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ULTRASONIC METHODS FOR CHARACTERIZING THE NON-LINEAR ELASTIC PROPERTIES OF FRICTION MATERIALS

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ABSTRACT

Brake pad stiffness mediates friction force and contributes to brake squeal. It is now recognized that static stiffness data, even static stiffness at low loads, does not provide sufficient boundary conditions for modeling and simulation of brake squeal. As early as 2006, the non-linear, load dependence of friction material dynamic stiffness was suggested as an important characterization parameter.[1] More recently, several researchers have shown that there are significant differences between dynamic stiffness measured at a few kilohertz and static stiffness.[2-6]

Ultrasonic methods are particularly well suited to measure non-linear load-dependent behavior of friction materials. Several different friction material types ranging from those which exhibit linear behavior to those whose stiffness varies by more than 70% when loaded from 0.25 MPa to 4.0 MPa have been analyzed in this study. Ultrasonic investigations are carried out over the frequency range from 200 kHz to 1 MHz. Like the dynamic stiffness measured in the low kHz frequency band, ultrasonic data are higher than the static values and exhibit a greater dependence on the load. Hysteresis has also been observed in the ultrasonic data where the stiffness is higher when pressure load is decreasing compared with the stiffness measured when pressure load is increasing. In this paper we describe test methods, calibration data, and compare data obtained on three different friction materials.

BACKGROUND

Early investigations using ultrasound to measure the elastic constants of friction materials indicated that it was necessary to control and monitor the coupling pressure in order to obtain reproducible measurements of time-of-flight (ToF). This load-dependence was treated more as a nuisance, limiting the precision of measurements. Procedures were developed to control and monitor the coupling pressure. In all friction materials, the reproducibility of the ToF measurement is improved at high loading, on the order of 4 MPa. As the result of "push-back" from the industry to reduce loading pressure, a procedure was developed where elastic constants are measured over a loading range of 0.5 MPa to 5.0 MPa.

As early as 2006, the effect of non-linear, load dependent properties common for friction materials and their relationship to elastic property measurements was described[1]. At that time, it was suggested that the quantification of these properties might be an important friction material characterization tool. More recently, measurements of the large difference between static and dynamic modulus in the kilohertz frequency regime has rekindled interest. The dynamic modulus of friction materials is dependent upon material preload, strain rate, and strain amplitude[5]. These factors also appear in ultrasonic measurements. In this study, we describe in some detail the ultrasonic methods and how the behavior of friction materials differ from that of linear elastic materials. Furthermore, we compare observations made using the ultrasonic methods with those found by other researchers measuring the dynamic modulus in the kilohertz frequency domain.

METHODOLOGY

In order to relate ultrasonic measurements to friction material properties, it is first necessary to quantify the response of the ultrasonic system to preload, strain rate, and displacement amplitude. This is best done by conducting initial characterizations on linear materials. We will first characterize a steel gauge block which is a linear elastic material. These experiments serve not only to demonstrate the behavior of linear materials in our measurement system but also to provide baseline data for the comparison of the friction material results to be presented later. In contrast to conventional static testing where the moduli are determined by direct measurement of stress and strain, for the ultrasonic technique the basic parameter that is measured is the ToF.

All measurements are done using a through-transmission method. The basic concept of ultrasonic testing is illustrated in Figure 1. A short burst of high frequency sound (typically 1 MHz) is generated from the transmitting transducer and propagates through the sample to the receiving transducer. ToF measurements are made using timing optimized digitization of the ultrasonic signal many times the Nyquist rate, on the order of 100MHz. For typical friction material thicknesses, the ToF is on the order of 10 microseconds and precision of 0.1 % is readily achievable. Significantly higher measurement precision is possible when using autocorrelation methods. Given a known thickness, the ultrasonic velocity can be determined from the ToF measurement. By measuring velocities of shear and longitudinal wave modes for different sample orientations, the material elastic constants can be determined.[7] The fundamental relationships between velocity and material elastic constants are based on Hooke's law.

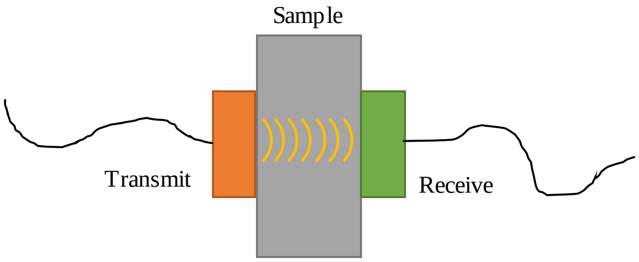

Figure 1 Through-transmission geometry used for ultrasonic measurements

The measurement process is relatively straight forward. As illustrated in Figure 1, a sample is sandwiched between a pair of sending and receiving sensors and the variation in the ToF is measured as load is applied. Results are generally presented as percent modulus (or stiffness) variation as a function of load. Two different modulus are reported. Both are proportional to the square of the measured velocity. For longitudinal waves, the elastic constant or longitudinal modulus $C_{33} = \rho(V_{33})^2$ is calculated where V_{33} is the longitudinal wave propagating in the out-of-plane direction. For friction materials, the longitudinal modulus is typically 15% to 20% higher than the Young's modulus measured in the out-of-plane direction. A shear wave propagating through the thickness of a pad with polarization in the plane of the pad (V_{31} or V_{32}) is used to measure the shear modulus or elastic constant $C_{44}=\rho(V_{3x})^2$. In some cases, the stiffness is plotted directly, which is simply the relevant modulus divided by the thickness.

