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subject: NMSBA High Frequency Modal Analysis of a Solid Metal Cylinder

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1 INTRODUCTION

This memo documents the results and methodology of the high-frequency modal test performed on a solid metal cylinder, provided by Vibrant Corporation, in September 2014 at Sandia National Laboratories. The purpose of this test was to measure mode shapes of the unit (torsion, axial, and bending) as high in frequency as achievable with a Polytec PSV-400 scanning laser Doppler vibrometer.

2 TEST ITEM DESCRIPTION

The unit tested was a solid, metal cylinder provided by Vibrant Corporation listed as part number TE_P_05_110068 with ID 71A1G. The length of the unit was 3.0 in. and maintained a constant diameter of 0.5 in. The unit recorded a weight of 3.0 oz.

3 TEST SETUP

A modal analysis was performed on the unit using a Polytec PSV-400 scanning laser Doppler vibrometer (LDV). Excitation of the unit was performed by a single piezoelectric device integrated into the test fixture provided by Vibrant Corporation. A burst chirp signal was used to drive the exciter with a bandwidth of 200 kHz at a single location on the unit.

3.1 Boundary Conditions and Fixtures

The unit was placed in the test fixture, which holds the unit at four piezoelectric point locations. Two locations are positioned on each side of the unit at 45° below horizontal.

Normal use of the test fixture allows for actuation via one point location and sensing at two other locations. For this test, sensing was provided via laser. The test fixture was used primarily to excite the unit. A small amount of super glue was placed between the unit and the point locations to reduce chatter between the test fixture and unit, which resulted in improved coherence signals. The unit was not placed directly centered between the four point locations for this test. Approximately 0.5 inches of the unit extended beyond the test fixture on the drive end, and 0.25 inches extended beyond the test fixture on the sense end. Figure 1 shows a photo of the unit in the test fixture.

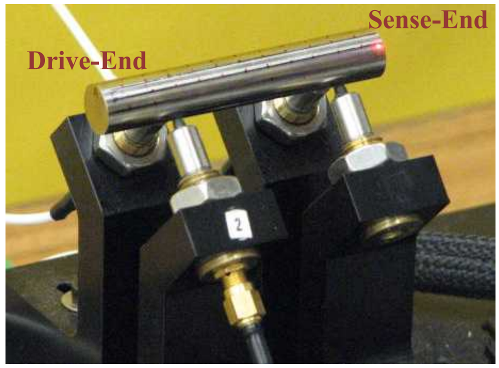


Figure 1: Unit in test fixture.

An approximate free-free boundary condition would be desirable, so the experimental results could be more easily compared to computational results. Using thin wire or string to suspend the unit could improve this boundary condition. However, actuation of the unit could be challenging in that a thin, flexible piezoelectric patch with sufficient displacement would be required to excite the unit.

3.2 Coordinate System and Measurement Locations

A cylindrical coordinate system was used to define the node locations along the length of the unit for radial deflection tests. The origin was located at the center of the cylinder face at the drive end of the unit. The length of the unit contained 33 equally spaced node locations that repeated for 17 angles around the radius: -25 º, -15 º:15 º:195 º, 205 º. The entire radius of the unit could not be measured due to limitations of both the test fixture and laser head fixture. Each axial face contained 59 node locations.

A final measurement utilized reflective tape adhered to the unit and performed a full scan of the top of the unit from an angle of 90º that contained 315 measurement locations. Reflective tape was required to diffuse the laser signal such that measurement locations near the edges of the unit would still reflect some laser signal back to the laser head.

3.3 Excitation

The reference excitation force was produced by providing a voltage to a piezoelectric exciter at the drive location. A Krohn-hite Model 7500 amplifier was used to amplify the signal from the generator to the piezoelectric actuator. The voltage into the exciter was limited to 14V. A burst chirp signal from 10 kHz to 200 kHz with 25% burst length was used. Coherence was initially a problem, but it improved to a suitable value at the peaks with super glue between the test fixture and unit. Frequency response coherence allowed for measurements up to approximately 155 kHz.

3.4 DAQ Setup

The Polytec data acquisition system (DAQ) was set up to measure data between 10 kHz and 200 kHz with a frequency resolution of 3.9 Hz. No windows were applied. The system recorded 8 averages at each measurement location.

4 ANALYSIS AND RESULTS

Post-processing was conducted using Polytec software and MATLAB. Three types of measurements were recorded: radial deflection tests, axial deflection tests, and a full scan of the unit.

