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EVOLUTION OF BRAKE NOISE PERFORMANCE AND ITS RELATION TO VARIATIONS IN FRICTION MATERIAL ELASTIC PROPERTIES

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ABSTRACT

In this study two measurement methods, the ETEK and SHAKE are used to measure the dynamic modulus of brake pads over preloads from 10 bar to 30 bar. When direct out-of-plane modulus measurements are made by both testing methods on the same samples, the results are highly correlated (R^2 =0.98). Additional tests are carried out comparing ETEK modulus measurements made non-destructively on as-manufactured pads with destructive SHAKE modulus measurements on small cylinders cut from pads. When this work, which involved ten pads and five different formulations, is combined with the previous results, the correlation between ETEK and SHAKE measurements is R^2 =0.92. The reduced correlation is attributed to spatial non-uniformity of the pads. Although highly correlated, the ETEK modulus values are systematically higher than the SHAKE values. This difference is attributed to the friction materials viscoelastic nature and the strain rate dependence of the dynamic modulus. A "scaling model" has been developed which can be used to relate ETEK and SHAKE data. This scale factor is consistent with observations of the dynamic modulus frequency dependence observed in the kHz frequency range. The non-destructive methods based on ETEK have been automated. The ETEK test methods can be applied to intact, as-manufactured brake pads. The non-destructive test results include out-of-plane dynamic modulus, preload sensitivity, hysteresis, and pad uniformity. These techniques are useful for selecting pads based on out-of-plane modulus values prior to noise performance testing as well as quantifying the variation of out-of-plane modulus as the result of performance testing. Noise performance tests using the pad formulations measured by SHAKE and ETEK are currently in process.

INTRODUCTION

Dynamic stiffness in friction materials is believed to play an important role in determining the noise performance of braking systems. The dynamic stiffness of the pad is higher than the static stiffness and is greatly dependent on pressure load and strain amplitude. It is dynamic stiffness and not static stiffness of the pads that correlates better with squeal and NVH performance. This observation has led to a number of research activities directed at acquiring out-of-plane dynamic stiffness data in the kHz frequency range relevant to NVH[1-7]. The Sinusoidal High-Frequency Analyzer for K-matrix Evaluation, SHAKE, developed by Brembo is one of several measurement methods currently being used to characterize friction material. To date these kHz frequency test methods are destructive since samples are small cylindrical segments, 30 mm in diameter, cut from pads. Work is in progress to scale this method so that full size pads can be tested.

Dynamic stiffness can also be measured by ultrasonic methods using the ETEK[8]. In contrast to the SHAKE which operates in the kHz frequency range, the ETEK system operates in the low MHz regime. Although, like the SHAKE, the ETEK method is fundamentally based on Hooke's law. The ETEK uses precise timing of propagating waves and not stress-strain measurements. As such, there are concerns regarding the use of vibrations in the MHz regime to probe friction materials and the relevance of ETEK test results to NVH performance as well as dynamic modulus measured in the kHz frequency by methods such as SHAKE. It is important to compare and understand the differences between the ETEK and SHAKE test results for dynamic modulus measurements on friction materials.

Although the SHAKE has the advantage of making measurements in the frequency range relevant to NVH, there are issues regarding flexibility, scalability and application to as-manufactured brakes. Different hardware/procedures are required for in-plane, out-of-plane and shear modulus measurements. The current system is destructive and can only be applied to small samples cut from intact pads. Testing of full-size, as-manufactured pads using the same test methods is difficult. In contrast, the ETEK method can be used on small samples as well as full-size, as-manufactured components and is commercially available. The ETEK has been used for a number of years as a destructive test method to measure both the in-plane as well as the out-of-plane elastic properties of anisotropic friction materials[9,10]. More recently, ultrasonic methods, based on the ETEK, have also been used to non-destructively measure the uniformity, non-linear properties, and out-of –plane modulus in as-manufactured brake pads.

METHODOLOGY

Two different testing methods used in this study for dynamic modulus measurements are the ETEK and the SHAKE. The ETEK method is based on the measurement of propagation speed of a short, high frequency, ultrasonic pulse in the MHz frequency range. The SHAKE determines modulus by measuring strain response to stress applied in the 500 Hz to 2500 Hz frequency range.

The ETEK uses vibrations in the low MHz regime, sub-micron strains and zero net stress. Modulus is determined through precise measurements of time-of-flight (ToF) of a propagating ultrasonic wave. ETEK measures both in-plane and out-of-plane Young's and shear modulus, employs preload up to 5 MPa and can be operated over a temperature range from ambient to 300°C. Figure 1a shows a typical through-transmission ETEK configuration used for the out-of-plane modulus measurement. Measurements can be carried out using either intact, as-manufactured pads or friction materials where the steel backing is removed. For the measurement of as-manufactured pads, the data must be corrected for the propagation time in the steel backing. The correction factor is generally less than 10% as the steel has a well-controlled modulus and is independent of load. Figure 1b shows dynamic modulus data for an unbacked friction material as a function of preload from 0.3 MPa to 4.5 MPa.

