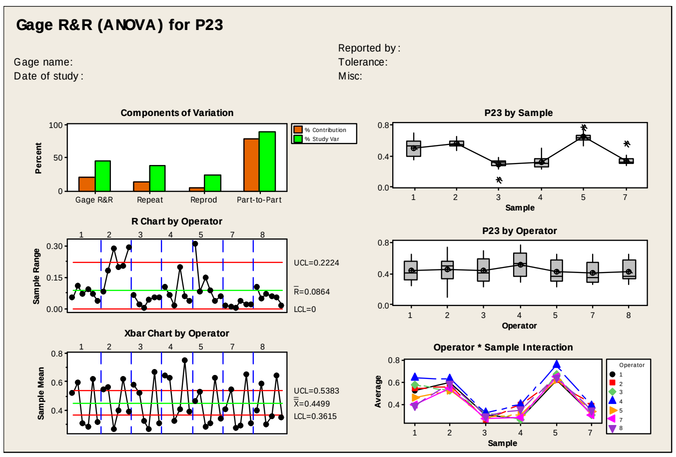


Figure 13.P_{23} Gage R&R.

Using the 22 replicates for each of 6 samples in the 40 bar round robin data, the mass, thickness, and transit time standard deviations were derived. From the data, $\sigma_{density}$ = 0.015 g/cm^2. Assuming σ_{mass} = 0.01 g (scale resolution), the $\sigma_{thickness}$ was calculated to be 0.003 cm. This is reasonable, as the specified sample parallelism is 0.0025 cm.

Standard deviations were calculated for each measured velocity. Using the previously calculated $\sigma_{density}$ = 0.015 g/cm^2, σ_{time} = 0.01 μsec was calculated for every mode except V_{33}. Inspection of the V_{33} standard deviation data revealed three general magnitudes of variation. These three levels corresponded with initial load dependence classification of the linings (Table VI). From the observed velocity σ's (again assuming $\sigma_{density}$ = 0.015 g/cm^2) approximate $\sigma_{time}(V_{33})$ of 0.1 μsec, 0.3 μsec, and 0.5 μsec were obtained.

Table VI. Standard Deviation of V_{33} Velocity and Time

Sample	Load Dependence	$\sigma_{velocity}$ (km/s)	$\sigma_{time}(V_{33})$ (μs)
A1	Severe	0.13	0.5
A2	Moderate	0.06	0.3
A3	Slight	0.03	0.1
A4	Moderate	0.07	0.3
A5	Severe	0.10	0.5
A7	Slight	0.04	0.1

The elastic equations in terms of measured parameters were entered into MATLAB and all partial derivatives were calculated for use in the error propagation equation (Appendix). The average measured physical properties of sample 7 measured by instrument 5 were used for comparison. This has no effect on the results other than to ensure the magnitudes are in the observed range. Having used the round robin data to calculate the standard deviation of all measured values, these deviations can now be propagated to all the calculated elastic parameters. The only measurement which exhibited sample dependent variability was $\sigma_{time}(V_{33})$, so the results of the error propagation will explore the influence of this variation on all computed elastic parameters.

Figures 14, 15, and 16 depict the results of the error propagation. As mentioned above, the magnitudes are from sample 7 and of minor significance. The critical data is contained in the error bars. By comparing the magnitudes of the error bar and mean value, the uncertainty in the measurement can be assessed. Lighter bar shading indicates high uncertainty in the parameter magnitude.

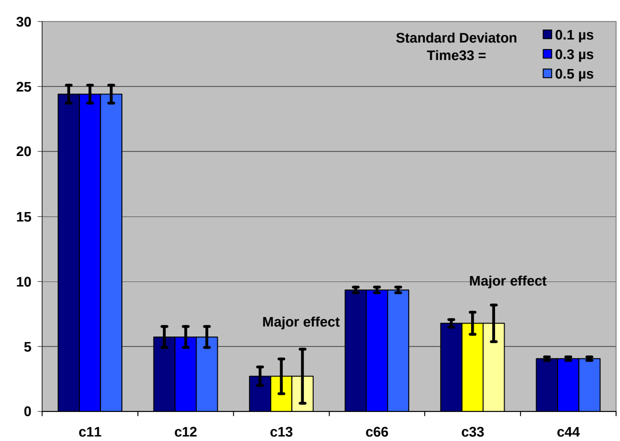


Figure 14 Elastic constant variation for three different levels of $\sigma_{time}(V_{33})$.

