Quality Assurance Measurements
on
4 As-manufactured Brake Pads

Summary

This report describes the results obtained from ultrasonic measurements using the ETEK on 4 intact automotive brake pads. These pads were labeled by IMS Inc. as pad A, pad B, pad C, and pad D. For each pad, we measure 4 different positions in the "out-of-plane" (through-the-thickness) direction and 4 different positions propagating in-the-plane of the pad. For each of these positions we measure both the longitudinal and shear propagation speeds. All data has been corrected for the presence of the steel backing so that the data is representative of only the friction material. Graphic presentation of the data is given in this report. Tabular data is included in the Appendix A. In Table S-I we summarize the mean measured values for each mode. The "Group" % deviations indicate the pad-to-pad variations while the "Pad" % deviations refer to the average measurement variation within each individual pad. In this material the pad-to-pad variations generally exceed the variation found within individual pads.

Table S-I Comparison of Group and Individual Pad Deviations (n=4)

			Avg	Min	Max
Mode	Group	Group	Pad	Pad	Pad
	AVG	% Dev	% Dev	% Dev	% Dev
V32	1.107	3.04	0.55	0.34	1.01
V33	1.225	3.32	1.13	0.44	1.81
V21	1.624	0.51	1.33	0.52	1.97
V22	2.582	0.43	0.85	0.427	1.28

The load dependence for these materials was not measured.

For completeness, we analyzed one of the samples destructively using the conventional ultrasonic analysis methodology (SAE 2725 Specification) to extract the complete set of elastic constants. These results are presented in Appendix B for the test sample, the pad, and the entire group of 4 pads. The results for the entire group are reproduced below.

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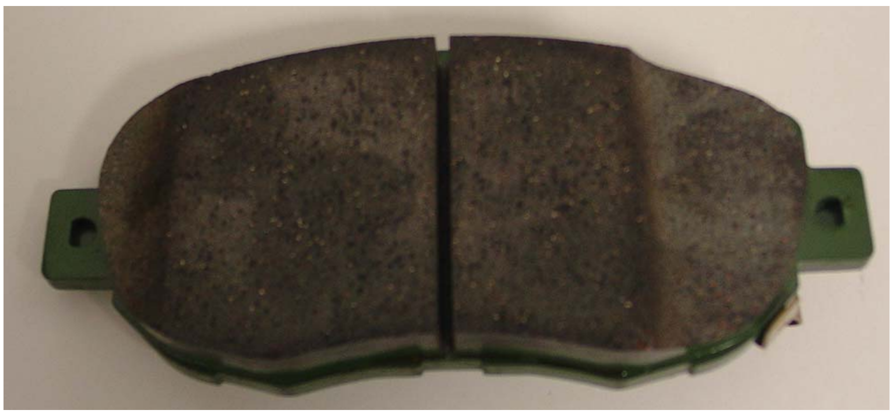
Ultrasonic Velocity Data on 4 Brake Pads

Documentation

The 4 pads were labeled by IMS Inc. as A, B, C, and D.

For each pad, we measure 4 different positions in the "out-of-plane" direction and 4 different positions propagating in-the-plane of the pad. For each of these positions we measure both the longitudinal and shear propagation speeds. All data has been corrected for the presence of the steel backing so that the data is representative of <u>only</u> the friction material. The location of the various measurement points are shown in Figure 1 where we show the trajectory of the ultrasound. The arrows show the propagation path for modes V_{21} and V_{22}, while the circles show V_{32} and V_{33} positions.



