2010-01-1701

Comparative Studies of Non-destructive Methods for As-manufactured Brake Pads

Donald E. Yuhas, Carol L. Vorres, & Jack Remiasz
Industrial Measurement Systems Inc.

Earl Gesch
Performance Friction Corporation

Takeshi Yamane
Nisshinbo Automotive Manufacturing, Inc

ABSTRACT

In this study several non-destructive test methods have been applied to as-manufactured automotive brake pads. The primary emphasis of our study is the formulation and development of ultrasonic methods where 4 independent velocity modes are measured on each pad. For two of the measurements, the ultrasound is propagated in-the-plane of the pad, while in two other measurements the ultrasound is propagated through-the-thickness (out-of-plane). Over 300 pads from 5 different manufacturers have been tested. In many cases, the ultrasonic data is compared with other testing methods including conventional compressibility tests, modal analysis, and hardness testing. In some cases, measurements have been made of several different batches of materials to test long term consistency of the material properties in the production environment. In other studies the production process has been deliberately altered to help establish specific cause and effect relationships.

Whereas many of the other testing methods measure the properties of the brake pad component, the ultrasonic technique uniquely measures only the friction material properties. Furthermore, the ultrasonic methods have spatial resolution on the order of one square centimeter, thus it is possible to make multiple measurement within a single pad. Data will be presented comparing the variation observed within pads, to the pad-to-pad variations and batch-to batch variations. These ultrasonic data will be correlated with compressibility, modal data, and hardness data.

The development of the ultrasonic measurement technique applicable to as-manufactured components will be described in detail. The reproducibility and repeatability of the methods are quantified by comparing repeat measurements on the same samples as well as comparing measurement made by different operators/instruments. Lastly, the ultrasonic measurement process is intrinsically fast and can be readily automated. We will discuss how these methods can be automated in order provide in-line quality assurance measurement capability at the point of manufacture.

INTRODUCTION

Brake noise, a major source of warranty costs, is a complex problem involving a myriad of design and processing variables that include friction material properties, rotor design, caliper design, and vehicle suspension. The mechanical properties of friction materials are thought to play an important role in braking system noise performance. Although brake noise is minimized through proper design and appropriate friction material formulation, the realization of noise-free brakes requires that the manufacturer maintain these properties in production. Process variations can significantly alter friction material properties. This can adversely influence noise performance. Better measurement tools applied at the point of manufacture are desirable.

EXPERIMENTAL METHODS

ULTRASONIC

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. These methods have been described in a number of books and review articles.[1-5] For automotive friction materials the primary application for ultrasonic measurements has traditionally been the determination of the material elastic constants. This is a destructive test requiring the removal of the friction material from the steel backing plate. By measuring sound speeds of longitudinal and shear waves along various directions the elastic constants can be calculated. This method is described in detail in SAE J2725[6]. However, ultrasound is inherently a non-destructive method. Although it is currently not possible to measure the complete set of elastic constants on as-manufactured brakes, it is possible to measure the relevant ultrasonic velocities both in-the-plane of the pad and through-the-thickness of the pad. Because of its relationship to the elastic constants, the magnitude and uniformity of the measured velocity is useful as a potential process quality assurance measurement.

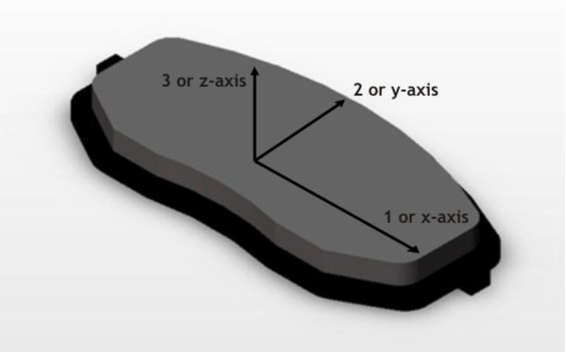
The symmetry of both drum brake segments and disc brakes is transversely isotropic owing to the compression molding manufacturing methods. The elastic properties are, to a good approximation, isotropic in the direction perpendicular to the pressing direction, but are 4 to 5 times more compressible in the pressing direction due primarily to flow and orientation of fibers perpendicular to pressing direction[7]. Figure 1.-1a shows the coordinate definition for a typical disc brake pad where the “3” direction (through-the-thickness) is along the pressing direction. The “3” direction is also the direction which force is applied in a braking application. The “1” and “2” directions are in-the-plane of the pad and perpendicular to the pressing direction. Figure 1.-1b shows the elastic constant matrix for this coordinate definition and transversely isotropic symmetry showing that there are 5 independent elastic constants.

The ultrasonic velocities that in part contribute to all of the diagonal elements of the elastic constant matrix can be determined non-destructively. Specifically, the elastic constant is directly related to the density times the square of the appropriate ultrasonic velocity. Measurement of the compression velocity, V_{33} through-the-thickness and V_{22} in-the plane yield the C_{33} and C_{22} while measurement of the shear velocities V_{32}, and V_{21} yield the diagonal constants C_{44} and C_{66}

$C_{33} = \rho*(V_{33})^2$ $C_{44} = \rho*(V_{32})^2$ through-the-thickness

$C_{22} = \rho*(V_{22})2$ $C_{66} = \rho*(V_{21})^2$ in-plane

With the velocity in (Km/sec) and the density, ρ, in (gm/cc) the above product yields modulus in GPa. V_{33} and V_{22} are compression velocities while V_{32} and V_{21} are the shear velocities. The through-the-thickness velocities should be inversely related to the material compressibility while the in-plane velocities will be more closely related to the flexural and torsion modes of the pad.



$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}C_{22} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{13} & 0 & 0 & 0\\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{rr}\\ \varepsilon_{\theta\theta}\\ \varepsilon_{zz}\\ \varepsilon_{\theta z}\\ \varepsilon_{rz}\\ \varepsilon_{r\theta}\end{bmatrix}$$

Figure 1-1 a) Coordinate definition for disk brake pad; 1-1b) Elastic constant matrix for transversely isotropic symmetry with the “3” direction as the unique axis.