The radial deflection tests consisted of 33 equally spaced measurement nodes along the length of the unit. These tests were performed at 17 angles around the radius of the unit, and the resulting shapes were compiled using MATLAB. The radial deflection tests were used to identify both bending and some axial modes. Torsion and additional axial modes were not observable in the radial deflection data. Not all scans identified all modes. The modes that were not identified in a scan are displayed as zero deflection in the MATLAB mode shape image. A photo of the test setup for a laser head angle of 45° is shown in Figure 2. Definition of the laser head angle is given in Figure 3.

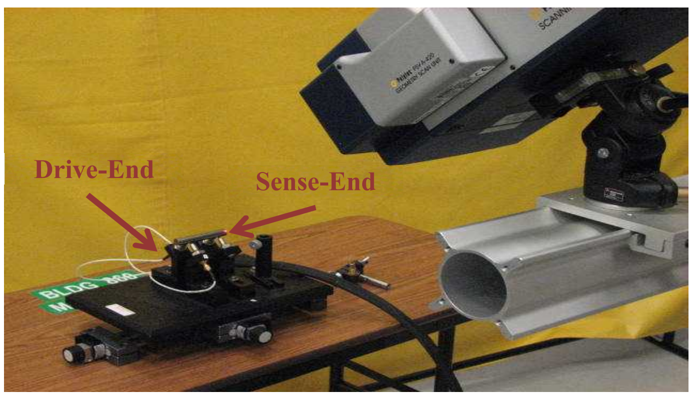


Figure 2: Experimental test bed for radial deflection test with a laser head angle of 45º.

The axial deflection tests consisted of 59 measurement nodes on each face of the cylindrical unit. The drive end of the unit is defined by the cylindrical face that is closest to the piezoelectric driver. The sense end of the unit is the opposite cylindrical face. The axial deflection tests were used primarily to identify axial modes of the unit.

The full-unit scan was performed with the laser head at 90°. Reflective tape was placed on the unit to provide sufficient laser return on scan points nearest 0° and 180°. The full unit scan measured the unit response at 315 locations. For this particular test, the mode shapes depicted are comprised of gray circles that represent true measured data and an interpolated, colored mesh that corresponds to the displacement of the shape. The full-unit scan was used to verify bending and some axial modes in the radial deflection test and also to identify torsion modes.

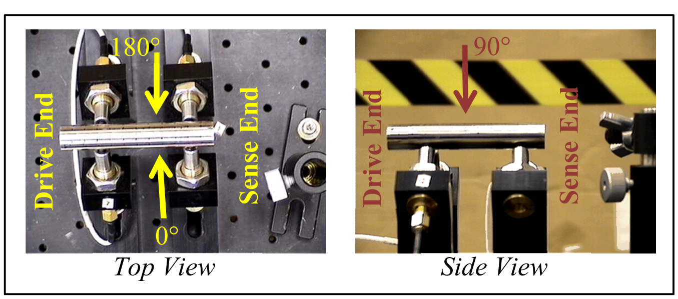
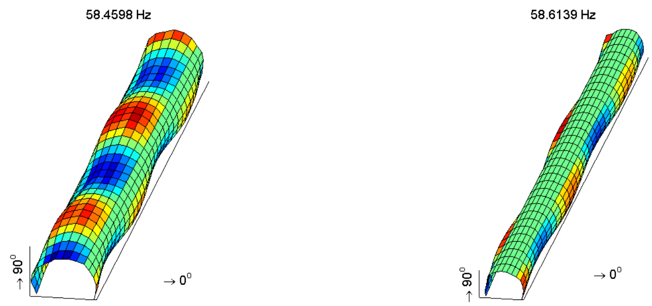


Figure 3: Definition of laser head angles for radial deflection tests.

4.1 Bending Modes

Bending mode pairs between 10 kHz and 155 kHz were extracted using the radial deflection tests. Bending modes appeared in pairs where the bending of each pair was orthogonal. An example of a bending mode shape pair appears in Figure 4.