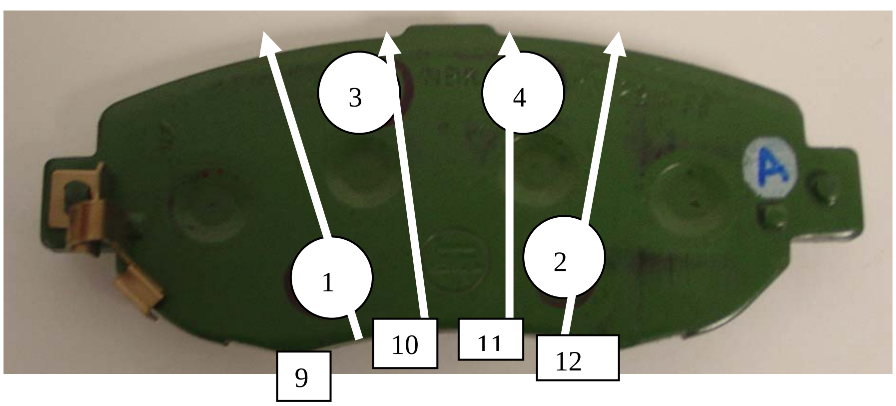


Figure 1 Location of measurement positions in friction materials. The "footprint" of the sensor is approximately 1 centimeter in diameter.

Out-of-plane velocity modes are related (sometimes in mysterious ways) to the compressibility. The in-plane measurements, V22 and V21 are related to in-plane Young's and shear modulus and thus more related to the bending modes of the pad. The relationship between the velocity and the relevant elastic constant is given below: For the presentation of the data we use the measured ultrasonic velocity.

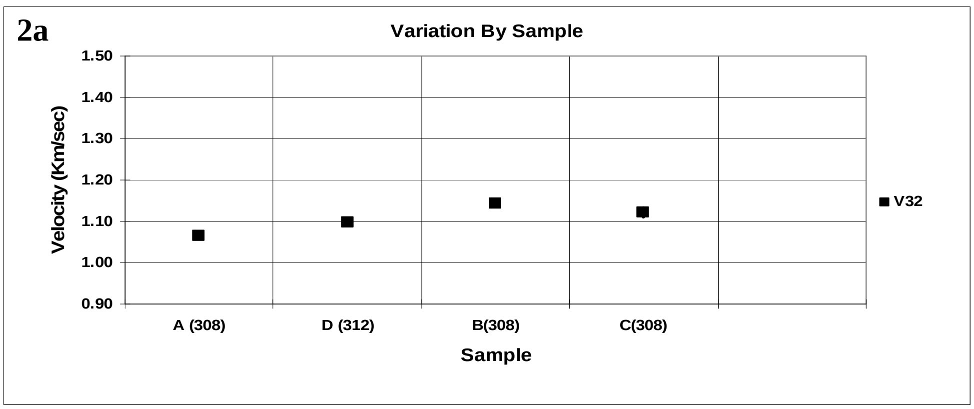
$C_{33} = \rho*(V_{33})^2$ $C_{44} = \rho*(V_{32})^2$ out-of-plane

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

With the velocity in units of (Km/sec) and the density in (g/cc), the product yields modulus in GPa. In this work only the ultrasonic velocity is measured and presented. The measurements for all 4 modes are presented in 2 different ways. In one plot the average value for each pad is presented along with the standard deviation within the pad. This presentation format allows one to visually compare the pad-to-pad variation with the variation within each pad. The second format involves computing the average and standard deviation of the measured velocity at each position for all 4 pads.

Figure 2 shows the average out-of-plane data for the shear velocity (2a) and the longitudinal velocity (2b) for all 4 brake pads. The standard deviation bar on each point quantifies the measured variation within each pad (n=4) while the variation across the plot from pad A to pad D indicates the pad-to-pad variation. In Figure 2 the variation within each pad is quite small. The standard deviation is less than the thickness of the plotted points for both the shear and the longitudinal measurement. Data in this Figure suggests a general correlation between the shear and longitudinal measurements. For this material the variation within the individual pads is typically smaller than the pad-to-pad variations. There is a slight trend for the average velocity measured in pads B and C to be greater than that measured in pad A and D. All data is summarized for all modes in Table I.

Ultrasonic velocity measurements on all 4 Brake Pads (Out-of-plane modes).