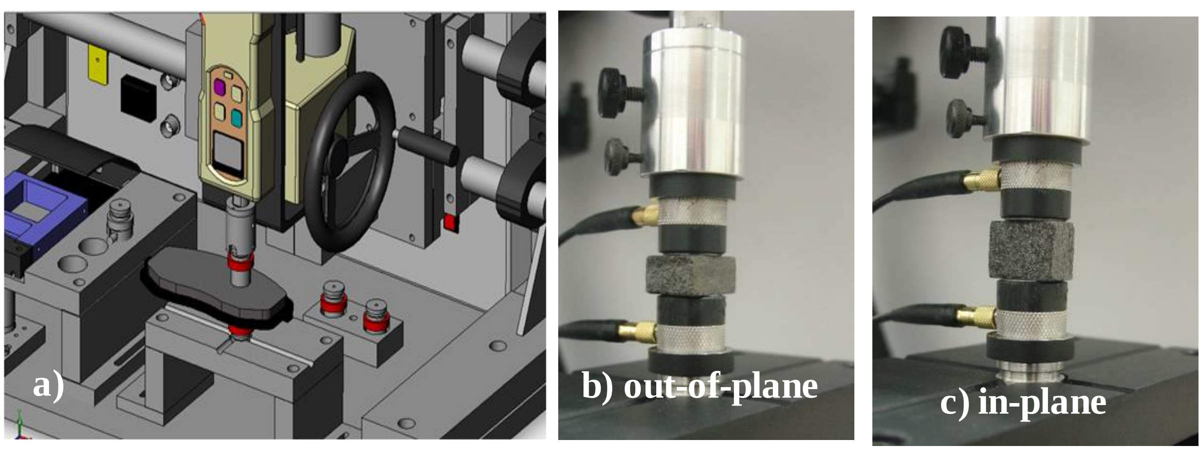

Figure 2 a) Configuration showing the measurement of an as-manufactured pad; b) close-up view of small rectangular friction material samples oriented in the out-of-plane and c) in-plane directions

As illustrated in Figure 2, by varying the sample orientation, the in-plane as well as the out-of-plane properties can be measured. In this study, the analysis has concentrated primarily on the measurement of variations found in the out-of-plane properties. In previous studies, it has been noted that the in-plane properties do not exhibit any significant variation with load[1]. For the data presented in this report, sample size is comparable to the "footprint" of the compressive load. In this case, the coupling pressure is a good approximation of the load experienced by the sample. These methods can be applied readily to intact, as-manufactured pads using the same testing set-up (Figure 2a). However, it may be necessary to scale the loading appropriately in order to account for the load-bearing influence of the steel backing plate.

Figure 3 shows the baseline characteristics of the ultrasonic measurement system. Figure 3a shows the measured variation in the longitudinal modulus of steel as a function of coupling pressure. As can be seen, there is no measurable variation at the coupling pressures above 0.5 MPa. The small decrease in modulus below 0.5 MPa is attributed to a combination of "play" in the mechanical system and variation in the ultrasonic coupling at these low loads. There is a loading and an unloading cycle in this plot. However, there is no measureable hysteresis. The behavior observed on loading is identical to that observed when the load is reduced. Figure 3b shows the measurement of the modulus of the steel calibration block as a function of frequency. This data was obtained using 4 different sensors with center frequency which varied from 1 MHz to 10 MHz. For our steel gauge block which is not viscoelastic, there is no measureable variation in velocity with frequency. The measurement of velocity dispersion in friction materials will be discussed in the next section.

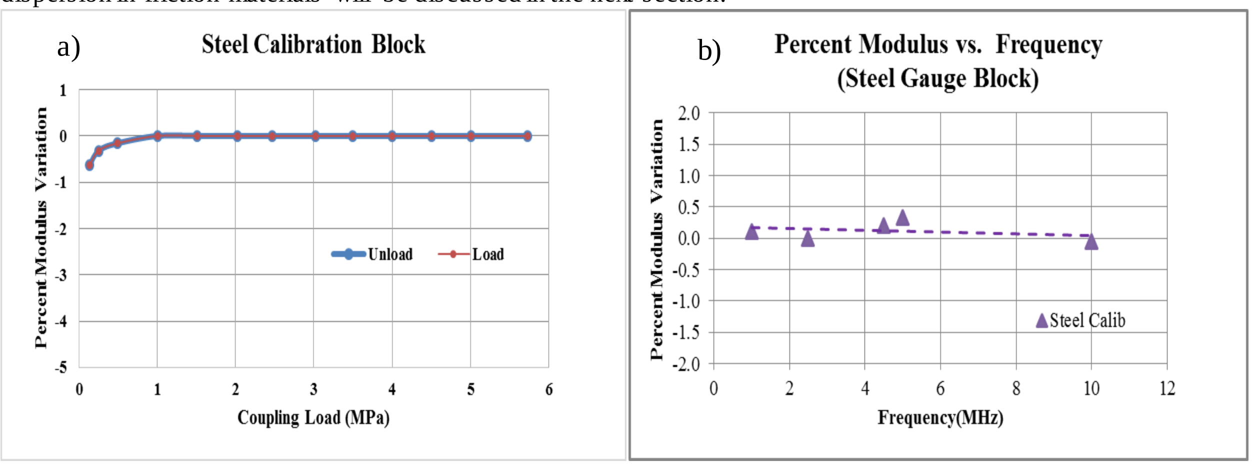

Figure 3 a) Baseline data showing pre-load dependence on a steel calibration block; b) Modulus measured on the steel calibration block