All elastics constants that do not depend on V_{33} have low standard deviations (Fig. 14). However, C_{13} and C_{33} both have significant variation as $\sigma_{time}(V_{33})$. This is especially true of C_{13}, which has V_{33} in the calculation two times.

The Young's and shear moduli have low variation overall (Fig. 15). The shear moduli are uncoupled from the V_{33} measurement and thus are not influenced by $\sigma_{time}(V_{33})$. The variation of the computed Young's moduli E_1 and E_3 is increased by $\sigma_{time}(V_{33})$ but the effect is minor. In contrast, the influence of $\sigma_{time}(V_{33})$ on all the Poisson's ratios is significant due to the multiple occurrences of V_{33} in the calculation.

FURTHER WORK - It is clear that the uncertainty in the V_{33} velocity measurement drives much of the uncertainty and poor performance of the several gage R&R parameters. The measurement of V_{33} needs improvement. Some operators were able to repeatably measure this velocity mode with a corresponding improvement in the gage R&R results. For example, statistical analysis of the data from the 2 operators from machine 5 yield a gage R&R percent contribution for V_{33} of 5.4 %. In this case, coupling pressures in excess of 4 MPa were used to identify the measurement point. Load was then reduced to 4 MPa to acquire the data as required by the specification. It is recommended that these measurement techniques be incorporated into the revised SAE J2725 specification.

Additionally, the current draft SAE test specification J2725 only specifies one load condition. Brake noise can occur under different, specific loading conditions. The procedure may need revision so that load dependent materials are identified and results can be obtained for multiple loading conditions. It is suggested than the load dependence of the V_{33} mode should be measured over a coupling pressure range from near 0 to 6 MPa. This in itself will not only serve as an additional material characterization method but also will alert the user to situations where accurate measurements might be problematic. Further study of the measurement techniques and the origin of the pulse distortion as well as methods to determine the proper measurement point should improve repeatability. Analysis is also needed to specify the required resolution for the elastic parameters.

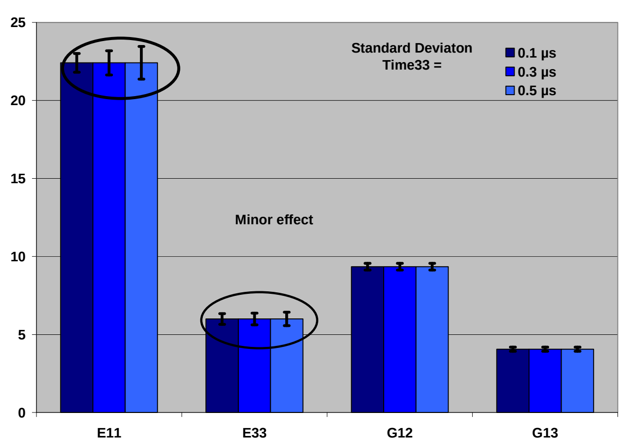


Figure 15. Engineering moduli variation for three different levels of $\sigma_{time}(V_{33})$.

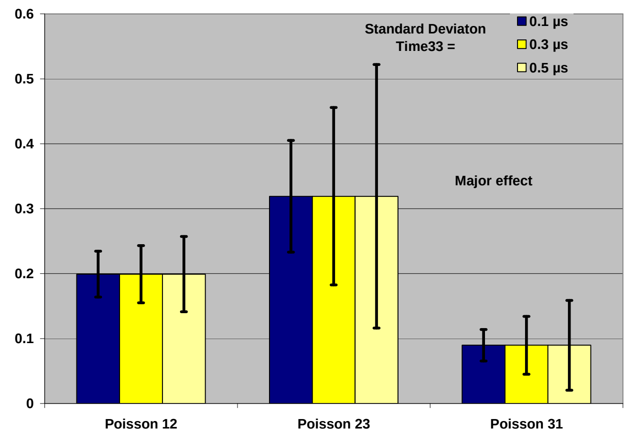


Figure 16. Poisson's ratio variation for three different levels of $\sigma_{time}(V_{33})$.