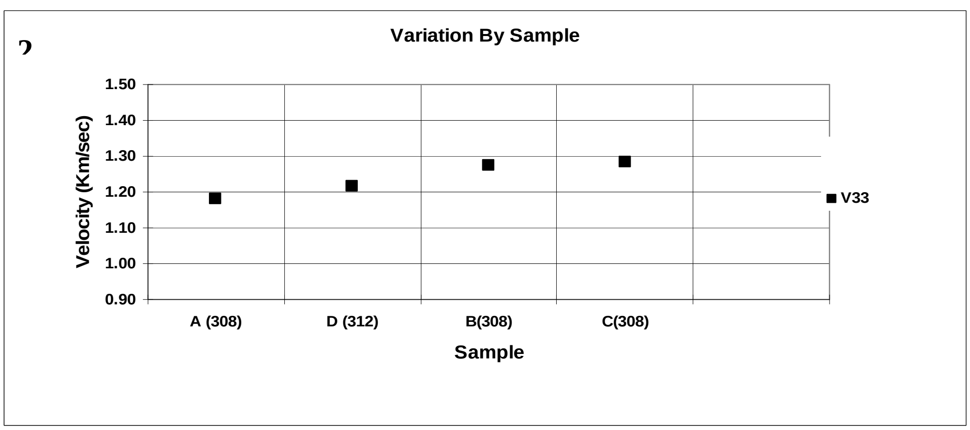
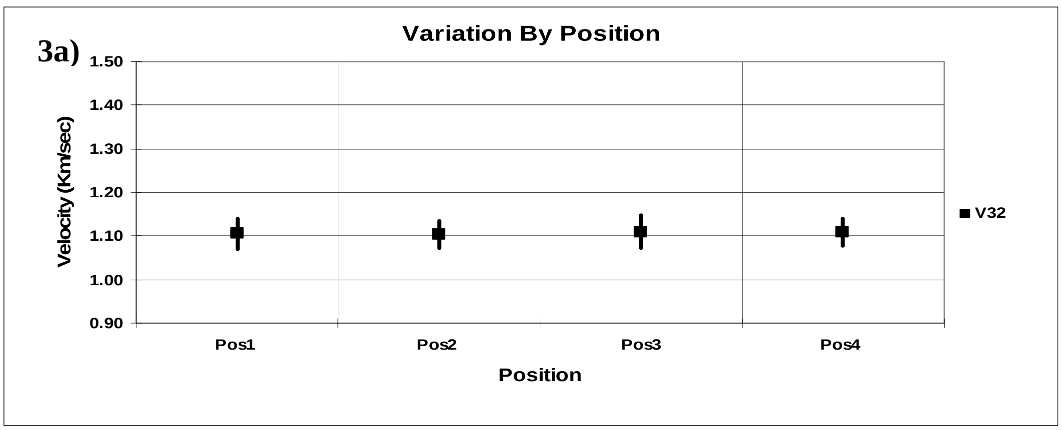


Figure 2 a) Mean V_{32} shear velocity and standard deviation of 4 measurements made on all 4 brake pads. b) Mean V_{33} longitudinal velocity (n=4) and standard deviation of all 4 brake pads. The standard deviations are smaller than the plotted points and thus are not visible in these plots.

Table I Comparison of Group and Individual Pad Deviations

Mode	Group AVG	Group % Dev	Avg Pad % Dev	Min Pad % Dev	Max Pad % Dev
V32	1.107	3.04	0.55	0.34	1.01
V33	1.225	3.32	1.13	0.44	1.81
V21	1.624	0.51	1.33	0.52	1.97
V22	2.582	0.43	0.85	0.43	1.28

Figure 3 shows the same data presented in Figure 2. However, in this case, we have averaged the data by position. The value of this presentation format is to determine if there are systematic spatial variations in the pad velocity measurements. This might indicate specific processing variations. These results suggest that the individual pads exhibit excellent uniformity. The error bars, though small, suggest some pad-to-pad variations in the measured velocity.