Lastly, it is important to introduce some of the general aspects of the dependence of friction materials on preload. Figure 4 shows representative characteristics of a moderately load-dependent friction material for both the in-plane and out-of plane orientation. The load dependence, like the modulus, is anisotropic. Even for materials that show a high degree of load dependence for the out-of-plane modulus, C_{33} and C_{44}, the variation of modulus for the in-plane direction, C_{22} and C_{66} is minimal. The lack of any preload sensitivity for the in-plane modulus appears to be a general characteristic of friction materials. The remarkable aspect of this data is that it was all obtained on the same small rectangular piece of friction material. The volume through which the ultrasound was propagated was identical in each case. Only the ultrasonic wave type, shear or longitudinal or the direction of propagation, in-plane or out-of-plane was changed.

EXPERIMENTAL RESULTS

Preload

The dominant variable affecting the measured stiffness or modulus of the friction material is preload. This is true both in dynamic modulus measurements made in the kHz frequency range[5,6] and for ultrasonic measurements. Although the static measurements of stiffness exhibit variations as a function of preload, the changes are subdued relative to the dynamic modulus variations with preload.[5]

Three friction material samples were chosen to conduct load dependent studies presented in this section. Table I lists some of the relevant properties. Friction materials FM#1 and FM#3 were chosen because they have similar elastic properties but somewhat different load sensitivity. The sample FM#2 has a much higher density and significantly less load sensitivity. In Table I E_3 is the Young's Modulus for the out-of-plane direction.

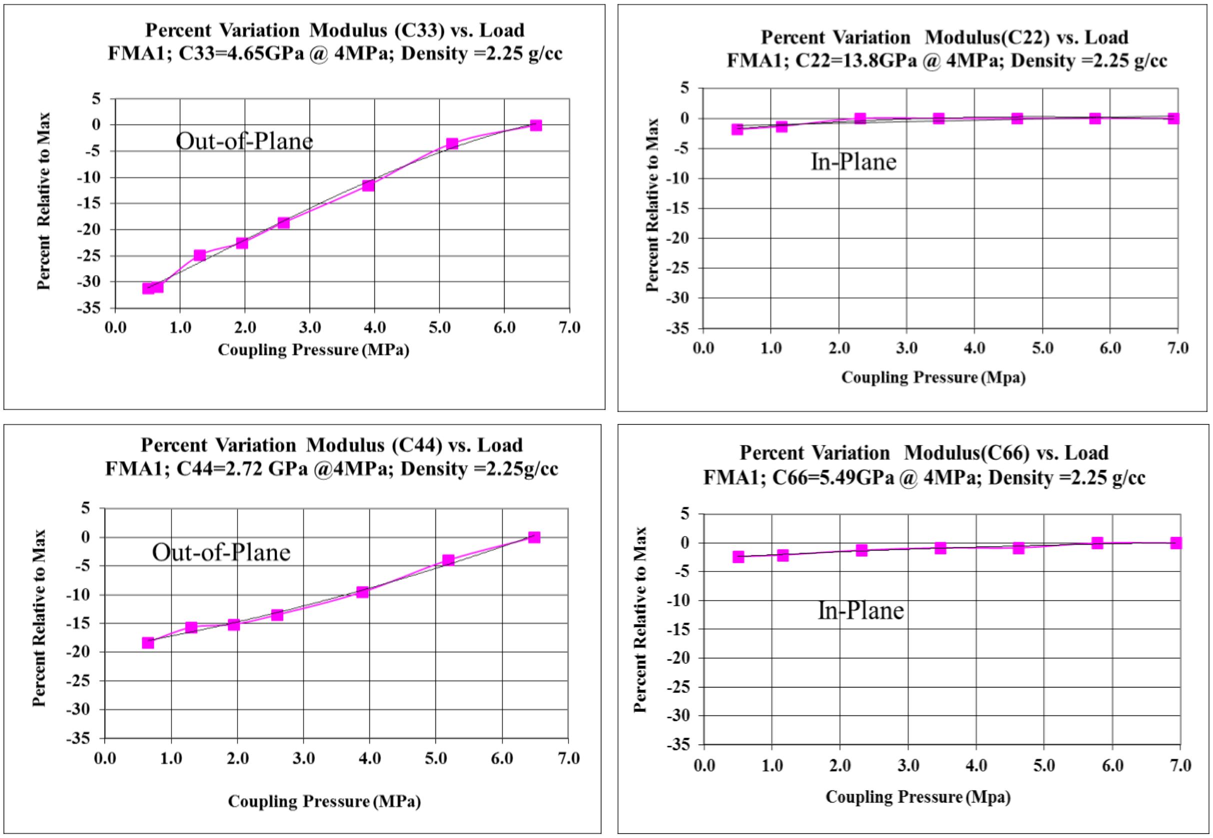

Figure 4 Representative data showing pre-load sensitivity for friction materials in the in-plane and out-of-plane directions