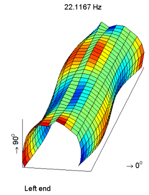
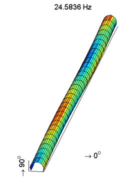
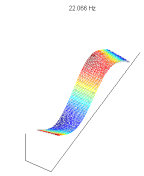
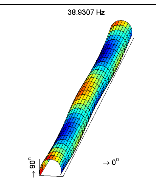
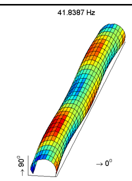
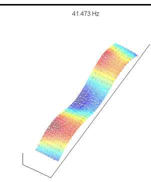
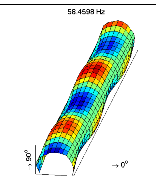
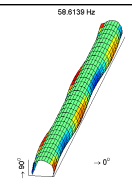
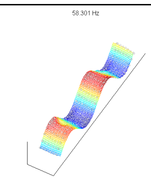
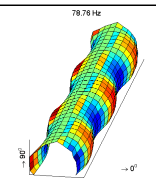
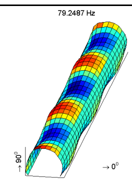
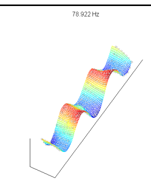
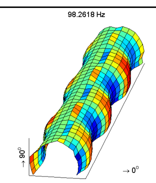
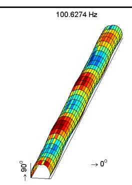
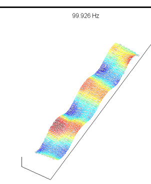
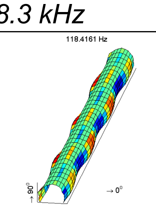
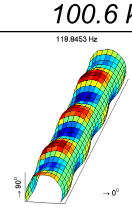
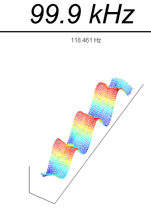
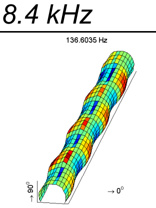
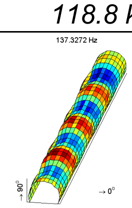
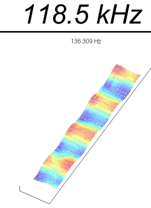


(a) (b)

Figure 4: Example of a bending mode shape pair from the radial deflection tests.

Figure 4(a) shows the bending mode active in the 90° direction, and Figure 4(b) shows the same bending mode active in the 0° direction. Table 1 summarizes the seven bending mode pairs that were measured from the radial deflection tests and the full scan. Note that the bending mode pairs are orthogonal to each other, so scan angles near 90º observed one of the pair better than scan angles near 0º. Likewise, scan angles near 0º observed the other of the pair better than scan angles near 90º. Since the full scan was performed with the laser head at 90°, only one member of the pair was observable for each bending mode. Bending modes greater than 140 kHz were difficult to process as they contained localized effects near the boundary conditions at the test fixture attachment locations.

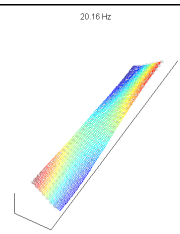
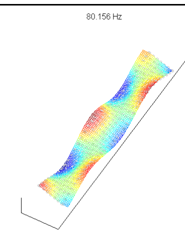
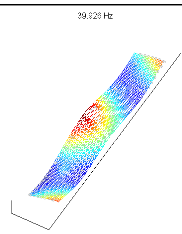
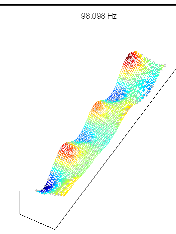
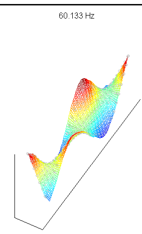
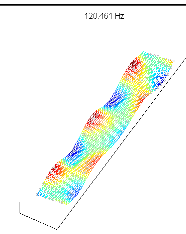
Table 1 – Summary of Measured Bending Mode Pairs

Mode Pair	Shape Pairs from Radial Deflection Test		Shape from 90° Full Scan
1	 *22.1 kHz*	 *24.6 kHz*	 *22.1 kHz*
2	 *38.9 kHz*	 *41.8 kHz*	 *41.5 kHz*
3	 *58.5 kHz*	 *58.6 kHz*	 *58.3 kHz*
4	 *78.8 kHz*	 *79.2 kHz*	 *78.9 kHz*
5	 *98.3 kHz*	 *100.6 kHz*	 *99.9 kHz*
6	 *118.4 kHz*	 *118.8 kHz*	 *118.5 kHz*
7	 *136.6 kHz*	 *137.3 kHz*	 *136.3 kHz*

4.2 Torsion Modes

Torsion mode shapes were not cleanly extracted from the radial deflection runs, but they were observable in the full-unit scan. Table 2 displays the 6 recorded torsion mode shapes.