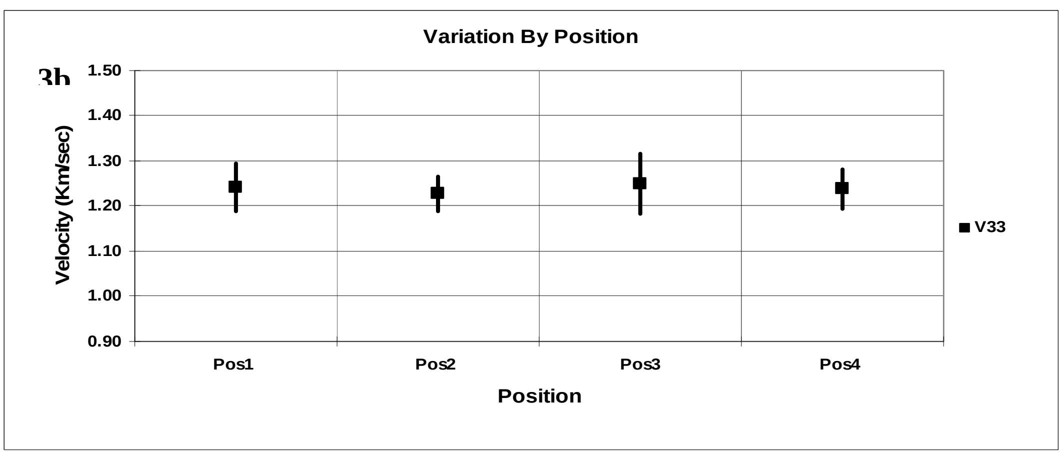


Figure 3 a) Out-of-plane shear velocity, V_{32}, measured on 4 positions of the 4 brake pads. b) Out-of-plane longitudinal velocity, V_{33}, measured on 4 positions of the 4 brake pads.

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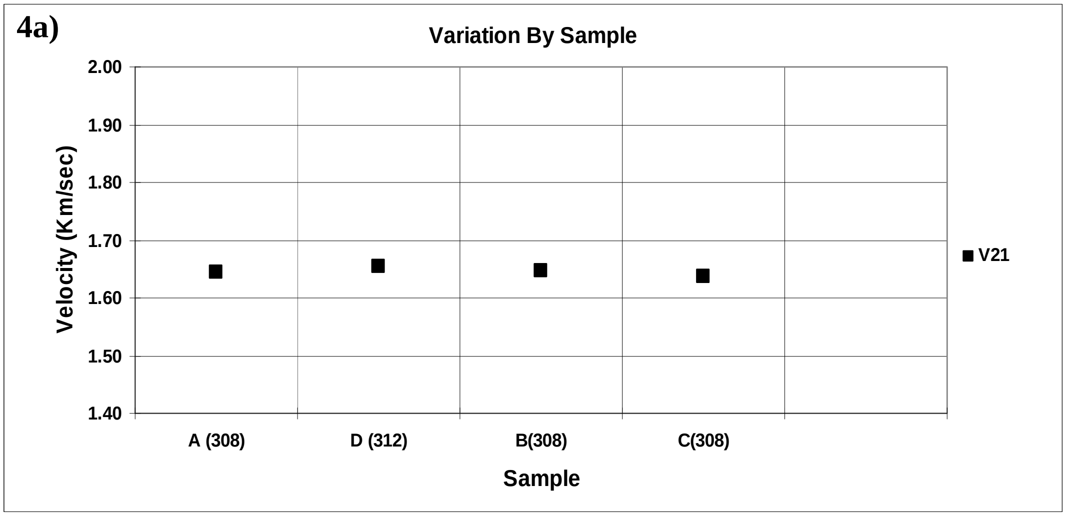