The Sinusoidal High-Frequency Analyzer for K-matrix (*stiffness matrix*) Evaluation, SHAKE, allows the measurement of the out-of-plane (E_z) and in-plane (E) elastic modulus of friction material samples in the squeal frequency range from 0.5 to 3 kHz. The braking pressure is applied on the specimen as a static preload in the NVH relevant range between 1 and 50 bar and from this starting condition a sinusoidal excitation is applied by means of a piezoelectric actuator with displacement amplitudes between 0.1μm and 2 μm. The stiffness is then estimated using the ratio between the dynamic signal from a load cell and the sample deformation which is estimated through an integration of accelerometer's response. Although the specific details of operation differ somewhat, similar measurement techniques have been reported by several researchers.[3-7] The SHAKE operating principles have been described in detail in previous work.[1,2] Figure 2 shows a photograph of the SHAKE hardware. Figure 3 shows typical data.

a) b)

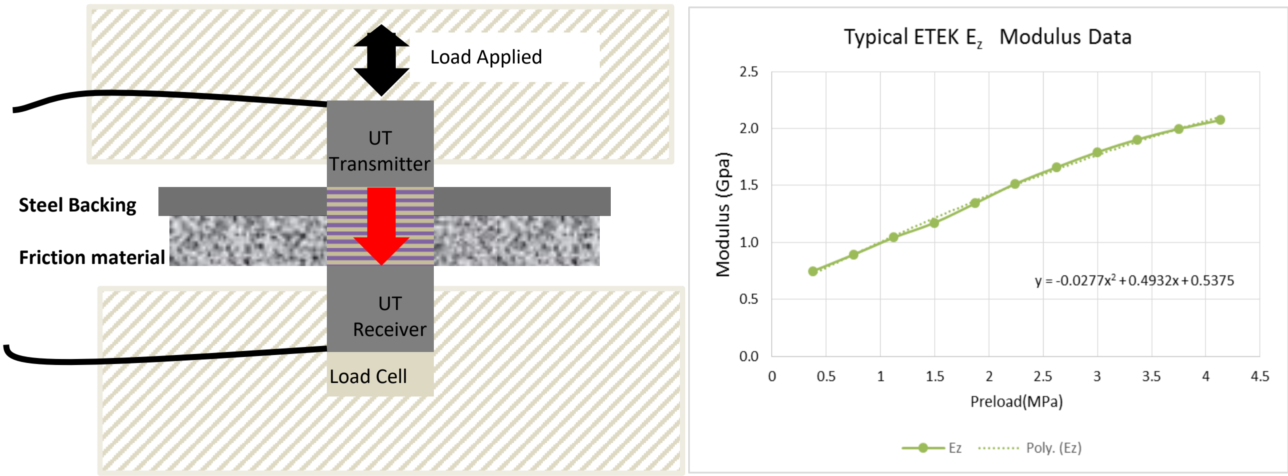

Figure 1. a) ETEK through-transmission configuration for out-of-plane measurement; b) ETEK generated dynamic modulus data.

