Analysis of Friction Material
XXX
Supplied by Company Name

Submitted: February 25, 2009

By:
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2760 Beverly Dr. #4
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Under the Direction of:

P.O. #

Report on the Analysis of Friction Material
XXX

Introduction

Ultrasonic methods were used to characterize the XXX friction material. This analysis was carried out using the **ETEK** instrument manufactured by Industrial Measurement Systems Inc. The **ETEK** system uses precise measurements of ultrasonic wave speeds to determine the elastic constants. From these, the more familiar engineering constants were derived. This report is divided into three sections: **Summary, Velocity Data for Ambient Temperature Elastic Constants, and Elevated Temperature Data.** Application notes describing the methods and the analysis routines are given in Appendix A.

Summary of Test Results

Samples

XXX Friction Material

Three disc type friction materials were received for this analysis. Two test samples were extracted from each component and they were labeled as follows:

From one material two test samples were extracted: a rectangular piece labeled XXX_a and a 45 degree cut labeled XXX_a_45a.

From the next material two test samples were extracted: a rectangular piece labeled XXX_b and a 45 degree cut labeled XXX_b_45a.

From the last material two test samples were extracted: a rectangular piece labeled XXX_c and a 45 degree cut labeled XXX_c_45a.

Table 1 shows the summary results from the measurements of five different ultrasonic modes on the three different test samples. All results are referenced to the coordinate system shown in Figure 1. The Table shows the average and the standard deviations for all measured modes. We have combined the measurements of modes V_{11} and V_{22} as well as the modes V_{32} and V_{31}. The observations, $V_{11} \sim V_{22}$ and $V_{31} \sim V_{32}$, indicate that the material is transversely isotropic. The properties along the "1=x" and "2=y" axes are nearly identical and the unique axis is oriented out of the plane of the pad ("3=z").

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Table 1 Ultrasonic Velocities for Seven Modes

Velocity Data Summary						
Sample ID	**V_{33}**	**$<V_{22};V_{11}>$**	**$<V_{31};V_{32}>$**	**V_{21}**	**V_{45}**	**Density**
	(km/s)	**(km/s)**	**(km/s)**	**(km/s)**	**(km/s)**	**(g/cm^3)**
XXX_a	1.528	2.565	1.115	1.545	1.122	3.320
XXX_b	1.533	2.565	1.117	1.543	1.126	3.320
XXX_c	1.536	2.565	1.116	1.541	1.128	3.320
Average	**1.532**	**2.565**	**1.116**	**1.543**	**1.125**	**3.320**
% STDEV	**0.27**	**0.01**	**0.10**	**0.14**	**0.24**	**0.00**