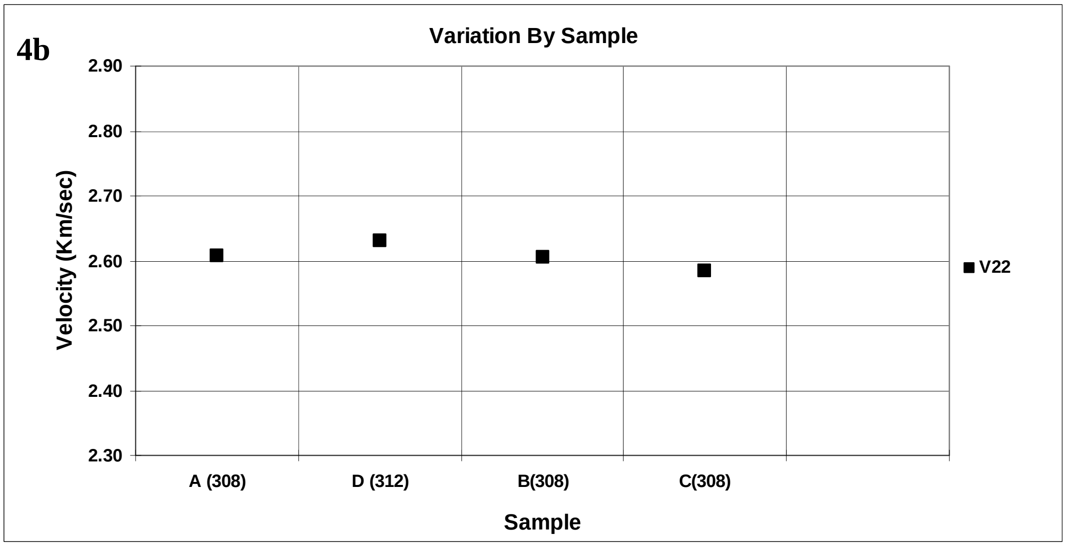
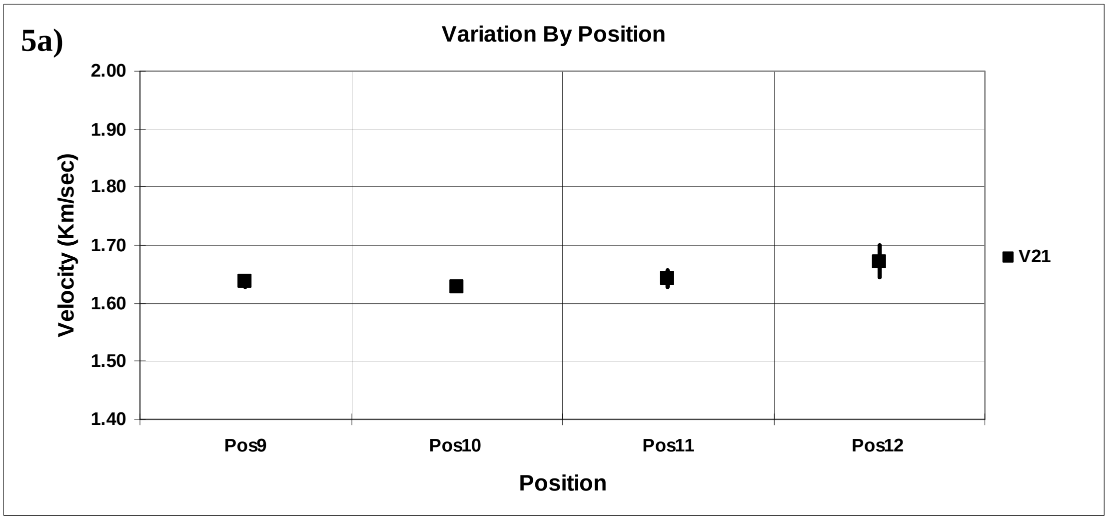


Figure 4 a) Mean V_{21} shear velocity and standard deviation of 4 measurements made on all 4 brake pads. b) Mean V_{22} longitudinal velocity and standard deviation of all pads. The standard deviations are smaller than the plotted points.

Unlike the out-of-plane modes, this data indicates that there appear to be no obvious features that distinguish one pad from another using the in-the-plane modes. For these in-plane modes the variation within each pad appears to be comparable to the pad to pad variation.