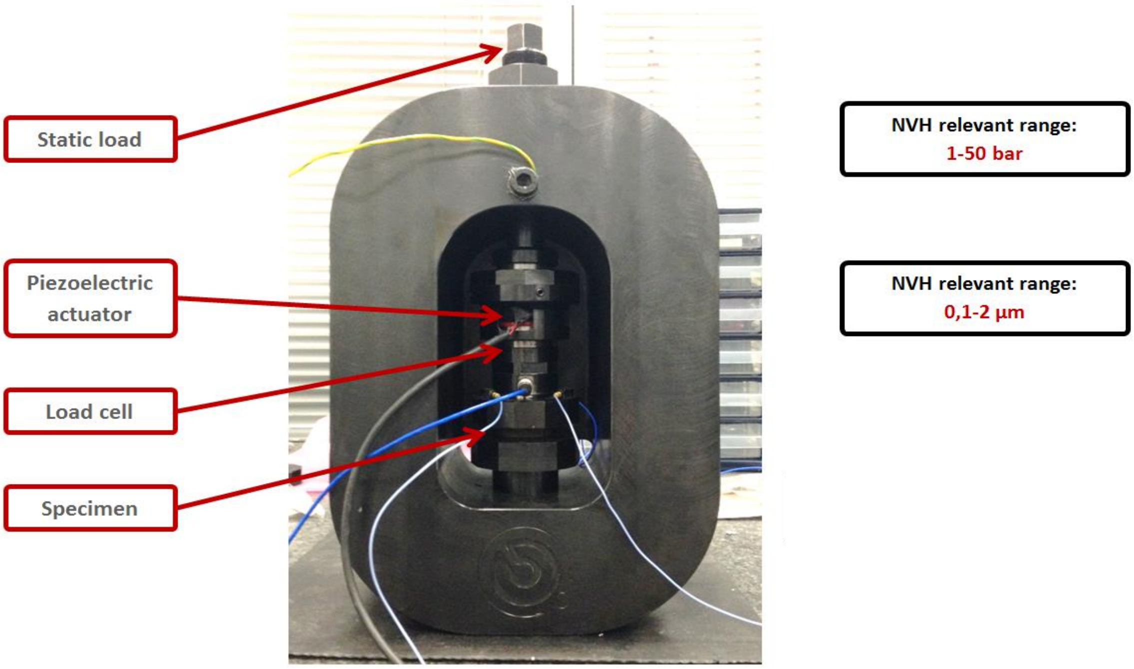

Figure 2 Brembo SHAKE measurement system

RESULTS

ETEK-SHAKE Analysis

The intent of this work is three-fold; 1) to compare dynamic modulus results obtained with the SHAKE and ETEK measurements on the same samples; 2) to investigate the relative importance of temperature and preload on the variation in out-of-plane dynamic modulus and 3) to formulate test methods applicable to intact, as-manufactured brakes.

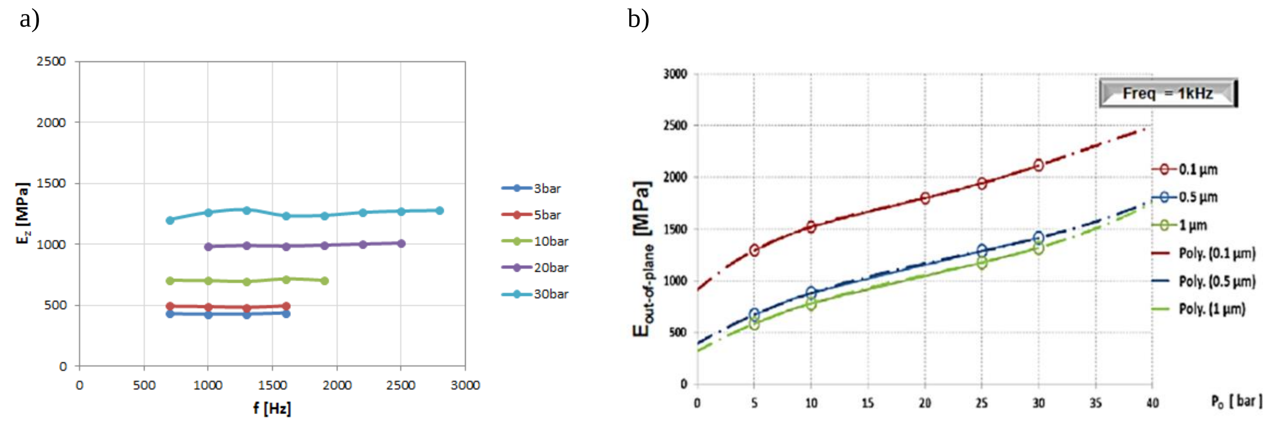

Figure 3 Typical SHAKE data a) frequency dependence of modulus as a function preload as a fixed excitation amplitude (0.5μm); b) Dynamic modulus as a function of preload for a range of excitation amplitudes for a 1kHz excitation frequency.

Initial studies were carried out on a series of four test samples of two different material types. The test samples are unbacked cylindrical specimens, 30 mm in diameter, 8 mm thick, removed from production pads. This sample size is typical for SHAKE instrument and the out-of-plane modulus measurement, E_z. Two samples (20_A, and 28_A) are NAO materials and the other two are a low steel formulation (2A and 22_A). These samples were measured with both the ETEK and SHAKE as a function of preload from 10 bar to 40 bar. The modulus data is presented in Figure 4. The SHAKE data was obtained at a frequency of 1.0 kHz and a dynamic displacement of 0.5 microns. The ETEK data used ultrasonic sensors with a center frequency of 1 MHz. For the ETEK data, the out-of-plane Young's modulus, E_z, is estimated from the measurement of the longitudinal velocity, V_{33} and the elastic constant $C_{33}=\rho(V_{33})^2$. Historically, for friction materials, the Young's modulus, $E_{z,}$ can be estimated as E_z~0.85 C_{33}. As shown in Figure 4 the ETEK data is systematically higher than the SHAKE modulus. Curiously, the dependence of the modulus on preload from 10 bar to 30 bar, as measured by the slope, is similar for both the ETEK and the SHAKE data.