The measurement geometry for both the through-the-thickness and in-plane velocities on as-manufactured pads is illustrated in Figure 2. The through-the-thickness direction is straightforward. By design, the thickness of the entire pad (steel backing and friction material) is well controlled and the steel thickness is known. The time of flight (ToF) attributed to the steel is then subtracted and the velocity of the friction material is determined. This is a relatively minor correction due to the high modulus of the steel. Typically, the ToF for the composite is on the order of 15 microseconds while the ToF attributed to the steel is only 1.5 microseconds. All data presented in this report uses velocities which have been corrected for the steel backing contribution. It also should be noted that the ultrasonic measurement has a small "footprint" which is determined by the size of the sensors. This makes it possible to measure the spatial uniformity within as-manufactured pads. For these studies the diameter of the sensor was 1.2 centimeters, thus multiple measurements can be made on each pad. Lastly, the steel backing may contain structures (attachment clips and blowholes) which preclude measurements on specific pad areas.

The measurement configuration is different for the in-plane propagation as illustrated in Figure 2a. For the in-plane direction, coupling must be done into the “sidewalls” of the pad. These sidewalls on opposite sides of the pad are often, by design, not flat and parallel. Furthermore, in some brake structures the sidewalls may be chamfered in such a way as to preclude measurement. In any case, small aperture sensors or sensors with compensating lenses have been used to facilitate these measurements when required.

One of the advantages of ultrasonic methods applied to measuring as-manufactured brakes is that ultrasonic measurement is intrinsically fast. Time required to propagate ultrasound through a brake pad is on the order of 10 to 20 microseconds. As a consequence, the method has potential for high speed operation. The fastest way to acquire data on an entire brake pad is to use multiple sensors and electronic scanning. An alternate way to automate the process is to mechanically scan the sensors over the part. Though slower, this approach is more flexible and able to more easily accommodate the wide range of component configurations. For this study parts were measured manually. Work is being done in parallel to automate the process with the appropriate parts handling and automated measurement capability. The emphasis in this study is on the integrity of the data, its relation to other non-destructive tests, and ultimately the relevancy to controlling NVH and brake manufacture.

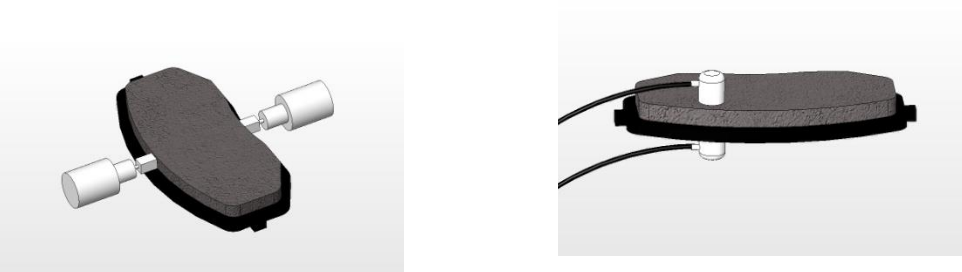


Figure 2a) In-plane coupling configuration; b) through-the-thickness configuration.

For each pad, multiple locations were measured. In some pads, eight measurements were made while in others only three measurements were made of each mode. In all cases, a force of 720 N (162 lbs) was used to couple the transducers to the friction material. A viscous, organic coupling compound, (IMS-SWC), was used to promote ultrasonic transmission. In general, in order to make a meaningful measurement of the ultrasonic velocity, it is necessary to have flat and parallel entrance and exit areas for the ultrasonic beam. For those pads that have holes in the steel backing plate, it is necessary to avoid these zones and thus they are excluded from the measurement process.

The measurement process begins with generating a scanning template which is illustrated in Figure 3. In this case, we measure seven locations in each pad as indicated by the numbered circles in Figure 3. The smaller, shaded circles indicate the steel backing through holes. Each measurement area is 12.5 millimeters in diameter.

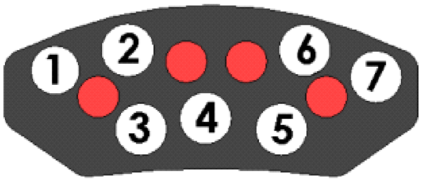


Figure 3. Illustrates an example of a measurement template for a generic brake pad. The numbered circles indicate the measurement locations whereas the shaded areas were avoided due to holes or raised areas in the steel backing.

COMPRESSIBILITY & HARDNESS

The compressibility of all pads investigated in this study was measured in accordance with SAE J2468. Brake lining compressibility is the reduction in lining thickness due to compressive forces. A test rig as described in J2468 was used to measure the compressibility in the disc brake pad assembly loading configuration. The brake pad is subjected to a pre-load of 5 bar pressure. The pressure is then increased to 100 bar at a rate of 80 bar/s. 100 bar pressure is maintained for 1 second, and then the pressure is decreased at a rate of 80 bar/s to a pressure of 5 bar and maintained for 1 second before another cycle. The pad is subjected to 3 cycles and the deflection at 100 bar of the third cycle is reported. All measurements were conducted at room temperature.

MODAL ANALYSIS

The resonant frequencies of the brake pads were obtained using a single point laser vibrometer and a mini force hammer. The laser vibrometer was used to pick up the response velocity of the brake pad due to impact excitation from the force hammer. The pad was placed on foam and the response was measured at the corner of the pad ear and impact excitation was applied to the corner of the opposite ear. Five averages were used for all measurements and calculated frequency response functions. Resonant frequencies were found from the FRF data.

RESULTS & DISCUSSION

Production Studies

One method for evaluating the sensitivity of ultrasonic methods to consistency and uniformity of as-manufactured brake pads is to compare data obtained on several different production pads. Although this does not establish the relationship between the ultrasonic measurable and NVH performance, it will serve to identify the representative variability found in production parts.