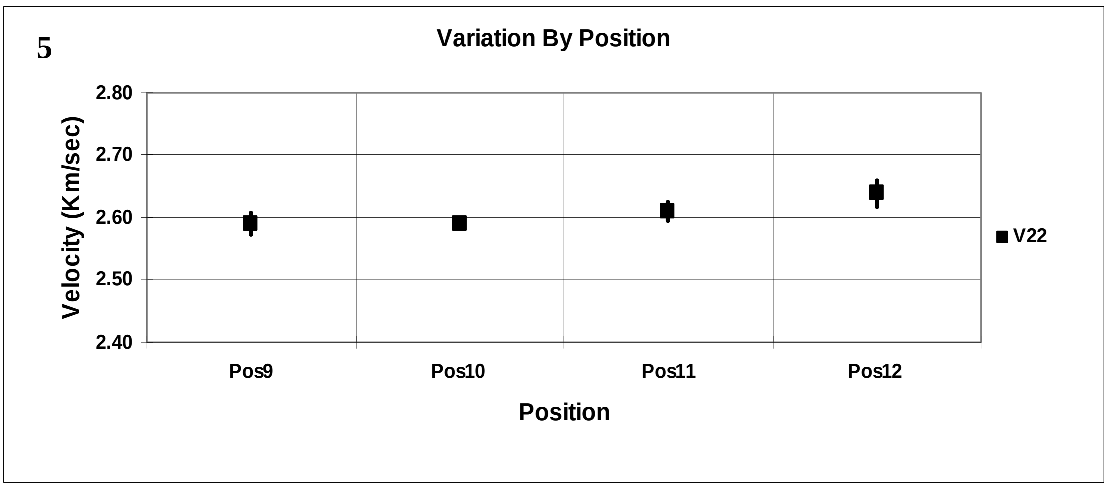


Figure 5 a) In-plane shear velocity, V_{21}, measured on 4 positions of the 4 brake pads. b) In-plane longitudinal velocity, V_{22}, measured on 4 positions of the 4 brake pads.

APPENDIX A

RAW DATA

AS_MANUFACTURED PADS

All velocity numbers are in units of Km/sec

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Table I Out-of-plane V_{32}, Shear Mode Measurements

V32	A (308)	D (312)	B(308)	C(308)
	(km/sec)	(km/sec)	(km/sec)	(km/sec)
Pos1	1.062	1.098	1.149	1.110
Pos2	1.069	1.090	1.140	1.115
Pos3	1.061	1.098	1.144	1.135
Pos4	1.071	1.098	1.142	1.126
avg	1.066	1.096	1.144	1.122
std dev	0.005	0.004	0.004	0.011
avg+std	1.070	1.101	1.148	1.133
avg-std	1.061	1.092	1.140	1.110
std %	0.47	0.40	0.34	1.01

Table II Out-of-plane V_{33}, Longitudinal Mode Measurements

V33	A (308)	D (312)	B(308)	C(308)
	(km/sec)	(km/sec)	(km/sec)	(km/sec)
Pos1	1.176	1.219	1.297	1.271
Pos2	1.184	1.208	1.246	1.271
Pos3	1.172	1.219	1.288	1.318
Pos4	1.185	1.219	1.265	1.282
avg	1.179	1.217	1.274	1.285
std dev	0.006	0.005	0.023	0.022
avg+std	1.186	1.222	1.297	1.308
avg-std	1.173	1.211	1.251	1.263
std %	0.52	0.44	1.81	1.73

Table III In-plane V_{21}, Shear Mode Measurements

V21	A (308)	D (312)	B(308)	C(308)
	(km/sec)	(km/sec)	(km/sec)	(km/sec)
Pos1	1.630	1.638	1.630	1.649
Pos2	1.629	1.624		1.631
Pos3	1.628	1.657	1.651	1.632
Pos4	1.692	1.699	1.659	1.639
avg	1.645	1.654	1.647	1.638
std dev	0.031	0.033	0.015	0.008
avg+std	1.676	1.687	1.662	1.646
avg-std	1.613	1.622	1.631	1.629
std %	1.90	1.97	0.92	0.52

Table IV In-plane V_{22}, Longitudinal Mode Measurements

V22	A (308)	D (312)	B(308)	C(308)
	(km/sec)	(km/sec)	(km/sec)	(km/sec)
Pos1	2.590	2.607	2.585	2.595
Pos2	2.591	2.602	2.592	2.578
Pos3	2.609	2.638	2.611	2.572
Pos4	2.638	2.675	2.634	2.592
avg	2.607	2.631	2.606	2.584
std dev	0.023	0.034	0.022	0.011
avg+std	2.630	2.664	2.628	2.595
avg-std	2.585	2.597	2.584	2.573
std %	0.87	1.28	0.84	0.43

APPENDIX B

ELASTIC MODULUS CALCULATIONS

For the intact, as-manufactured, pads we measure 4 of the five ultrasonic velocities needed to compute the elastic constants and engineering constants. The 5th elastic constant requires destructive analysis of the pad to measure a velocity, V_{45} propagating along a non-principal axis. The density is also required. We only measured one sample destructively in order to obtain the complete elastic constant matrix and density. The results are presented below for three cases.