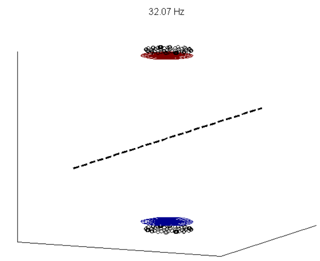
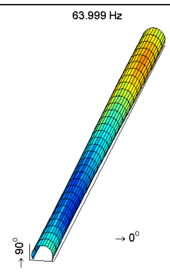
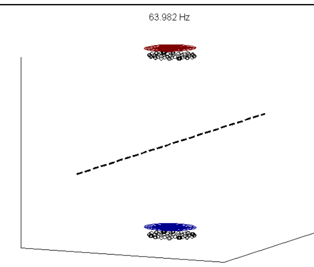
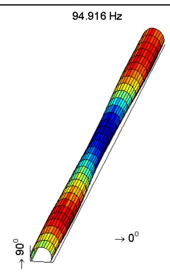
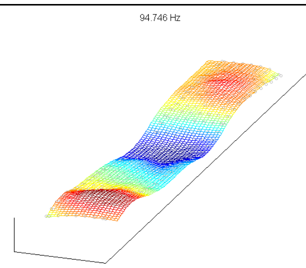
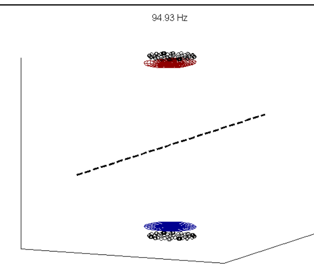
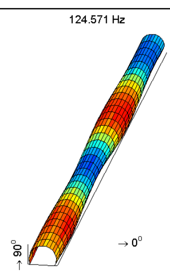
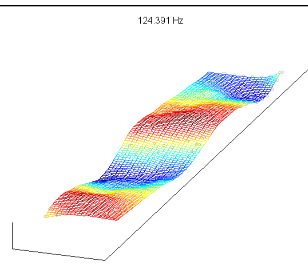
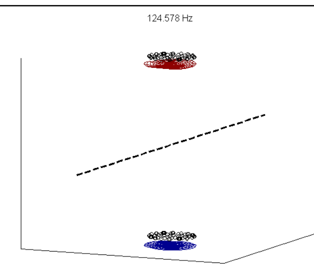
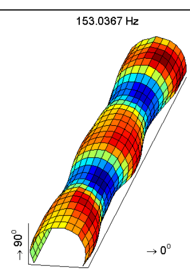
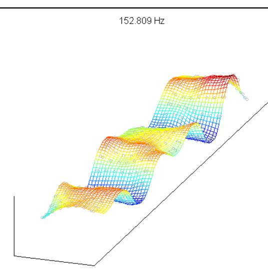
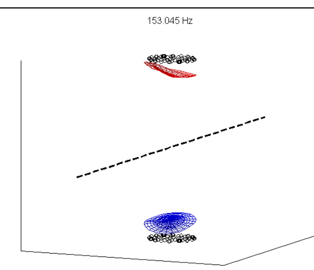
Table 2 – Summary of Measured Torsion Modes

Frequency (kHz)	Shape from 90° Full Scan	Frequency (kHz)	Shape from 90° Full Scan
20.2		80.2	
39.9		98.1	
60.1		120.5	

4.3 Axial Modes

Five axial modes were extracted by combining information from all 3 tests (Table 3).

Table 3 – Summary of Measured Axial Modes

Freq. (kHz)	Shape from Radial Deflection Test	Shape from 90° Full Scan	Shape from Axial Test
32.1	*Not observable*	*Not observable*	
64.0		*Not observable*	
94.8			
124.5			
152.9			

4.4 Comparison to Computational Values

Hand calculations were performed to check results of the mode shapes using estimations on material parameters that fit the measured data. The hand calculations assumed a density of 8.8108E+03 kg/m^3, a Young's Modulus of 203 GPa and a Poisson Ratio of 0.3. Bending frequencies were computed using the Timoshenko beam formula [Blevins, RD, 1995, *formulas for Natural Frequencies and Mode Shapes*, Van Nostrand, p 108 and 181]. Axial and torsion frequencies were computed using approximate formulas for modes of a beam [Blevins p 183 and Blevins p 193, respectively]. Table 4 compares all of the measured frequencies with the hand calculations. For the estimated material properties, all modes are within a couple percent of the computed values.