Table I summaries ultrasonic velocity data for the through-the thickness modes on 6 different groups of production parts. The V_{33} data is the compression wave while the V_{32} data corresponds to the shear wave. All data has been corrected for the influence of the steel backing. To facilitate the comparison all data has been normalized to the mean of the group. The pads differ in thickness, form factor, and number of samples within a group. Thus, the number of measurements possible within each pad varies. For example, in Pad A, only three measurements were possible while in pads B, E, and F, eight independent measurements were made on each pad. The data for the samples are summarized in Table I. In this Table the Pad-to-Pad variation is computed by determining the % standard deviation for all of the pads within the group. The "within pad" variation is the mean of the % standard deviations for each pad within the group. The measurement error is estimated by repeat measurements on the same pad. This varies somewhat for the different pads but is approximately +/- 0.7 % for the V_{33} mode and +/-0.4 % for the V_{32} mode.

Table I Pad-to-Pad and Inter-Pad variation for 6 different friction materials

			V32	V32	V33	V33
Pad ID	Quantity	positions	pad-pad	within pad	pad-pad	within pad
			%	%	%	%
A	30	3	5.75	5.12	5.63	7.20
B	53	8	3.63	8.29	4.7	9.83
C	20	5	1.12	1.32	1.05	1.35
D	42	4	2.22	2.83	1.97	2.48
E	20	8	2.52	5.27	3.2	6.28
F	20	8	3.04	2.3	3.35	3.13

In comparing the various pads, one finds a wide range of variability. In terms of magnitude, the minimal variations are on the order of 1%, however in one case the average variation observed within the pads is almost 10 %. In all but one pad type, Pad F, the average variation observed within a pad is larger than the pad-to-pad variation. The within pad variations found in the compression mode, V_{33} are generally higher than those observed using the shear mode V_{32}. However, the data from the 2 modes is highly correlated with R^2 >0.91.

The character of the observed variations varies considerably from one pad type to the next. It is of interest to explore some of the data in more detail. For example, Figure 4 shows the individual measurements along with the standard deviations on the 53 components which comprise Pad B which showed the highest variation both in terms of Pad-to-Pad variation and variation within a pad. For this pad, 8 individual measurements were made of through-the-thickness velocity, V_{33} as indicated in the sketch shown in Figure 5a. Figure 5b indicates that the variation within a pad is not random, but exhibits a complex pattern of behavior. The average value of the velocity found at position 3 is almost 20 percent higher than that measured at position 7. In contrast Figure 6 and 7 show comparable data obtained on Pad F. For the Pad F group only 20 pads were analyzed but like pad B eight positions were measured on each pad. The most obvious feature in Figure 6 is the "outlier" pad # 12. The spatial variation observed in this pad is less than a few percent for all positions.

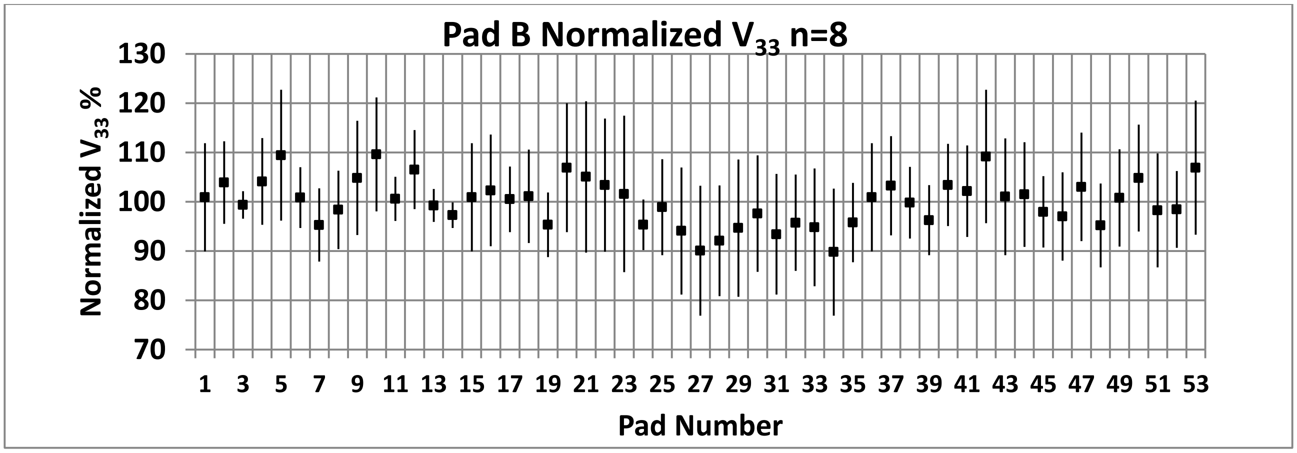


Figure 4. V_{33} data for 53 pads; error bars are the standard deviation for the eight measurements made on each pad.

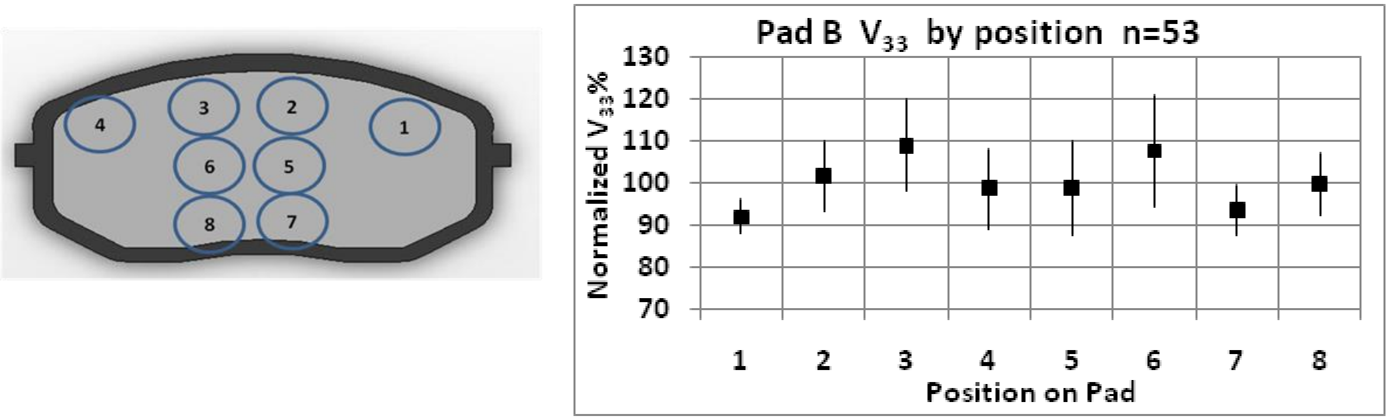


Figure 5 a) sketch showing measurement locations; b) V_{33} data by location for 53 pads; error bars are the standard deviation for the 53 measurements at each location.