Table I Relevant properties of load study samples

Material	Density	C_{33}@4MPa	E3@4MPa	C_{44}@4MPa
	g/cm^3	GPa	GPa	GPa
FM#1	2.5	3.2	2.5	2.35
FM#2	3.1	4.8	4.08	3.3
FM#3	2.2	3.2	2.46	2.35

Figure 5 compares the load sensitivity for the out-of-plane longitudinal and shear modulus for the three friction materials listed in Table I. For each plot, a series of 3 different samples were measured and the average and standard deviation of the percent variation in modulus is plotted. All data for each modulus is normalized to the modulus measured at the highest load. The samples were initially loaded to beyond 5 MPa. The data was taken while the sample was unloaded from the high load down to 0.5MPa. This procedure was developed primarily to enhance the reproducibility of the measurement. The lower density samples exhibit greater sensitivity to load than the higher density sample, FM#2. For FM#2 the load sensitivity of the shear modulus, C_{44} is less than that of the longitudinal modulus, C_{33}. For FM#1 the shape of the loading curve for the longitudinal modulus differs from that of the shear modulus. In contrast, for FM#3 the shapes and the magnitude of the modulus variation is comparable over the entire load range. For sample FM#2 and FM#1 the load sensitivity appears to saturate near the higher load, while for FM#3 the modulus appears to be undergoing significant variation even at 5.5 MPa.

Motivated by the recent work of Oura et.al., our efforts were directed at looking more closely at the ultrasonic measurements made while the sample is being loaded and unloaded[5] The data presented previously in Figure 5 were obtained by recording the ToF while the sample was being unloaded. The sample was initially loaded to at a high level (~ 5.5 MPa) and the ToF monitored upon reducing the load. The characteristics of several friction materials have been investigated by carefully monitoring the ToF for multiple loading and unloading cycles. This data is shown in Figure 6. Although the data shows some systematic variability on the initial loading with the initial apparent stiffness being low, the subsequent cycling of the loads reveals that there is a consistent difference between the loading and unloading cycle. The unloading portion of the curve always exhibits a higher modulus.

Figure 6 shows the typical hysteresis observed using ultrasonic methods. In this example the sample was initially loaded to a pressure of 5.5 MPa and held for 5 minutes. The sample was then unloaded in 0.5 MPa increments (unload 1). The sample was then reloaded at the same rate and the modulus measured at each step. At 5.5 MPa the sample was held for 5 minutes and then unloaded to 0.25 MPa. This experiment was done manually so the residence time at each step was somewhat uncontrolled but was on the order of 15 seconds. These results indicate that the modulus is measurably higher during unloading (depressurization). These results are repeatable and consistent with the behavior observed in the kilohertz frequency range by others. For the example shown here the difference is on the order of 6% at 3 MPa.

Figure 7 shows that hysteresis is observed in the other 2 friction material types listed in Table I. In these Figures we have replaced the percent longitudinal modulus variation with the stiffness as a function of load. This is calculated using the measured sample thickness and the value of the measured longitudinal modulus. In these Figures two cycles of loading are used. Although the first loading is sometimes variable, there is a consistent difference between the modulus measured during the load and unload portion of the various plots. The magnitude of the difference appears to scale with the overall load sensitivity.