Additionally, a finite element model of the test unit was created. CUBIT was used to generate a mesh consisting of approximately 40,000 HEX8 elements. The model employed free-free boundary conditions and assumed the same material properties listed above. SIERRA/SD (SALINAS) was used to compute the eigensolution up to 510 modes (approximately 475 kHz). The comparison of the frequencies computed using finite element method to the hand calculations and the measured values is also included in Table 4.

Table 4 – Comparison of Measured and Calculated Frequencies

Mode Shape Description	Average Measured Frequency (kHz)	Hand Calculations		Finite Element Method	
		Calculated Frequency (kHz)	% Difference	Calculated Frequency (kHz)	% Difference
Bending	*Out of Bandwidth*	9.0	--	9.2	--
Torsion	20.2	19.5	3.6%	20.5	1.5%
Bending	22.9	23.0	0.4%	22.9	0%
Axial	32.1	31.5	1.9%	32.9	2.4%
Torsion	39.9	39.1	2.0%	40.9	2.4%
Bending	40.7	40.4	0.7%	40.1	1.5%
Bending	58.5	59.5	1.7%	59.2	1.2%
Torsion	60.1	58.6	2.6%	61.4	2.1%
Axial	64.0	63.0	1.6%	65.6	2.4%
Bending	79.0	79.4	0.5%	79.1	0.1%
Torsion	80.2	78.1	2.7%	81.9	2.1%
Axial	94.8	94.5	0.3%	97.5	2.8%
Torsion	98.1	97.7	0.4%	102.4	4.2%
Bending	99.6	100.9	1.3%	99.2	0.4%
Bending	118.6	121.3	2.2%	118.9	0.3%
Torsion	120.5	117.2	2.8%	122.9	2.0%
Axial	124.5	126.0	1.2%	128.2	2.9%
Torsion	*Not Observed*	136.7	--	143.4	--
Bending	136.7	141.7	3.5%	136.9	0.1%
Axial	152.9	157.5	2.9%	156.7	2.4%

5 SUMMARY

A Polytec PSV-400 was used to measure velocity response of a solid, metal cylinder due to burst chirp input from a piezoelectric exciter in order to record natural frequencies and mode shapes of the unit. The frequency range measured was from 10 kHz to 155 kHz. By using a variety of scans, bending modes, axial modes, and torsion modes were extracted. MATLAB was used to piece together the results from multiple scans. Since not all modes were observable in all runs, the modes included in this report are not assumed to be all-inclusive of all natural frequencies of the unit within the bandwidth. Improvements to the test setup are recommended for future work; however, the experiment demonstrated a viable method of obtaining mode shape information of the solid metal cylinder up to 155 kHz. Despite the boundary conditions of the test fixture, the measured frequencies were found to be within 3.5% of approximate hand calculations and within 4.2% difference of finite element method computations.

6 TEST LOGS

Below is the log of the test runs that were recorded.

Run No.	Measurement Type	Laser Angle	Notes
1	Radial Deflection	0°	Test scan to evaluate various excitation signals - not included in results
2	Radial Deflection	30°	33 Measurement locations
3	Radial Deflection	15°	33 Measurement locations
4	Radial Deflection	-30°	Test fixture impeded scan - not included in results
5	Radial Deflection	-15°	33 Measurement locations
6	Radial Deflection	-25°	33 Measurement locations
7	Radial Deflection	0°	33 Measurement locations
8	Radial Deflection	45°	Average spectrum orders of magnitude too low - not included in results
9	Radial Deflection	60°	33 Measurement locations
10	Radial Deflection	75°	33 Measurement locations
11	Radial Deflection	90°	33 Measurement locations
12	Radial Deflection	45°	33 Measurement locations
13	Radial Deflection	105°	33 Measurement locations
14	Radial Deflection	120°	33 Measurement locations
15	Radial Deflection	135°	33 Measurement locations
16	Radial Deflection	150°	33 Measurement locations
17	Radial Deflection	165°	33 Measurement locations
18	Radial Deflection	180°	33 Measurement locations
19	Radial Deflection	195°	33 Measurement locations
20	Radial Deflection	205°	33 Measurement locations
21	Axial Deflection	Sense-end face	59 Measurement locations
22	Axial Deflection	Drive-end face	59 Measurement locations
23	Radial Deflection	Scan at 90°	315 Measurement locations