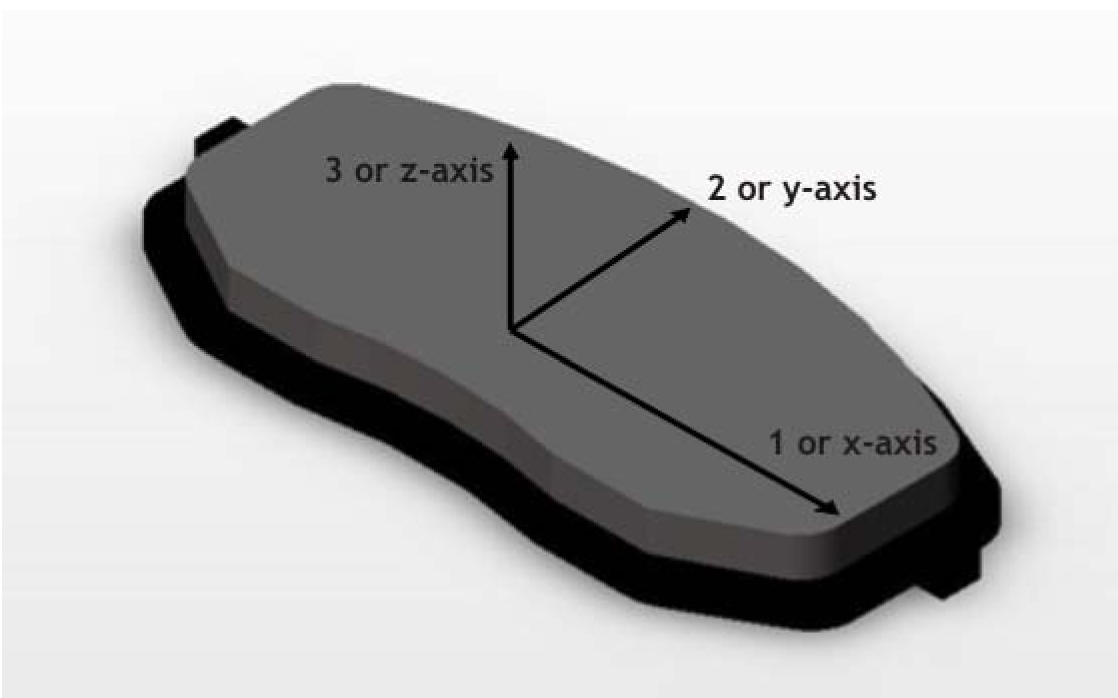

Figure 1 Coordinate Definition

The average values shown in Table 1 are used to compute the elastic and engineering constants for the **XXX** friction material. These results are presented below in Table 2.

Table 2 Average Engineering Constants & Elastic Constants for XXX

Ultrasound Velocity							
V_{33}	$<V_{22};V_{11}>$	$<V_{31};V_{32}>$	V_{12}	ρ	V_{45}		
(km/s)	(km/s)	(km/s)	(km/s)	(g/cm^3)	(km/s)		
1.532	2.565	1.116	1.543	3.320	1.125		
Elastic Constants							
C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}	C_{12}	C_{13}
(GPa)	(GPa)	(GPa)	(GPa)	(GPa)	(GPa)	(GPa)	(GPa)
21.84	21.84	7.80	4.13	4.13	7.91	6.03	3.73
Engineering Constants							
	(GPa)	(ksi)					
E_x=E_y	19.16	2779	Young's Modulus (in-Plane)				
V_{12}=V_{21}	0.21	0.21	Poisson's Ratio				
E_Z=E_3	6.80	986	Young's Modulus (out-of-Plane)				
V_{31}=V_{32}	0.13	0.13	Poisson's Ratio				
V_{23}=V_{13}	0.38	0.38	Poisson's Ratio				
G_{13}=G_{23}	4.13	599	Shear Modulus				
G_{12}	7.91	1147	Shear Modulus				

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Ambient Temperature Velocity Data for Elastic Constants

(Results for individual samples)

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Ambient
Temperature Velocity Data

From the brakes in as-received condition, smaller, 15 mm by 20 mm by ~4.5 mm rectangular test specimens were cut. The longest sample dimension, (20 mm), corresponds to the longest dimension of the original pad ("1=x" direction in our defined coordinate system). The 4.5 mm dimension always corresponds to the thickness dimension ("3=z" direction in our defined coordinate system). From these samples, all of the diagonal elements of the elastic constant matrix and one off-diagonal element can be determined. One rectangular piece was taken from each pad.

A second sample type, cut 45° relative to the thickness direction, was used to obtain one of the off-diagonal elements to the elastic constant matrix. This sample was cut from a sample section directly adjacent to the rectangular pieces. Only one 45-degree piece was extracted from the pad.

Sample density is determined by dividing the weight of the sample by the measured volume. The dimensions of each rectangular piece are measured with a micrometer. Each sample is weighed using a scale with a precision of .01 grams.

In some friction materials the attenuation (signal loss) in the V_{33} mode is very high (in excess of 70 dB). The wave shape may also be distorted and materials are non-linear (velocity varies with load). We find that the signal level and wave shape distortion can be improved if measurements are made under load. For this mode, as well as the V_{31} and V_{32} mode, we use ~700 Newtons (160 lbs), of force to couple the transducers. Because the contact area is approximately 1.71 square centimeters, this force translates to a pressure of 4.1 MPa (600 psi).