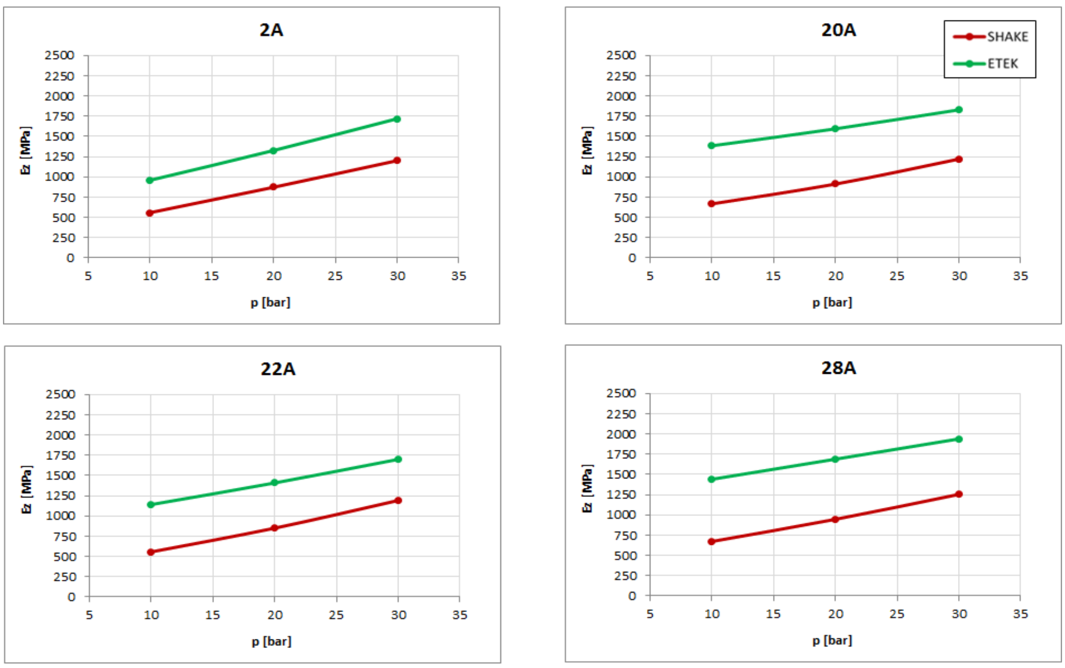

Figure 4 Direct comparison of out-of-plane dynamic modulus measured by SHAKE and ETEK.

Figure 5 shows the correlation between the ETEK and the SHAKE measurements at a load of 30 bar. The correlation coefficient, R^2, is 0.98. This result is significant in two respects: 1) The strong correlation between the SHAKE and ETEK suggests that they are measuring similar properties; 2) The ETEK modulus data is obtained by measuring a single ultrasonic velocity, V_{33}, propagating in the thickness direction. This measurement is relatively easy to make and can readily be made on as-manufactured pads.

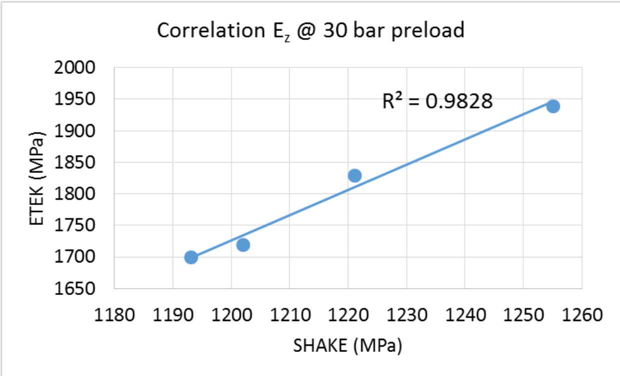

Figure 5 Correlation between SHAKE and ETEK Modulus data at preload of 30 bar.

In a second series of tests, ten as-manufactured pads of five different formulations and two different applications were first measured non-destructively using the ETEK technique. For this analysis, the ultrasonic measurement used a newly developed iETEK system. This system automates the measurement process and continuously measures modulus as a function of pre-load. The iETEK is applicable to both as-manufactured pads as well as small test samples cut from pads.