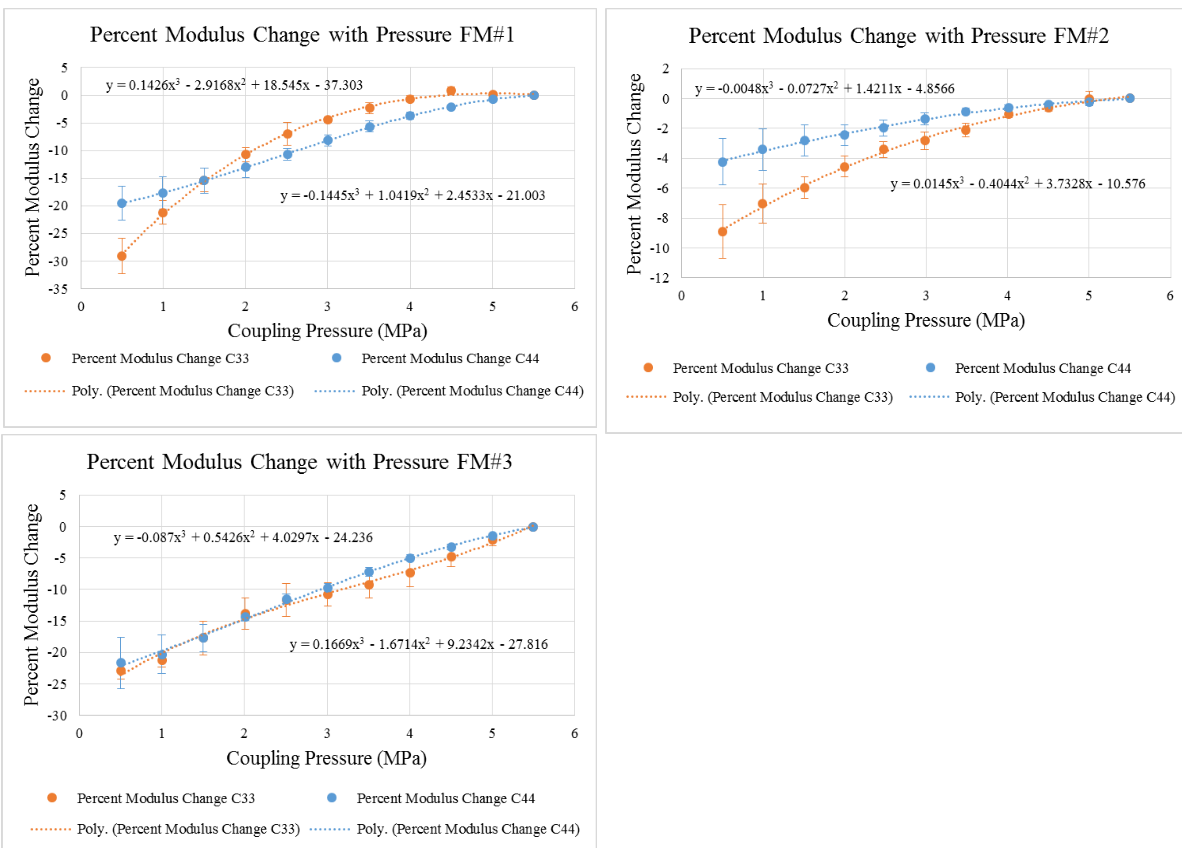

Figure 5 Longitudinal and shear modulus measurements as a function of coupling pressure for the three friction material formulations listed in Table I.

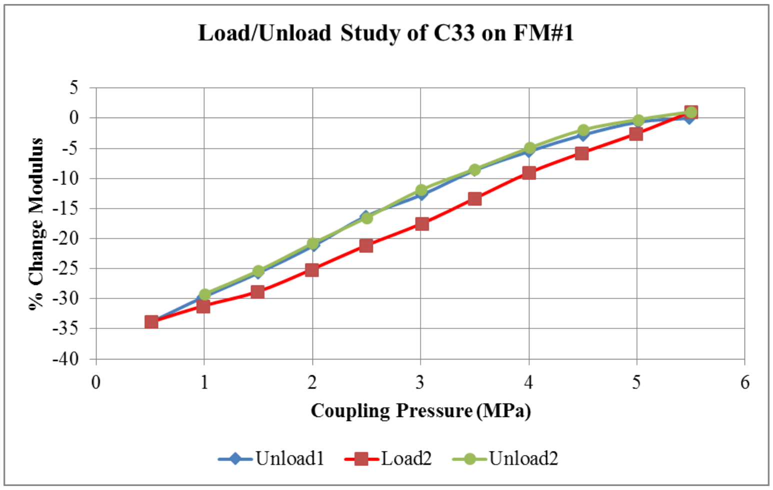

Figure 6 Response of FM#1 to multiple loading.