The elastic constant data contained in this report used methods described in preliminary Specification SAE J2725 at a coupling pressure of ~4 MPa. For the in-plane modes, neither wave shape nor measured transit time appear to be load sensitive. However, for consistency, we use a coupling force which leads to a pressure of ~4 MPa (600 psi) for the samples in this orientation.

The definition of the terminology used to identify the ultrasonic modes is given below:

V_{33} - Longitudinal mode propagating along the "3=z" direction
V_{11} - Longitudinal mode propagating along the "1=x" direction
V_{22} - Longitudinal mode propagating along the "2=y" direction
V_{31} - Shear mode propagating along the "3=z" direction polarized along the "1=x" direction
V_{32} - Shear mode propagating along the "3=z" direction polarized along the "2=y" direction
V_{21} - Shear mode propagating along the "2=y" direction polarized along the "1=x" direction
V_{12} - Shear mode propagating along the "1=x" direction polarized along the "2=y" direction

Along with all of the ultrasonic data, the modulus calculations on each individual piece are given in the following pages.

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Sample **XXX_a**

Mode	Corrected Transit Time (us)	Load (N)	Coupling Pressure (MPa)	Thickness (mm)	Velocity (km/s)
v33	6.593	675.0	3.87	10.07	1.527
v33	6.593	673.0	3.86	10.07	1.527
v33	6.593	673.0	3.86	10.07	1.527
v33	6.583	671.0	3.85	10.07	1.530
v22	5.743	548.0	3.98	14.90	2.594
v22	5.743	548.0	3.98	14.90	2.594
v22	5.733	547.0	3.97	14.90	2.599
v11	7.633	528.0	3.84	19.31	2.530
v11	7.623	526.0	3.82	19.31	2.533
v11	7.613	525.0	3.81	19.31	2.536
v32	8.997	636.0	3.65	10.07	1.119
v32	8.987	635.0	3.64	10.07	1.121
v32	8.997	634.0	3.64	10.07	1.119
v31	9.077	634.0	3.64	10.07	1.109
v31	9.077	631.0	3.62	10.07	1.109
v31	9.077	629.0	3.61	10.07	1.109
v21	9.647	494.0	3.59	14.90	1.545
v21	9.637	494.0	3.59	14.90	1.546
v21	9.647	494.0	3.59	14.90	1.545
v45	8.977	536.0	3.89	10.07	1.122
v45	8.977	535.0	3.89	10.07	1.122
v45	8.977	535.0	3.89	10.07	1.122
v45	8.957	534.0	3.88	10.07	1.124

Velocity Data Summary						
	V_{33} (km/s)	$<V_{22};V_{11}>$ (km/s)	$<V_{31};V_{32}>$ (km/s)	V_{21} (km/s)	V_{45} (km/s)	Density (g/cm^3)
Avg Velocity	1.528	2.564	1.115	1.545	1.122	3.320
# of Reps	4	6	6	3	4	
% Std Dev	0.076	0.116	0.032	0.060	0.112	

Elastic Constants						
	$<C_{11};C_{22}>$	C_{33}	$<C_{44};C_{55}>$	C_{66}	C_{12}	C_{13}
GPa	21.84	7.75	4.12	7.93	5.98	3.74

Engineering Constants							
	Young's Modulus		**Shear Modulus**			**Poisson's Ratio**	
	GPa	**ksi**		**GPa**	**ksi**	$V_{12}=V_{21}$	0.21
In-plane ($E_x=E_y$)	19.16	2779.40	$G_{13}=G_{23}$	4.12	598.20	$V_{31}=V_{32}$	0.13
Out-of-plane ($E_z=E_3$)	6.75	978.82	G_{12}	7.93	1149.60	$V_{23}=V_{13}$	0.38