For one vendor we have been able to measure properties over an extended period of time. In this case 20 pads were taken from production lots over the last 24 months and measured. This data has also been normalized to the mean value measured in the first batch. In this way we can track any long term drift. A value of 100% would indicate a velocity equal to the mean of the batch #1 group. The V_{33} data for 4 of the batches is shown in Figure 8

PROCESS STUDIES

The data presented in the previous section were "passive" studies where measurements were made on production pads in order to experimentally determine the typical range of variability encountered and our ability to quantify the variations. Although the measurements are motivated by our experience with measurements of elastic modulus made destructively, there is no direct connection between these measurements and the specifics of the manufacturing process or the pad NVH performance. In an effort to identify and quantify this relationship a series of production studies we undertaken. One of these studies involves measuring the influence of the underlayer thickness on the measured through-the-thickness velocities.

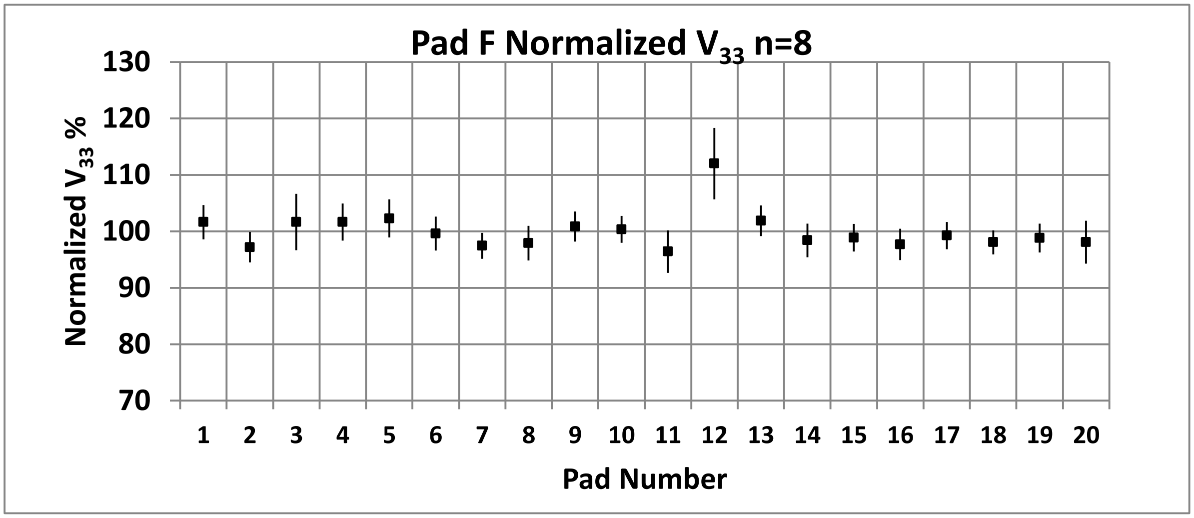


Figure 6 V_{33} data for 20 pads; error bars are the standard deviation for the eight measurements made on each pad.

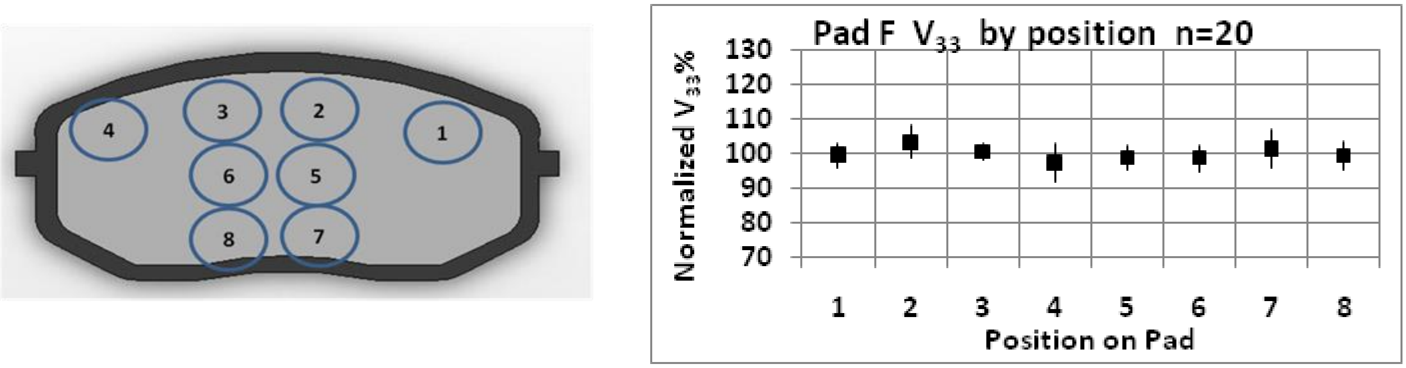


Figure 7 a) sketch showing measurement locations; b) V_{33} data by location for 20 pads; error bars are the standard deviation for the 20 measurements at each location.

Sample description

In this study a specific brake formulation was used to fabricate pads with varying thicknesses of underlayer ranging from 0 mm to 6 mm. A total of 64 in-board pads and 64 out-board pads were fabricated. Each of these groups was divided into 4 sub-groups of 16 pads with varying nominal underlayer thicknesses of 0 mm, 2 mm, 4 mm, 6mm. The friction material, Pad H, was a carbon metallic formulation.