Using the iETEK, modulus data is recorded as a function of load and displayed in real-time on the monitor. Samples are subjected to preloads ranging from 100 N to 850 N at a fixed loading rate of 20 N/sec. Data is continuously recorded for three load-unload cycles so that any hysteresis in the modulus data can be quantified. Measurements are carried out over a region of the pad corresponding to the "footprint" of the sensor which is 12 mm in diameter. Multiple measurements on a pad can be made to determine the spatial uniformity. Typical iETEK data for three load/unload cycles is shown in Figure 6.

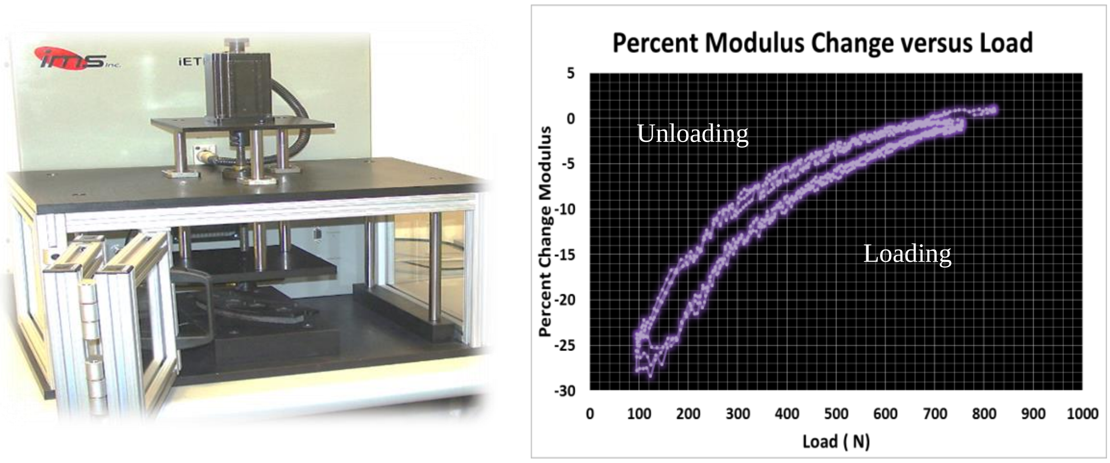

Figure 6 a) iETEK ; b) typical, out-of-plane modulus data measured as a function of preload.

For the iETEk analysis six different 12 mm diameter regions of each of the 10 pads were measured over three load/unload cycles. This data was subsequently analyzed to produce average pad properties. Upon completion of the iETEK analysis of the as-manufacture pads they were measured using the SHAKE technique. For the SHAKE analysis, each pad was cut to extract two 30 mm diameter cylinders used for the SHAKE analysis. The average iETEK and SHAKE data are shown in Figure 7. For the SHAKE data, two preload conditions, 20 bar and 30 bar are presented. For the iETEK data is given for the endpoint loading force of 100 N and 800 N. The loading force of 800 N roughly corresponds to a pressure of 20 bar.   As in the prior comparison of ETEK and SHAKE data the ETEK values are systematically higher. However, the correlation between the measurement methods remains excellent as illustrated by the correlation shown in Figure 8. In Figure 8 we combine the previous data where both techniques measured small cylinders with the average pad data. For the 10 as-manufactured pads there were two pads each with the same formulation.

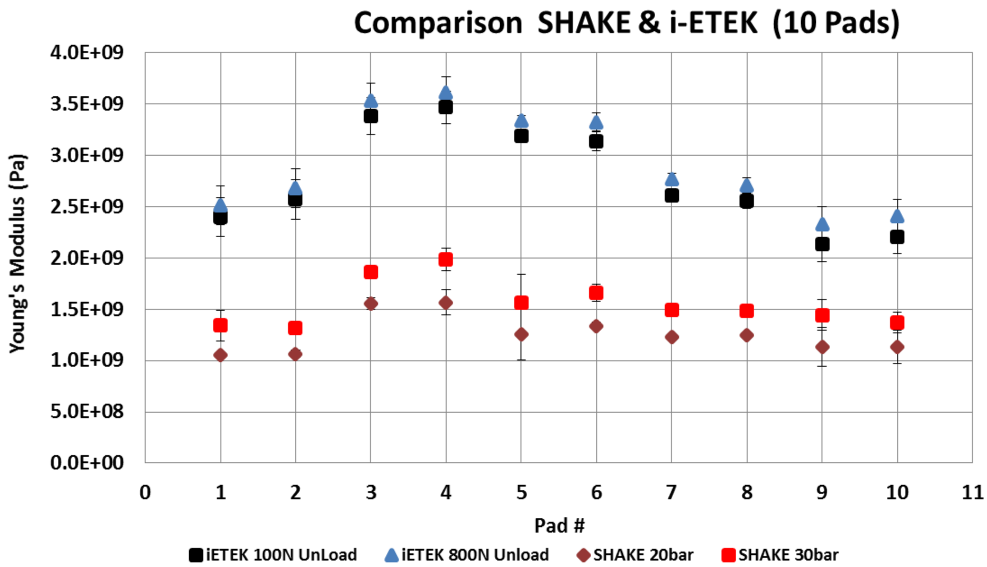

Figure 7 Comparison of iETEK dynamic modulus on as-manufactured pads with SHAKE measurements.