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Sample **XXX_b**

Mode	Corrected Transit Time (us)	Load (N)	Coupling Pressure (MPa)	Thickness (mm)	Velocity (km/s)
v33	6.573	659.0	3.78	10.07	1.532
v33	6.563	659.0	3.78	10.07	1.534
v33	6.573	658.0	3.77	10.07	1.532
v33	6.573	658.0	3.77	10.07	1.532
v22	5.733	505.0	3.67	14.90	2.599
v22	5.743	504.0	3.66	14.90	2.594
v22	5.743	503.0	3.65	14.90	2.594
v11	7.623	521.0	3.78	19.31	2.533
v11	7.623	520.0	3.78	19.31	2.533
v11	7.613	520.0	3.78	19.31	2.536
v32	9.007	646.0	3.70	10.07	1.118
v32	9.007	646.0	3.70	10.07	1.118
v32	8.997	645.0	3.70	10.07	1.119
v31	9.027	670.0	3.84	10.07	1.116
v31	9.027	668.0	3.83	10.07	1.116
v31	9.037	666.0	3.82	10.07	1.114
v21	9.637	497.0	3.61	14.90	1.546
v21	9.657	497.0	3.61	14.90	1.543
v21	9.667	496.0	3.60	14.90	1.541
v45	8.967	526.0	3.82	10.07	1.123
v45	8.947	525.0	3.81	10.07	1.126
v45	8.917	525.0	3.81	10.07	1.129
v45	8.937	525.0	3.81	10.07	1.127

Velocity Data Summary						
	V_{33} (km/s)	$<V_{22};V_{11}>$ (km/s)	$<V_{31};V_{32}>$ (km/s)	V_{21} (km/s)	V_{45} (km/s)	Density (g/cm^3)
Avg Velocity	1.533	2.565	1.117	1.543	1.126	3.320
# of Reps	4	6	6	3	4	
% Std Dev	0.076	0.088	0.064	0.158	0.233	

Elastic Constants						
	$<C_{11};C_{22}>$	C_{33}	$<C_{44};C_{55}>$	C_{66}	C_{12}	C_{13}
GPa	21.85	7.80	4.14	7.91	6.03	3.72

Engineering Constants							
	Young's Modulus		**Shear Modulus**			**Poisson's Ratio**	
	GPa	**ksi**		**GPa**	**ksi**	**V_{12}=V_{21}**	0.21
In-plane (E_x=E_y)	19.17	2780.52	**G_{13}=G_{23}**	4.14	600.61	**V_{31}=V_{32}**	0.13
Out-of-plane (E_Z=E_3)	6.81	987.10	**G_{12}**	7.91	1147.22	**V_{23}=V_{13}**	0.38

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Sample **XXX_c**

Mode	Corrected Transit Time (us)	Load (N)	Coupling Pressure (MPa)	Thickness (mm)	Velocity (km/s)
v33	6.563	653.0	3.74	10.07	1.534
v33	6.553	653.0	3.74	10.07	1.537
v33	6.553	681.0	3.91	10.07	1.537
v33	6.553	677.0	3.88	10.07	1.537
v22	5.743	510.0	3.70	14.90	2.594
v22	5.743	509.0	3.70	14.90	2.594
v22	5.753	509.0	3.70	14.90	2.590
v11	7.613	517.0	3.76	19.31	2.536
v11	7.613	517.0	3.76	19.31	2.536
v11	7.613	516.0	3.75	19.31	2.536
v32	9.037	665.0	3.81	10.07	1.114
v32	9.047	661.0	3.79	10.07	1.113
v32	9.037	660.0	3.79	10.07	1.114
v31	9.007	659.0	3.78	10.07	1.118
v31	9.027	658.0	3.77	10.07	1.116
v31	9.007	658.0	3.77	10.07	1.118
v21	9.677	506.0	3.68	14.90	1.540
v21	9.667	505.0	3.67	14.90	1.541
v21	9.667	503.0	3.65	14.90	1.541
v45	8.927	521.0	3.78	10.07	1.128
v45	8.937	520.0	3.78	10.07	1.127
v45	8.927	520.0	3.78	10.07	1.128
v45	8.927	520.0	3.78	10.07	1.128