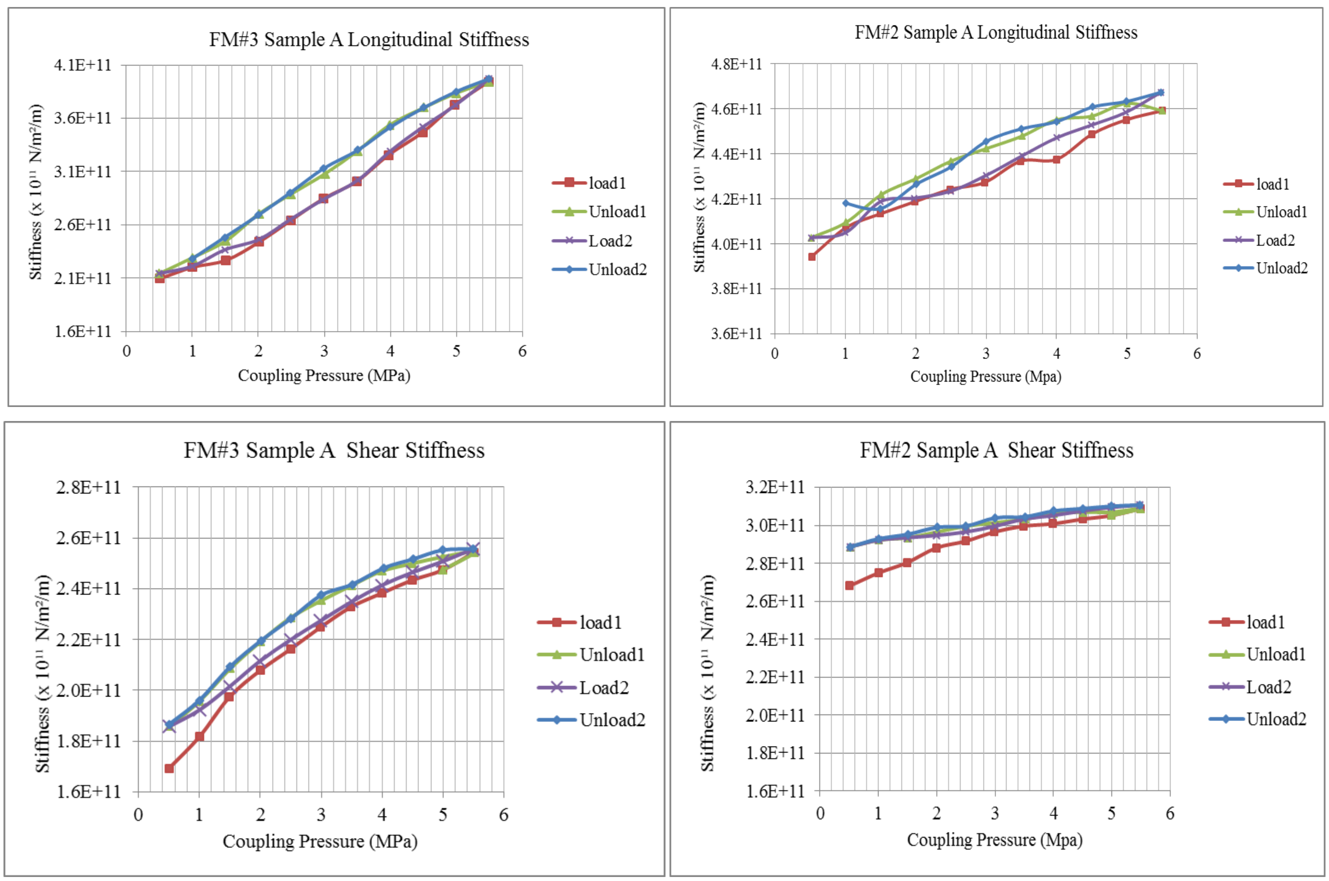

Figure 7 Longitudinal and Shear stiffness as a function coupling pressure for multiple loading cycles.

Strain Rate

One of the concerns regarding ultrasonic measurements of elastic properties in the MHz frequency range is that this range in significantly above that where squeal occurs. The ultrasonic estimates of elastic properties often yield values significantly higher than those obtained by static tests or modal analysis measured under unloaded conditions. Several researchers have attributed this behavior to the viscoelastic nature of the friction materials. In an effort to address the frequency dependence (strain rate) of the elastic properties, tests were conducted over a limited frequency range.

In order to measure the velocity as a function of frequency, gated pulses are needed to drive the transducers over a range of frequencies. The frequency range which can be measured is limited by a combination of the performance of the sensors and the length of the propagation path. To avoid diffraction and reverberation effects, it is desirable the limit the propagation path to less than the number of wavelengths contained within the ultrasonic pulse. This is illustrated in Figure 8a which shows a 4 cycle drive signal and the received signal after propagating through 114 mm thick aluminum sample. The yellow shaded portion shows the length of the propagation path which is 18.3 microseconds. In this case the 4 cycles or wavelengths fits comfortably inside the sample. For comparison Figure 8b shows a 4 cycle, 200 kHz transmit and receive signal in the same aluminum block along with the sample overlay. As can be seen, the length of the drive signal exceeds the dimensions of the block which leads to distortion in the phase of the received signal and uncertainty in the timing measurement. Using the gated pulse methods the ToF was measured over the useable frequency range from 3 MHz down to 200 kHz. The results are shown in Figure 9 where the % variation in measured velocity is plotted as a function of frequency. As expected for this thick aluminum sample which has linear elastic behavior there is no measureable variation in velocity with frequency.

In an effort to validate the gated pulse method, a polymer with known viscoelastic behavior, Plexiglas, was evaluated. In this case the sample was thinner, only 11.75 mm. This limited the lowest frequency that could be used to 400 kHz due to interference from reverberation. The velocity results are plotted in Figure 10. Also shown in the plot is data taken from the work of Capodagli and Lakes[8]. These researchers carried out somewhat extensive investigations of Plexiglas (aka PMMA) using a variety of methods and literature data measuring the loss tangent and modulus over the frequency range from 10^{-7} Hz to 200 kHz. Using these results one can estimate that the frequency dependence of the ultrasonic velocity should vary as frequency to the 0.0315 power, $(f/f_o)^{0.0315}$.

This data is shown in Figure 10 where we have normalized the data to the highest frequency that we have measured at 3 MHz. The agreement to our data is reasonable although both the predicted frequency dependence and the measured frequency dependence is small over the frequency range measured in this experiment (~ 7% reduction in velocity per decade in frequency).