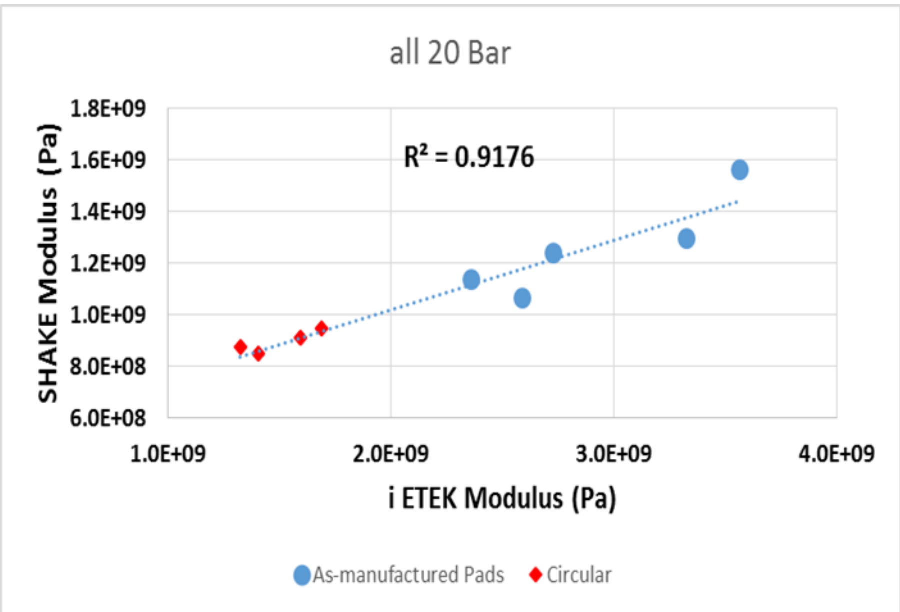

Figure 8 Correlation of iETEK dynamic modulus results with SHAKE measurements.

Even though there is good correlation between the ETEK and SHAKE modulus estimates, it is of interest to investigate the origin of the differences in the magnitudes. For the iETEK and SHAKE data shown in Figure 7 the 800 N, iETEK dynamic modulus values are on average 1.87 times the SHAKE values at 30 bar. There are potentially three causes for the differences in the magnitude and preload dependence: 1) anisotropic material properties; 2) viscoelastic material properties; and/or 3) non-linear properties. The most plausible explanation for the difference is the viscoelastic behaviour.

It is well known that viscoelastic behaviour gives rise to a strain rate dependence on modulus and thus measurements at different frequencies will be different. The ETEK measurements involve higher frequency vibrations MHz, versus kHz for the SHAKE. For viscoelastic materials there is a trend for materials to stiffen as the frequency is increased[11]. Quantitative data on the viscoelastic properties of friction materials formulations is limited. However the higher modulus obtained with the ETEK using MHz vibrations is in the direction that which would be expected for viscoelastic behaviour. The question is whether or not the magnitude of the observed differences are reasonable?

The modulus dependence on frequency can be characterized by a power law expression of the form:

$$E = E_o \left(\frac{f}{f_0}\right)^{\beta} \qquad \text{Eq.1}$$

Where f is the frequency and the exponent, β, is the unknown parameter related to the viscoelastic properties. It is possible to estimate β from the data shown in Figure 7. Using 1 MHz as the frequency for the iETEK data and 2 kHz for the SHAKE data a β value of 0.099 can be used to "scale" the SHAKE data at 30 bar to the iETEK data. In general the scaled SHAKE data agrees with the iETEK data within 2% with some points differing by as much as 13%. Using this same scaling factor over the frequency range from 1000 kHz to 4000 kHz predicts a frequency dependent modulus increase of only 15% which is consistent with the limited data available in this frequency range. One can conclude that the magnitude of the dependence of dynamic modulus on frequency is in line with that which might be expected as the result of viscoelastic behaviour.