Velocity Data Summary

	V_{33} (km/s)	$<V_{22};V_{11}>$ (km/s)	$<V_{31};V_{32}>$ (km/s)	V_{21} (km/s)	V_{45} (km/s)	Density (g/cm^3)
Avg Velocity	1.536	2.564	1.115	1.541	1.128	3.320
# of Reps	4	6	6	3	4	
% Std Dev	0.076	0.050	0.096	0.060	0.056	

Elastic Constants

	$<C_{11};C_{22}>$	C_{33}	$<C_{44};C_{55}>$	C_{66}	C_{12}	C_{13}
GPa	21.84	7.83	4.13	7.88	6.07	3.72

Engineering Constants

	Young's Modulus		Shear Modulus			Poisson's Ratio	
	GPa	ksi		GPa	ksi	$V_{12}=V_{21}$	0.21
In-plane ($E_x=E_y$)	19.15	2776.95	$G_{13}=G_{23}$	4.13	599.28	$V_{31}=V_{32}$	0.13
Out-of-plane ($E_z=E_3$)	6.84	992.21	G_{12}	7.88	1143.27	$V_{23}=V_{13}$	0.37

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Elevated Temperature Data

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Elevated Temperature Measurements

The same samples measured at ambient temperature are used for the elevated temperature measurements. For each material type, only the four unique modes are measured at elevated temperature: V_{33}, ($V_{32} = V_{31}$), ($V_{21} = V_{12}$), and ($V_{11} = V_{22}$). These measurements yield the diagonal elements of the elastic constant matrix C_{33}, $C_{44} = C_{55}$, C_{66}, and $C_{11} = C_{22}$, respectively. This data is presented in both tabular and graphical form in this section. The off diagonal element, C_{12}, is related to the diagonal elements and this relation is given directly by $C_{12} = C_{22} - 2*C_{66}$. The other off-diagonal element's temperature dependence, (C_{13}), is best estimated by assuming that it is similar to that of C_{12}.

The attenuation data is also presented. Particular care should be exercised in trying to interpret the attenuation data for shear wave measurement modes e.g. $C_{44} = C_{55}$, and C_{66}, since the coupling at the interface between the sample and transducer exhibits some thermal instability. The coupling layer is too thin to influence the velocity data. However, it does impact the attenuation data at elevated temperatures. This is less of a problem for the longitudinal waves (C_{33}, and $C_{11} = C_{22}$) where ultrasonic coupling and intrinsic sample attenuation appear to be more stable with temperature.

For the elevated temperature data, the velocities measured on each sample at ambient temperature are used to normalize the data. A heating profile involves heating the samples in a stepwise fashion at 50-degree Centigrade increments from 25° C to 325°C. At each interval, a holding time of 5 minutes is used to allow the sample to equilibrate before the velocity measurement is made. For a typical high temperature analysis, only the four diagonal elements of the elastic constant matrix are measured. Generally each mode is analyzed only once.

Specific temperature dependent data is plotted for each diagonal element of the three samples analyzed. The temperature dependence for C_{12} must be calculated. Similarly, the C_{13} temperature dependence is assumed to parallel that of C_{12}.