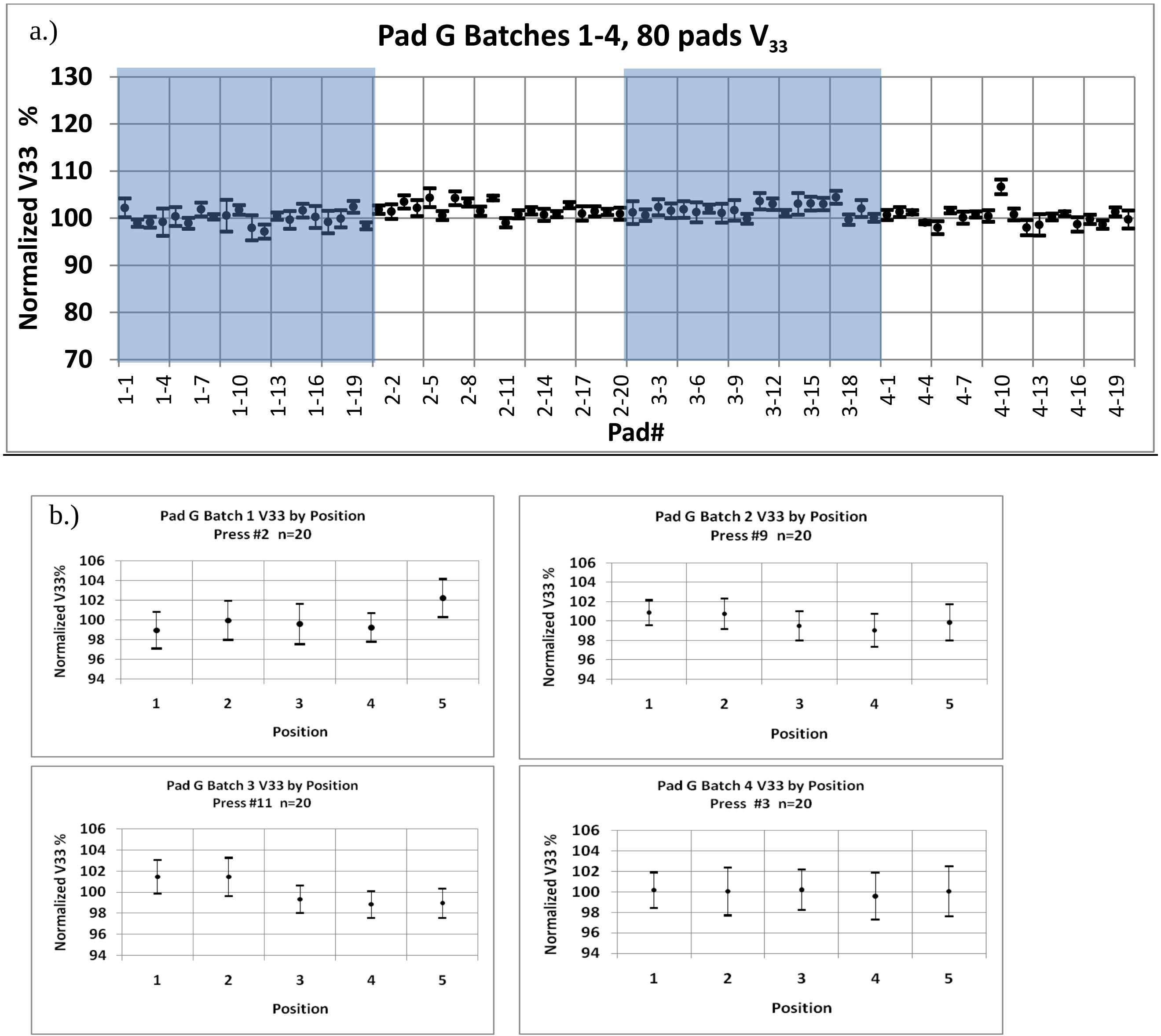


Figure 8a. Pad average V_{33} (normalized to average value for first group of 20) for 80 pads from 4 batches of 20 pads each. The error bars show the variability within each pad. Figure 8b) shows data from these same 80 pads where we looked at the normalized average of the velocity as a function of position. All values were normalized to the average of each batch. Each batch was made using a different press which may account for some of the variability.

The compression velocity, V33 and the shear velocity V32 were measured on all 128 pads. The results are similar for both modes. The V32, shear wave data is presented in Figure 9 where the individual pad measurements are grouped by underlayer thickness where 0-xx corresponds to 0 mm underlayer thickness and 6-xx corresponds to 6 mm underlayer. Each plotted point is an average of 8 different measurements made in the through-the-thickness direction. There is good agreement between the in-board and the outboard data in each underlayer thickness group. Clearly, the measured velocity shows a strong dependence upon the underlayer thickness. Figure 10 shows the average value and standard deviation of both V33 and V32 as a function of underlayer thickness. Clearly the underlayer has a lower value of both V33 and V32 and its inclusion tends to modify the overall stiffness of the pad. Using a layered model, the nominal thickness and the value of V33 and V32 obtained with no underlayer, the velocity of this underlayer material can be estimated. The best fit values are 0.87 Km/sec for V33 and 0.65 Km/sec for V32, which are considerably lower than that of the friction material. Subsequent to this analysis we have made direct ultrasonic measurements of the underlayer only samples which yield similar values of 0.73 Km/sec and 0.65Km/sec for V33 and V32 respectively.

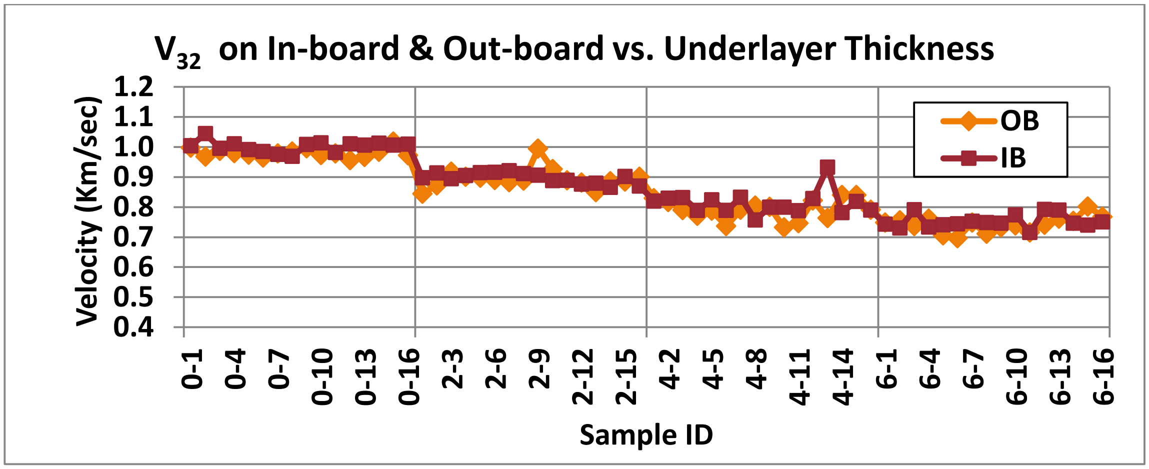


Figure 9 V_{32} data on in-board and out-board pads with nominal underlayer thickness from 0 mm to 6 mm.