Non-destructive Methods

The strong correlation between the SHAKE and iETEK and the formulation of appropriate scaling factors is significant. Non-destructive out-of-plane modulus data can be generated on as-manufactured pads prior to conducting noise performance testing. Furthermore, these same methods can be applied to specific brake pads used in performance tests to measure any irreversible changes. In addition to the out-of-plane modulus data, the pad modulus spatial uniformity, hysteresis, pad-to-pad variation, and preload dependence can also be determined non-destructively. Figure 9 illustrates the available non-destructive iETEK pad data available for pre and post noise testing. Figure 9a shows the raw data modulus versus preload data for multiple load/unload cycles for a single pad position, 9b shows the variation of modulus within a pad, and 9c compares average pad to pad variation and the average variation within a pad. All of these parameters can be measured prior to as well as after noise performance tests.

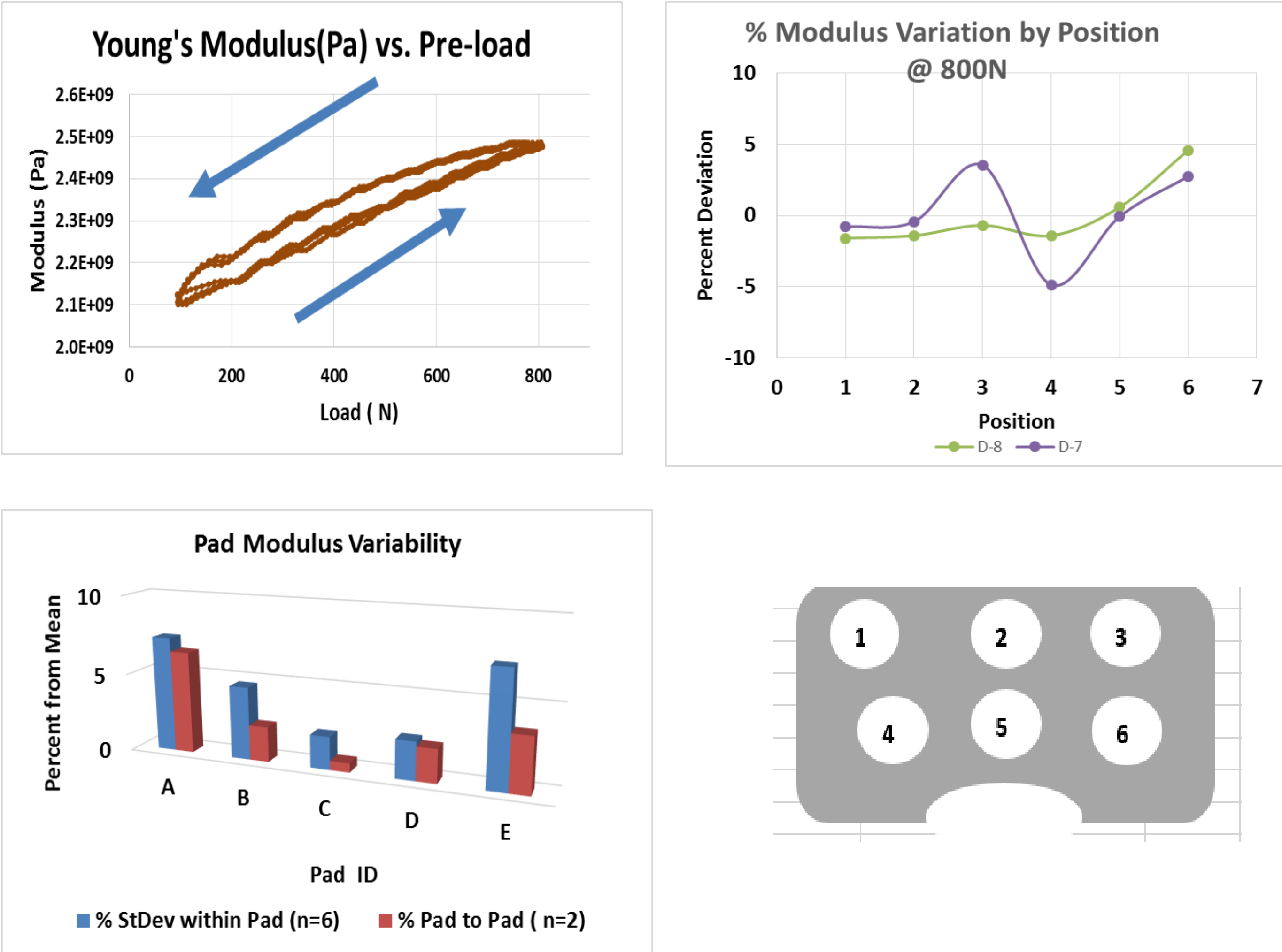

Figure 9 Non-destructive i-ETEK pad property data available for pre- and post- noise performance tests.