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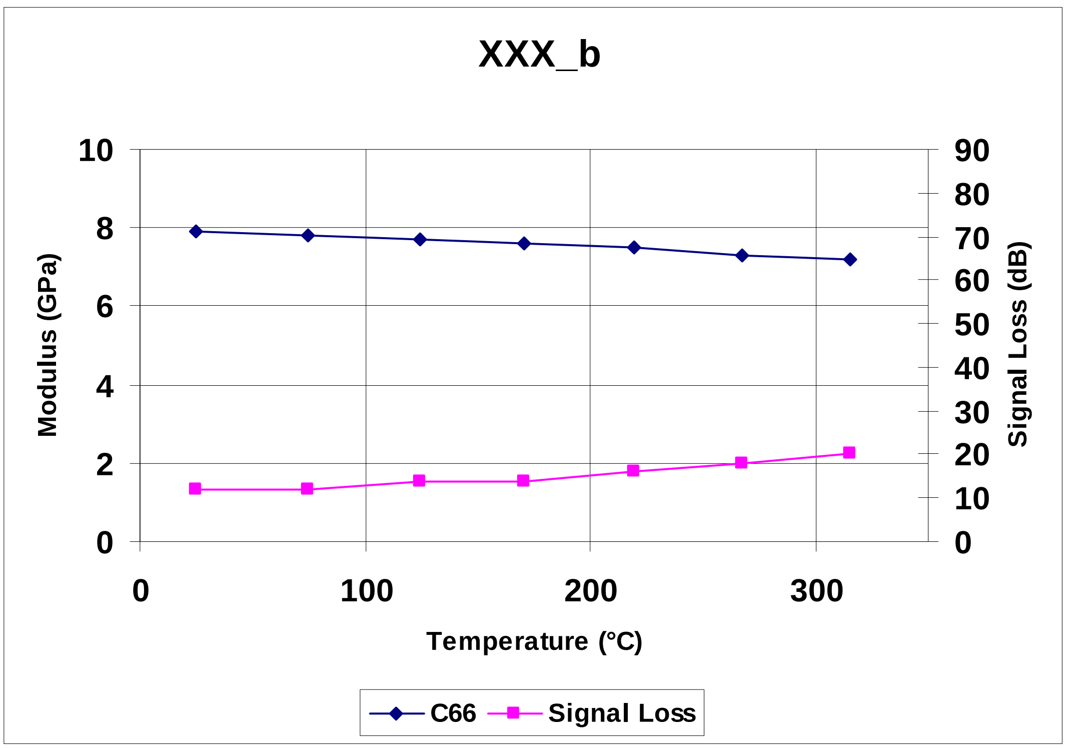
XXX_b				
Elevated Temperature Data for Mode v21(C66)				
Temp (°C)	Corrected Transit Time (us)	Velocity (km/s)	Elastic Constants	Signal Loss (dB)
25	9.65	1.544	7.915	12
75	9.72	1.533	7.801	12
124	9.78	1.524	7.706	14
171	9.86	1.511	7.582	14
219	9.92	1.502	7.490	16
267	10.06	1.481	7.283	18
315	10.12	1.472	7.197	20