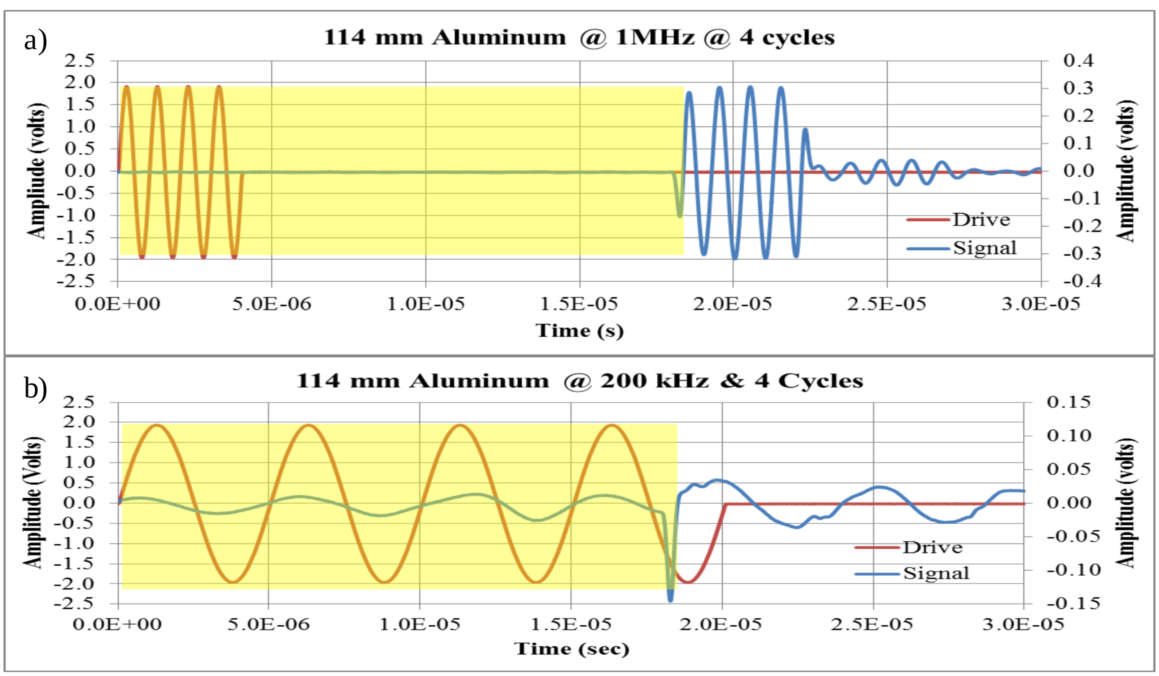

Figure 8 Gated pulse drive and receive signal with 4 cycle drive at a) 1MHz and b) 200kHz. The shaded region shows the "size" of the sample measured in wavelengths of sound. At 200kHz the drive signal duration exceeds the sample size.

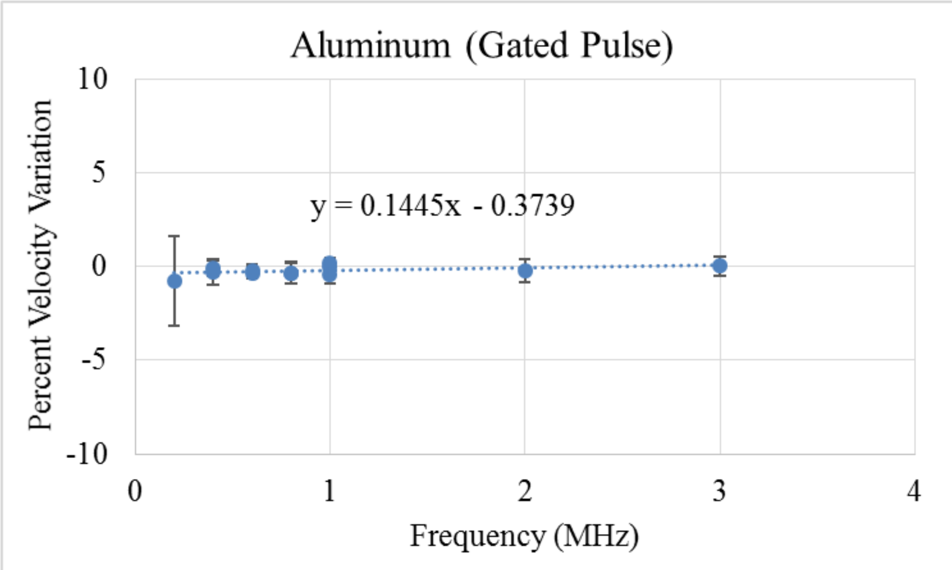

Figure 9 Baseline measurements of velocity vs. frequency for linear elastic material, aluminum.

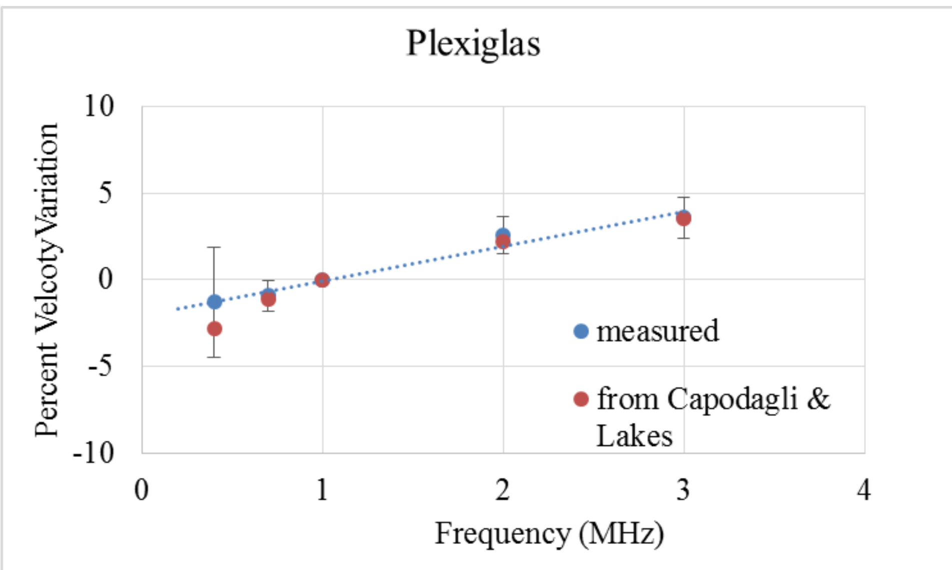

Figure 10 Comparison of gated pulsed velocity vs. frequency data with that derived from the literature for Plexiglas.