Case I: Test sample average

Results obtained on samples were extracted from single pad. Two samples were used, one was a rectangular piece 15 mm by 20 mm by 7 mm and the second was a smaller piece cut at 45 degrees to the "3" axis. We then applied standard laboratory measurement methods (SAE specification J2725). For this specification a coupling pressure of 4 MPa was used. This was less than that employed for the intact samples. The engineering and elastic constants were extracted from the data obtained on these two sample pieces.

Case II: Pad Average

Using the density and V45 value we obtained in the case I analysis and the velocities measured on the same intact sample, we calculated the engineering and elastic constants. This yielded a better estimate of the pad average. It also gave us some idea of our ability to quantitatively measure the friction materials in the intact condition.

Case III: Group Average

Using the density and V45 value obtained in the case I analysis and the velocities measured on the same intact sample, we calculated the engineering and elastic constants. This yielded a better estimate of the group average.

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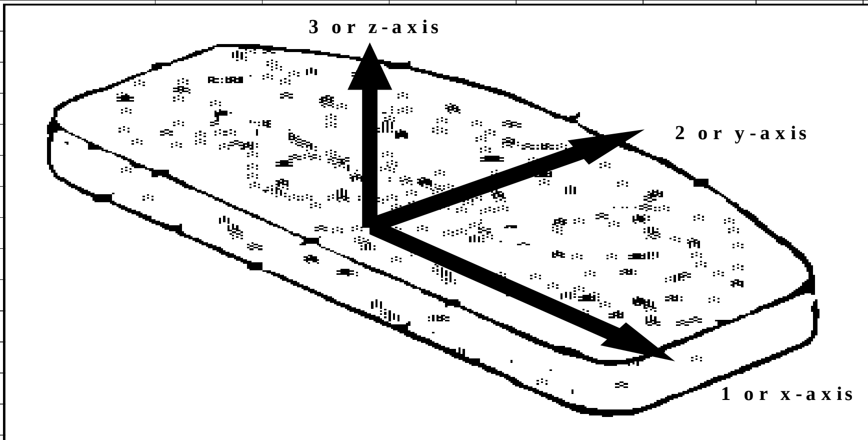
Case I: Test Sample Average (destructive, Sample A)

Disc Pad Coordinate Definition



Ultrasound Velocity

V33	<V22;V11>	<V31,V32>	V12	Rho	V45
Km/sec	Km/sec	Km/sec	Km/sec	Gm/cc	km/sec
1.199	2.527	1.054	1.593	2.429	0.920

Elastic Constants

C11	C22	C33	C44	C55	C66	C12	C13
Gpa	Gpa	Gpa	Gpa	Gpa	Gpa	Gpa	Gpa
15.51	15.51	3.49	2.70	2.70	6.16	3.18	2.71

Engineering Constants

	Gpa	Ksi	
Ex=Ey	13.31	1930.3	Young' Modulus(in-Plane)
v12=v21	0.08	0.08	Poisson's Ratio
Ez=E3	2.70	391.8	Young's Modulus (out-of Plane)
v31=v32	0.15	0.15	Poisson's Ratio
v23=v13	0.72	0.72	Poisson's Ratio
G13=G23	2.70	391.3	Shear Modulus(in-Plane)
G12	6.16	893.5	Shear Modulus (out-of-Plane)