Another interesting influence regarding the underlayer is its influence on the non-linear, load-dependent behavior of the measured ultrasonic velocity. All results presented above were obtained at a load pressure of 4 MPa (coupling force of 700 N) as specified in SAE Specification J2725. Figure 11 compares how the compression modulus, C_{33} and shear modulus, C_{44} varies with load. For the no underlayer sample, the shear modulus shows no load dependence and the compression modulus is reduced only 4% at the lowest load measured, 0.6 MPa. In contrast the sample with the 4 mm underlayer has developed significant load dependence.

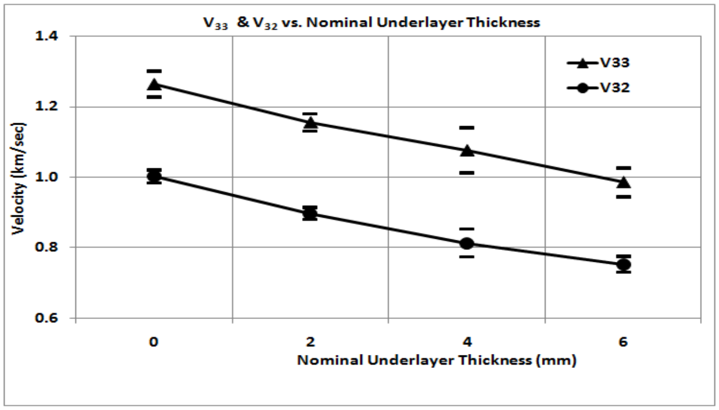


Figure 10 Group average and Standard deviation of V_{33} and V_{32} as a function of underlayer thickness.

CORRELATIONS

For several of the investigations, in addition to the ultrasonic tests we have been able to characterize these materials by other non-destructive methods including the whole brake component compressibility deflection and modal analysis. In pad C for the analysis of 80 pads the measure velocity varies by only +/- 2% and the compressibility deflection is in a narrow range of +/- 5% around 100 microns. In this case the correlation is poor. $R^2 < 0.01$. However, in situations where the deflection is larger, there appears to be a good correlation between either the V_{32} or the V_{33} and the compressibility deflection as illustrated in Figure 12.

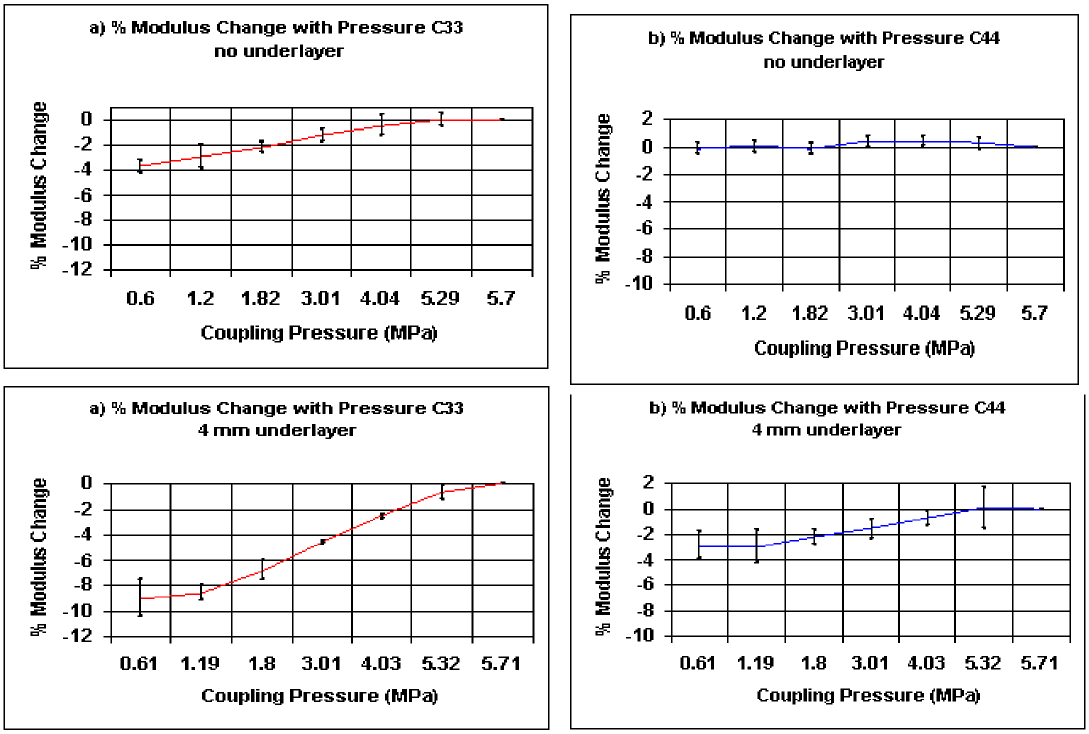


Figure 11 comparison load-dependence of compression modulus and shear modulus of 4 mm underlayer sample with that of the 0 mm underlayer sample.

Only in one of the pads studied was Gogan hardness data available for 20 of the pads. None of the through-the-thickness measurement data showed any correlation with the Gogan values. In two cases, Grindosonics vibration data was available. For Pad b comprised of 53 pads, there were three distinct chamfer configurations which preclude meaningful correlations. Even when one segregates the data by chamfer, no correlation with and ultrasonic measurement yielded correlation better than $R^2 = 0.45$. Similarly, for the 30 pads of Pad type A no correlation with R-square greater than 0.45 was found any ultrasonic mode and the Grindosonic vibration frequency.