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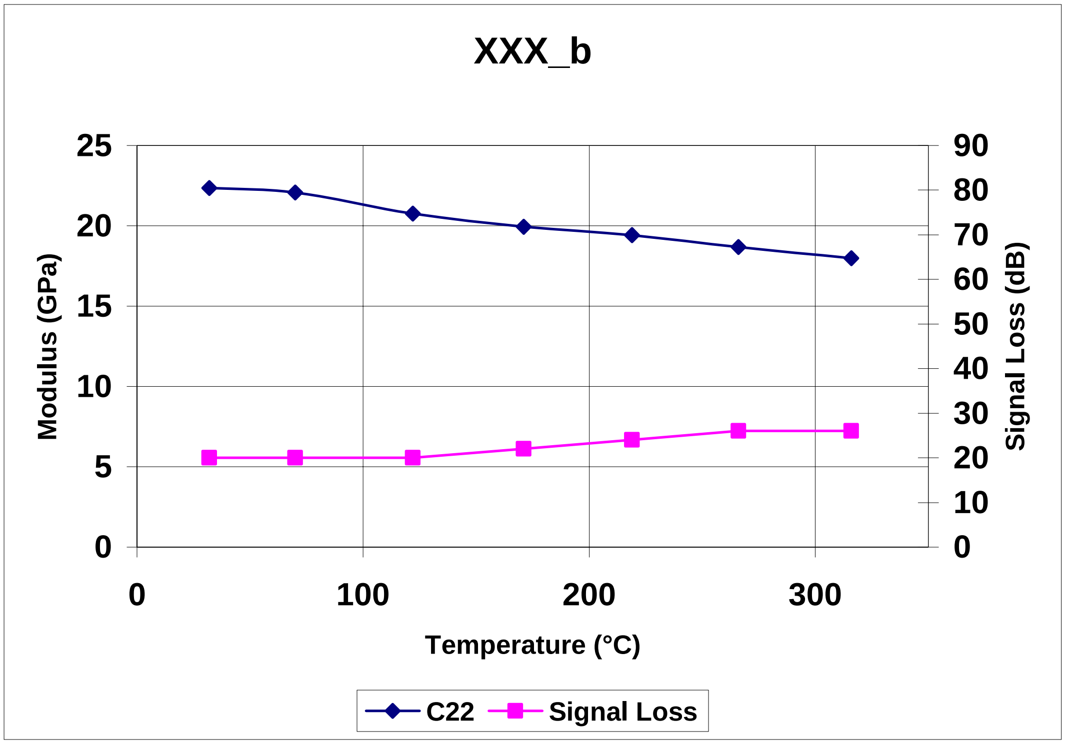
XXX_b				
Elevated Temperature Data for Mode v22(C22=C11)				
Temp (°C)	Corrected Transit Time (us)	Velocity (km/s)	Elastic Constants	Signal Loss (dB)
32	5.74	2.595	22.355	20
70	5.78	2.578	22.063	20
122	5.96	2.500	20.750	20
171	6.08	2.451	19.939	22
219	6.16	2.419	19.424	24
266	6.28	2.373	18.689	26
316	6.40	2.328	17.995	26



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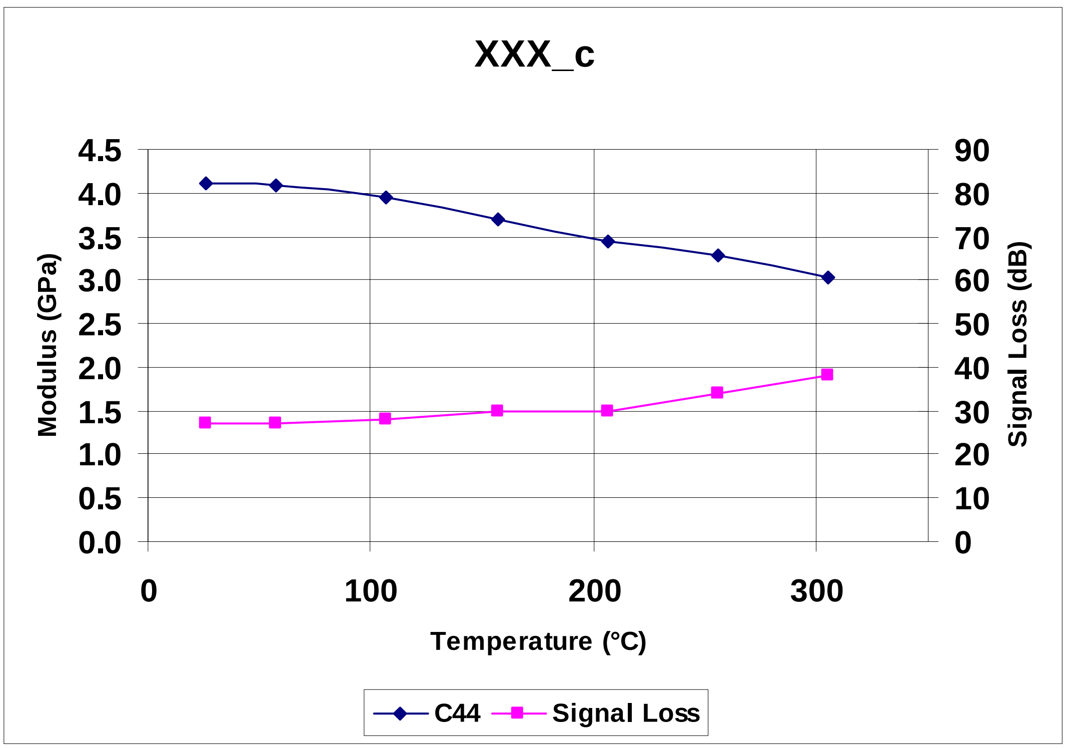
XXX_c				
Elevated Temperature Data for Mode v32(C44)				
Temp (°C)	Corrected Transit Time (us)	Velocity (km/s)	Elastic Constants	Signal Loss (dB)
26	9.04	1.114	4.120	27
57	9.08	1.109	4.083	27
107	9.22	1.092	3.960	28
157	9.54	1.056	3.699	30
206	9.88	1.019	3.449	30
256	10.12	0.995	3.287	34
305	10.54	0.955	3.031	38