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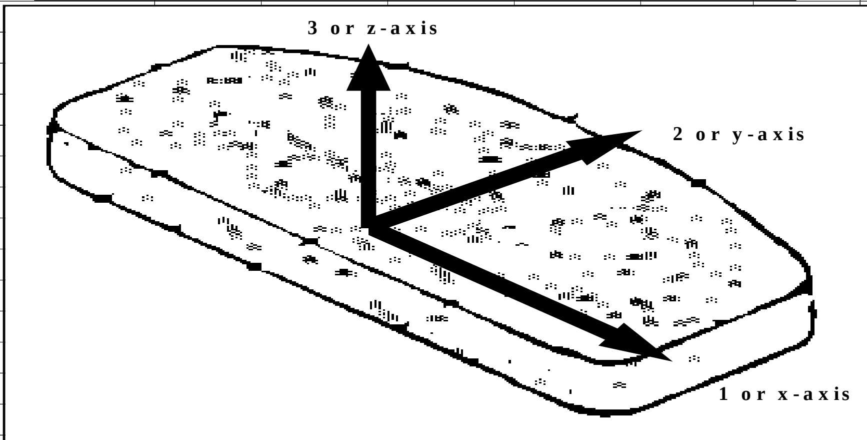
Case II: Pad Average (Intact, Sample A)

Disc Pad Coordinate Definition



Ultrasound Velocity

V33	<V22;V11>	<V31,V32>	V12	Rho	V45
Km/sec	Km/sec	Km/sec	Km/sec	Gm/cc	km/sec
1.179	2.608	1.066	1.645	2.429	0.920

Elastic Constants

C11	C22	C33	C44	C55	C66	C12	C13
Gpa	Gpa	Gpa	Gpa	Gpa	Gpa	Gpa	Gpa
16.52	16.52	3.38	2.76	2.76	6.57	3.39	2.79

Engineering Constants

	Gpa	Ksi	
Ex=Ey	14.14	2050.8	Young' Modulus(in-Plane)
v12=v21	0.08	0.08	Poisson's Ratio
Ez=E3	2.60	376.8	Young's Modulus (out-of Plane)
v31=v32	0.14	0.14	Poisson's Ratio
v23=v13	0.76	0.76	Poisson's Ratio
G13=G23	2.76	399.9	Shear Modulus(in-Plane)
G12	6.57	952.5	Shear Modulus (out-of-Plane)

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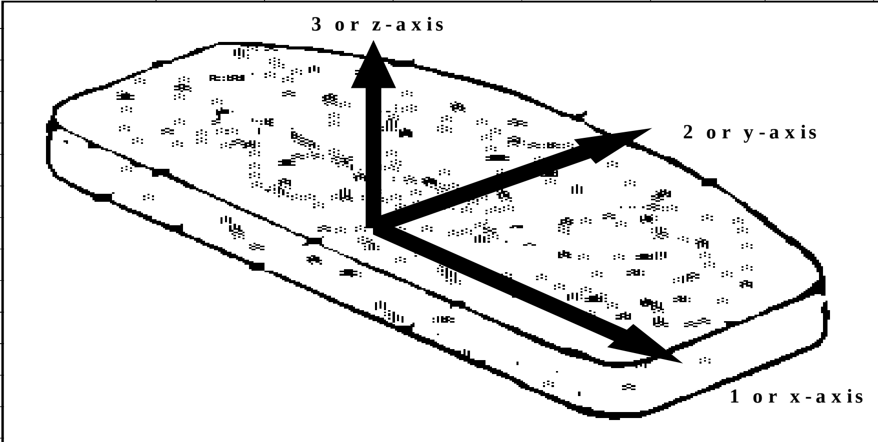
Case III: Group Average

Disc Pad Coordinate Definition



Ultrasound Velocity

V33 Km/sec	<V22;V11> Km/sec	<V31,V32> Km/sec	V12 Km/sec	Rho Gm/cc	V45 km/sec
1.225	2.582	1.107	1.624	2.429	0.920

Elastic Constants

C11 Gpa	C22 Gpa	C33 Gpa	C44 Gpa	C55 Gpa	C66 Gpa	C12 Gpa	C13 Gpa
16.19	16.19	3.64	2.98	2.98	6.41	3.38	3.17

Engineering Constants

	Gpa	Ksi	
Ex=Ey	13.41	1944.0	Young' Modulus(in-Plane)
v12=v21	0.05	0.05	Poisson's Ratio
Ez=E3	2.62	379.4	Young's Modulus (out-of Plane)
v31=v32	0.16	0.16	Poisson's Ratio
v23=v13	0.83	0.83	Poisson's Ratio
G13=G23	2.98	431.4	Shear Modulus(in-Plane)
G12	6.41	928.8	Shear Modulus (out-of-Plane)

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