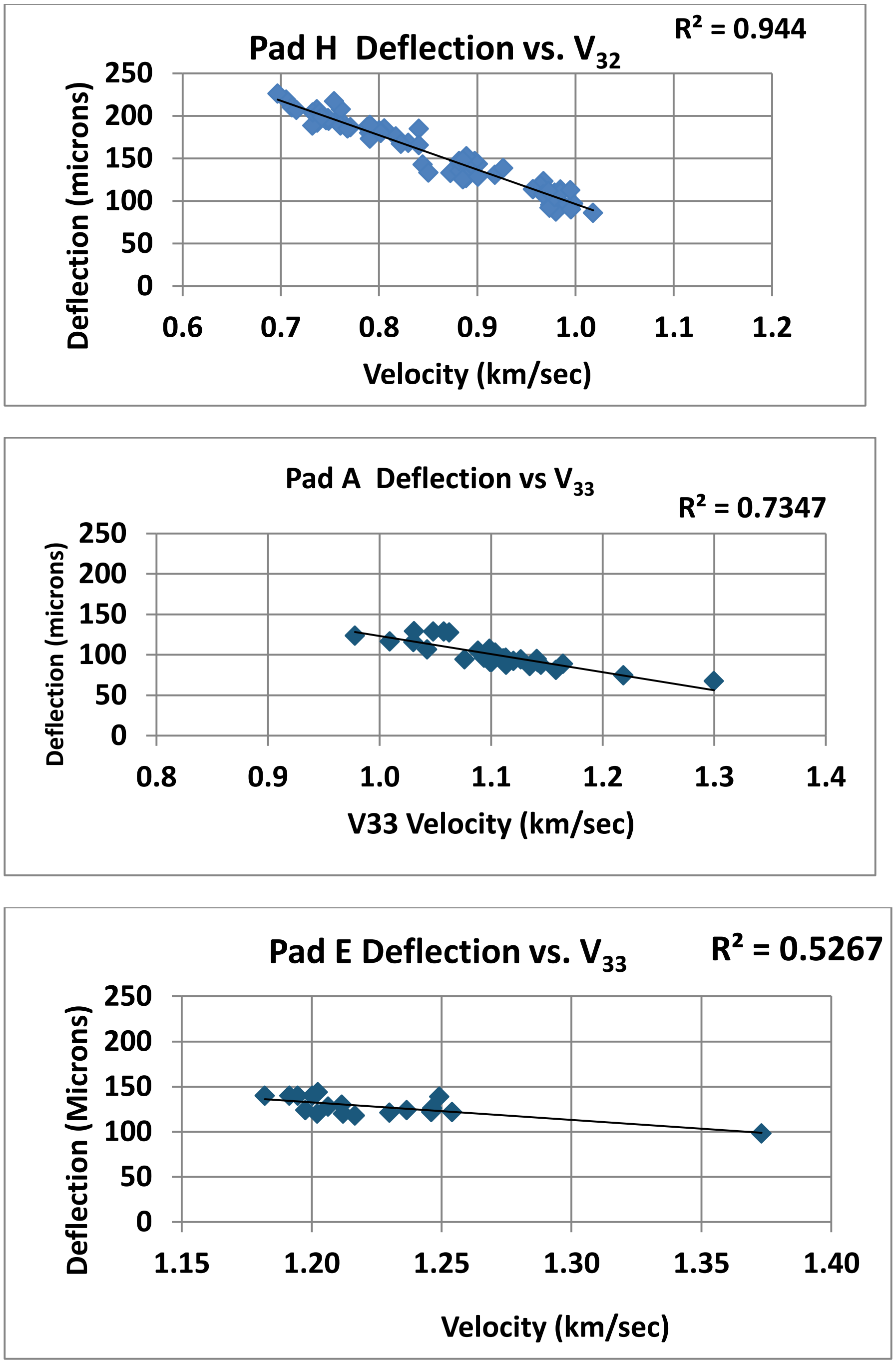
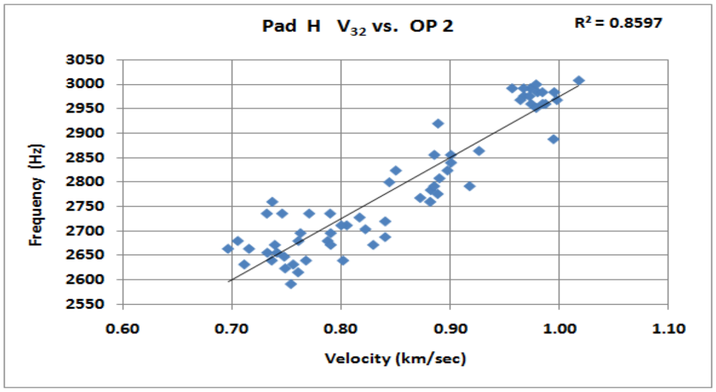
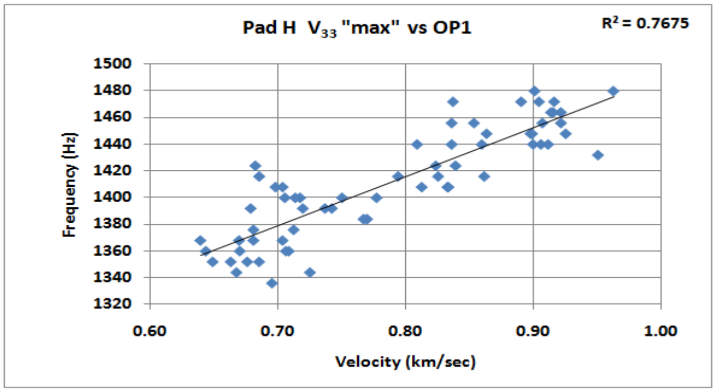
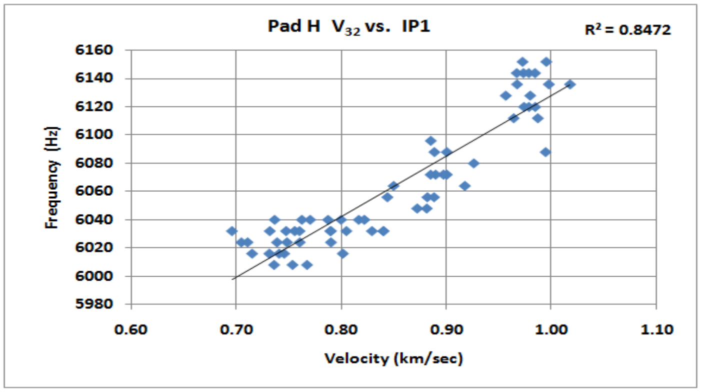


Figure 12 Ultrasonic velocities correlated with deflection derived from pad compressibility test.