Using this gated pulse technique, the frequency dependence of the velocity was measured on a thick section of underlayer and a rectangular friction material sample (FM1). Results are shown in Figure 11. For these measurements the pulse duration was limited to 3 cycles. The results are mixed with the underlayer exhibiting a slight decrease in velocity with frequency while the friction material shows a slight increase. Within the errors of the measurement, all are consistent with minimal or no variation in velocity with frequency. Relative to the large variation in velocity with preload, these variations are insignificant.

Strain Amplitude (Displacement)

In light of the potential importance of the magnitude of the displacement on the determination of dynamic modulus, it is important to make some comments on the amplitude of the ultrasonic waves used to characterize the friction materials. For the 1 MHz pulse used for our analysis, the peak intensity is ~500 W/cm^2. Using this intensity one can calculate the maximum amplitude of the displacement, the wave particle displacement, for a 1 MHz sinusoid. These calculations yield a maximum displacement of 0.23 microns. In addition it should be kept in mind that the ultrasonic signal loses about 60 dB when traveling through 10 mm of friction material. Thus, the exiting ultrasound will have a particle displacement of only $2.3X10^{-4}$ microns. In any case, the displacement amplitude for ultrasonic measurements will be sub-micron throughout the entire operating regime. We have measured the ultrasonic velocity in both linear elastic materials and friction material using particle displacement by altering the drive voltage of our transducer by more than 60 dB. No measurable variation was observed for displacements from 0.1 micron to $2.3X10^{-4}$ microns.

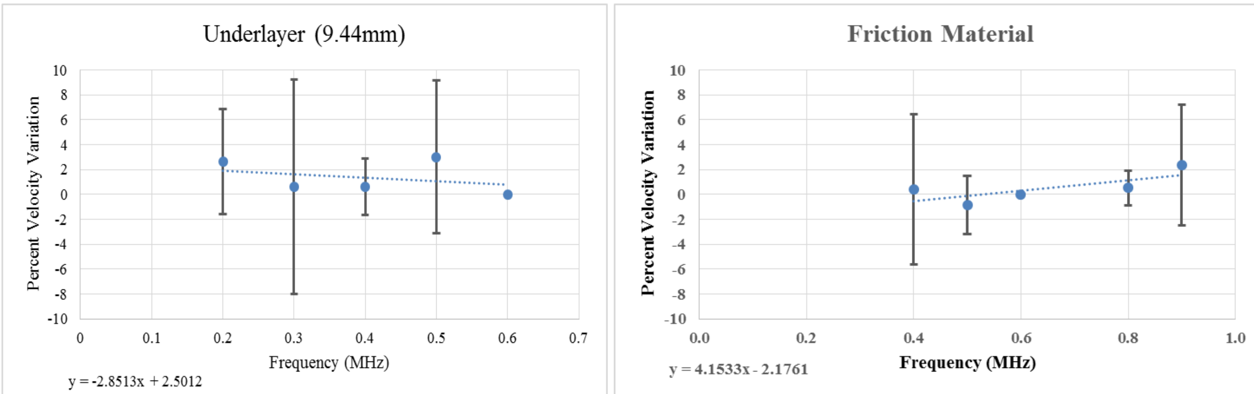

Figure 11 Gated pulse measurements of the dependence of velocity on frequency for an underlayer material and a friction material.

DISCUSSION

In this study we have investigated the influence of preload, strain rate and displacement amplitude on modulus measurements obtained from ultrasonic ToF measurements. Gated pulse measurement methods were developed and verified using known viscoelastic material. No significant variation in velocity (or modulus) was observed on friction materials over the frequency range from 0.2 MHz to 1 MHz. These results are consistent with those reported by Oura et.al which indicate that significant modulus variations were encountered from static to 100 Hz but the stiffness response of friction materials is flat from 100 Hz to 4 kHz[5]. This result combined with our finding suggests that viscoelastic behavior cannot be the source of the difference between static modulus measurements and ultrasonic dynamic modulus measurements.

Ultrasonic measurements of the dynamic modulus on three different friction materials show that the loading history influences the dynamic modulus. Specifically the modulus is always higher when unloading (depressurization) of the sample. The magnitude of this effect is different for different friction material formulations. Similar load hysteresis effects were obtained by experiments in the kHz frequency range[5].

The large differences observed between static modulus data and ultrasonic modulus data can be attributed to the non-linear character of the friction materials. For experiments in the kHz frequency range, it has been reported that the dynamic stiffness can be more than 4 times that of the static stiffness at preloads of 3 MPa. The dynamic stiffness shows larger variation with preload than the static stiffness. Furthermore, experiments carried out at a few hundred Hz indicate that the dynamic stiffness also depends on displacement amplitude. Specifically, more than a factor of 2 increase in dynamic stiffness has been measured as the displacement amplitude is decreased from 28 microns to 1 micron[5]. For all ultrasonic measurements the magnitude of the ultrasonic displacement is limited to the sub-micron range. Modulus values measured by higher frequency ultrasound appear comparable to dynamic modulus measurements at lower frequency. The dynamic stiffness of materials reported for the various low frequency experiments at 3 MPa correspond to elastic modulus of 2 to 2.5 GPa[3-5]. Two of the lower density materials used in this study have a modulus of 2.5 GPa.

Going forward, we would like to conduct studies to directly compare ultrasonic measurements with dynamic stiffness measurements in the kHz range. Characterizing this data in a way that is most useful to the NVH community is a critical priority. We will automate the measurement procedure to enhance and extend the measurement of hysteresis and we will extend the measurements to intact, as-manufactured, pads.

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