CONCLUSION

Ultrasonic methods offer one of the few testing methods that are capable of measuring the true anisotropic character of friction materials. This report describes the results of a round robin study using ultrasonic measurement methods to determine the elastic constants of friction materials. Eight different operators using 5 different instruments analyzed 6 different friction materials. Materials were chosen to be representative of the full range of materials encountered in production. The friction materials ranged in density from 2.3 to 3.2 g/cm^3, the in-plane modulus varied 11 to 25 GPa, and the through-the-thickness modulus varied from 3 to 7 GPa. All measurements were carried out at ambient temperature in accordance with procedures outlined in the draft SAE test specification (J2725).

Analysis of the data indicates that highly reproducible results can be obtained for all shear wave modes and for those modes propagating in the plane of a disc pad. Gage R & R % contribution values range form 1% to 5% for all of these modes.

One problem area is the measurement of the longitudinal mode V_{33}, especially in highly load-dependent materials. Table VII summarizes the gage R & R analysis, in which all parameters that are strongly dependent on V_{33} failed the measurement system analysis. V_{33} variation had a minor influence on the computed Young's moduli, but had a major effect on the Poisson's ratios producing unacceptably high % contribution gage R & R values.

The variation in the V_{33} measurement is attributed to the inability of different operators to consistently determine the appropriate measurement point. This appears to be particularly problematic in severely load-dependent materials. It is recommended that improved measurement techniques such as "over-pressuring" the samples be used to facilitate identification of the proper measurement point. Furthermore, measurements should be made over a range of coupling loads of interest for NVH studies.

Table VII. Gage R&R (Percent Contribution < 9 = Pass)

Parameter	Pass	Fail
Velocity	V_{11}, V_{22}, , V_{31}, V_{32}, V_{21}, V_{45}	V_{33}
Elastic Constants	C_{11}, C_{44}, C_{66}	C_{33}, C_{12}, C_{13}
Engineering Constants	E_1, E_3, G_{12}, G_{13}	ν_{12}, ν_{13}, ν_{23}

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APPENDIX

MEASURED PARAMETERS - Fundamental measured parameters such as mass, sample dimensions (thicknesses), and ultrasonic transit times.

$$mass$$
$$thick1, thick2, thick3, thick45$$
$$time11, time22, time33, time31, time32, time21, time45$$

EQUATIONS -

Mass

$$\rho = \frac{mass}{thick1 * thick2 * thick3}$$ (density)

Ultrasonic velocities

$$V_{11} = thick1 / time11$$
$$V_{22} = thick2 / time22$$
$$V_{33} = thick3 / time33$$
$$V_{31} = thick3 / time31$$
$$V_{32} = thick3 / time32$$
$$V_{21} = thick2 / time21$$
$$V_{45} = thick3 / time45$$

Elastic constants

$$c_{11} = \rho V_{11}^2 = c_{22} = \rho V_{22}^2$$
$$c_{33} = \rho V_{33}^2$$
$$c_{44} = \rho V_{31}^2 = c_{55} = \rho V_{32}^2$$
$$c_{66} = \rho V_{21}^2$$
$$c_{12} = c_{11} - 2c_{66}$$
$$c_{13} = \sqrt{[(2\rho v_{45s}^2 - 0.5(c_{22} + c_{33} + 2c_{44}))^2 - 0.25(c_{33} - c_{22})^2]} - c_{44}$$

Engineering constants

$$E_1 = E_2 = \frac{c_{33}(c_{11}^2 - c_{12}^2) - 2c_{13}^2(c_{11} - c_{12})}{c_{11}c_{33} - c_{13}^2}$$

$$E_3 = c_{33} - \frac{2c_{13}^2}{c_{11} - c_{12}}$$

$$G_{13} = G_{23} = c_{44}$$

$$G_{12} = \frac{1}{2}(c_{11} - c_{12})$$

$$\nu_{12} = \nu_{21} = \frac{c_{33}c_{12} - c_{13}^2}{c_{11}c_{33} - c_{13}^2}$$

$$\nu_{13} = \nu_{31} = \frac{c_{13}}{c_{11} + c_{12}}$$

$$\nu_{23} = \nu_{32} = \frac{c_{13}(c_{11} - c_{12})}{c_{11}c_{33} - c_{13}^2}$$

ERROR PROPAGATION – For example, if function z is V11, then variables (measured parameters) x and y would be thick1 and time11. If there were additional variables, further differentials would be added under the square root. Errors for all calculated parameters were propagated from the measured parameters.

$$\sigma_z = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial z}{\partial y}\right)^2 \sigma_y^2 + \ldots}$$