CONCLUSION

The dynamic out-of-plane modulus measurements made with the SHAKE in the kHz frequency range and ETEK in the MHz frequency range are highly correlated. Correlations are best when both measurement methods are applied to the same samples cut from pads. However, excellent correlations are achieved (R^2=.82) when iETEK non-destructive modulus measurements made on as-manufactured pads are compared with SHAKE measurements made samples cut from the same pads. The reduced correlation is attributed to the spatial non-uniformity in the pads and the fact that iETEK and SHAKE may sample different pad volumes. A frequency scaling method has been formulated to quantitatively relate the dynamic modulus measured by SHAKE at 2 kHz to iETEK results obtained at 1 MHz.

A commercially available ultrasonic method, the iETEK, has been automated so that modulus of multiple positions on intact, as-manufactured pads can be measured continuously as a function of preload. In addition to dynamic out-of-plane modulus, quantitative modulus variation with preload, spatial uniformity within a pad, and load/unload hysteresis can be made. The measurements are non-destructive, thus enabling the characterization of specific pads which can subsequently be used for noise performance tests. The same pads can be evaluated before and after noise performance tests.

Going forward noise dynamometer tests on the five as-manufactured formulations measured by iETEK and subsequently by SHAKE are currently in process. We will analyze this data to determine the relation between NVH performance and dynamic modulus as well as other characteristics e.g. preload sensitivity, uniformity, and hysteresis. Because of the need to compare modulus results obtained using the iETEK with the destructive measurement of modulus using the SHAKE, it was necessary to use different pads for noise performance tests in this study. However, we plan to measure the noise dynamometer tested pads using both measured with both the iETEK and the SHAKE after the completion of the dynamometer tests. This will not only contribute further to the correlation of the two methods but also quantify irreversible changes that may have occurred as the result of noise tests.

Our future plan is to use the non-destructive iETEK method to measure the actual pads subjected to noise dynamometer tests. Work will also be directed at formulating a more complete analysis of the iETEK loading profile and its relation to the pre-load variations in modulus. It is also of interest to look at the relation between the magnitude of the modulus preload dependence and the variation of modulus with temperature. For the SHAKE, efforts are underway to scale the testing system so that it may be possible to measure intact, as-manufactured pads. The ability to directly measure pads subjected to dynamometer noise performance tests will be a powerful tools for determining the relation between the dynamic out-of-plane modulus and noise performance.

REFERENCES

(1) Cucchi, F. and Cerutti, A, “Friction Optimization through Improved Characterization Techniques, Oral presentation, Eurobrake 2013, EB2013-FMC-005, Dresden, Gr, June 2013. Brembo SAE 2014
(2) Malmassari, C. and Cucchi, A., “Friction Material:A New Optimization Process (oral only), 32nd annual 2014 SAE Brake colloquium, Burlingame, CA, Oct. 2014.
(3) Oura, Y., Kurita, Y., Matsumura, Y., and Nishizawa, Y., "Influence of Distributed Stiffness in Contact Surface on Disk Brake Squeal," SAE Technical Paper 2008-01-2584.
(4) Oura,Y,Kurita, Y., and Matsumura, Y., "Influence of Dynamic Stiffness in Contact Region on Disk Brake Squeal", Joumal of Environment and Engineering, Vol.4, No.2, pp. 234-244,2009.
(5) Oura, Y., Kurita, Y., Nishizawa, Y., and Kosaka, K., "Comparison of Pad Stiffness under Static Pressure and Vibration with Small Amplitude”, SAE technical paper 2012-01-1818, pp.297-305, 2012.
(6) Hiroyuki Nonaka, Yukio Nishizawa,Yutaka Kurita, Yasunori Oura , Considering the Dynamic Pad Stiffness in FEM Analysis of Disk Brake Squeal, SAE Technical Paper 2012-01-1818, 2012.
(7) Hornig, S.A, and Von Wagner, U. Improvement of Brake Squeal Simulation Reliability by Measurement and Identification of Friction Material Properties. SAE Technical Paper 2012-01-1806
(8) Yuhas, D.E, Vorres C. L., Remiasz, J.R, & Lloyd, L.L., “Ultrasonic Methods for characterizing the non-linear properties of Friction Materials EuroBrake 2013 technical paper EB2013-TM-021, 2013
(9) Yuhas, D.E., and Yuhas, M.P., “Friction material elastic constant measurements”, Disc Brake Squeal Mechanism, Analysis, Evaluation, and Reduction/Prevention, Chapter 12, pp. 273-308, ISBN 10 0-7680-1248-1, 2005.
(10) SAE J2725 Test specification
(11) Julie Capodagli & Roderic Lakes, “Isothermal viscoelastic properties of PMMA and LDPE over 11 decades of frequency and time: a testof time–temperature superposition”, Rheol Acta 47:777–786,2008.