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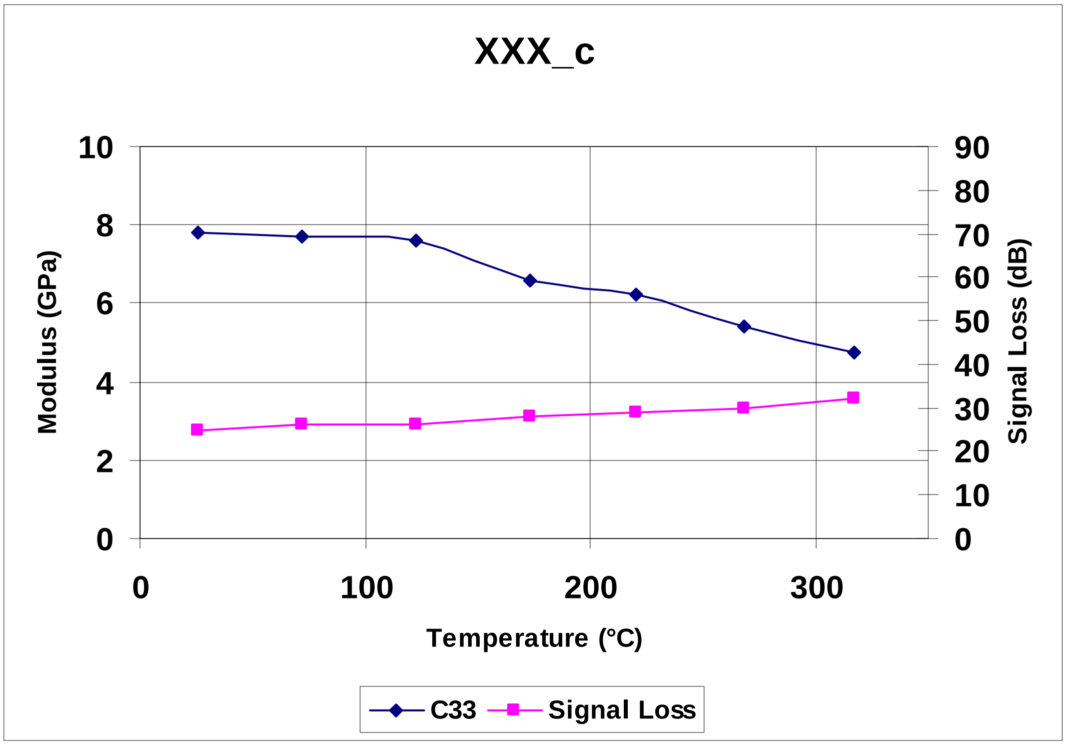
XXX_c				
Elevated Temperature Data for Mode v33(C33)				
Temp (°C)	Corrected Transit Time (us)	Velocity (km/s)	Elastic Constants	Signal Loss (dB)
26	6.56	1.535	7.823	25
72	6.60	1.526	7.729	26
123	6.66	1.512	7.590	26
173	7.14	1.410	6.604	28
220	7.36	1.368	6.215	29
268	7.88	1.278	5.422	30
317	8.44	1.193	4.726	32



Appendix A-1

Background Information
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Application Studies

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