Lastly, on one group of pads, pad type G we were able to compare the through-the thickness velocities to the various vibrational modes over the frequency range from 1 kHz to just beyond 10 kHz. This is the same Pad group where the V33 and V32 modes correlate well with the deflection measured in a standard compressibility test. For this pad the individual in-plane and out-of-plane modes appear to be highly correlated. These modes surprisingly show a strong correlation with both the V32 and the V33 data. Examples are shown in Figure 13 shows typical correlation for one OP and one IP mode with the through-the-thickness velocities V33 and V32. The in-plane velocities were also measured for these pads and the analysis of this data is still being carried out.







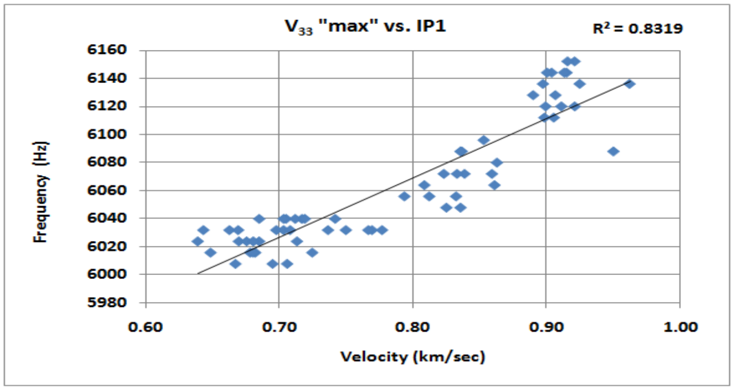


Figure 13 shows typical correlation for one OP and one IP mode with the through-the-thickness velocities V33 and V32.

SUMMARY/CONCLUSIONS

Ultrasonic characterization data has been generated on a range of intact, as-manufactured brake pads. Significant variations are found in the 6 different pads analyzed. The magnitude of the velocity variations found from one pad to the next can be as high as 9 percent. This corresponds to a modulus variation of almost 18 percent. The most uniform pads investigated exhibited variations on the order of 1% which is comparable to the measurement repeatability. Surprisingly the variation found within a single pad can often exceed the average pad-to-pad variations. Also in some pads systematic spatial variations spatial variations are observed which may be significant in controlling the manufacturing process as well as the brake performance. In the production study where brake pads were produced over a period of 2 years show excellent reproducibility to a level of 1%.

Process studies that monitor the variation in measured velocity as a function of underlayer thickness demonstrate the importance of the underlayer mechanical properties in controlling the brake pad elastic properties. In the pad construction used in the underlayer study, the elastic properties of the underlayer were found to be more compliant than the friction material. By controlling the underlayer thickness the overall compliance of the brake pad can be altered. It was also found that the underlayer contributes significantly to the load-dependent, non-linear properties of the composite pad. Good correlation is found between the deflection measured by compressibility and the measured through-the-thickness shear and compression velocity. In the few pads where hardness and Grindosonics vibration data were available, no significant correlations with the measured ultrasonic data were observed. For the Pad H samples used in the underlayer study, modal analysis was carried out measuring both the in-plane and out-of-plane modes up to frequencies as high as 12 kHz. These modes appear to be well correlated with one another as well as being significantly correlated with both the V33 and V32 modes.

Further investigations involves collecting and analyzing the in-plane ultrasonic velocity, continuing the long term process study and conducting NVH tests using outliers from the production study as well as NVH testing of selected components from the underlayer study.

REFERENCES

1. Schreiber, E., Anderson, O.L. and Soga, M., Elastic Constants and Their Measurement, McGraw-Hill, New York,1973
2. Truell, R., Elbaum, C. and Chick, B.B., Ultrasonic Methods in Solid State Physics, Academic, New York, 1969.
3. Thurston, R.N., in Physical Acoustics vol 1 eds. W.P. Mason and R.N. Thurston, Academic Press, New York, 1964.
4. Every, A.G. and McCurdy, A.K., Landolt-Bornstein New Series Group II, vol. 29a. ed. Madelung, Springer, Berlin,1992.
5. Every A.G., “Determination of the Elastic Constants of Anisotropic Solids”, NDT International Vol. 27, No. 1, p. 3, 1993.
6. Disc Brake Squeal, Frank Chen, Chin An Tan, and Ronald L. Quaglia eds. Chapter 12 D.E. Yuhas & M. P. Yuhas. Friction Material Elastic Constant Measurements ISBN 10 0-7680-1248-1
7. SAE Brake Lining Standards Committee, Works in Progress J2725 Friction Material Elastic Property Measurement, www.sae.org

CONTACT INFORMATION

Donald E. Yuhas, Founder and president of Industrial Measurement Systems Inc. 630-236 5901; dyuhas@imsysinc.com ;www.imsysinc.com

ACKNOWLEDGMENTS

We wish to thank all of the organizations and individual who have given their resources and time to make this analysis possible. This includes useful discussions with researchers and management at Federal Mogul, Continental Corporation, Motion Technologies, General Motors, and TRW. Special thanks go to Ms. Loretta Oleksak for her contribution to the measurements, data reduction, and production of this manuscript and to Joseph Lloyd for automation of the ultrasonic measurement process. Our research results are based upon work supported by the National Science Foundation Partnerships for Innovation (PFI) Program under Grant No. IIP-0945455. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

DEFINITIONS/ABBREVIATIONS