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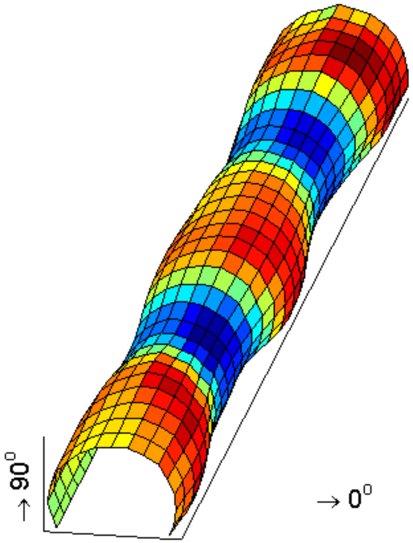

High Frequency Modal Analysis of a Solid Metal Cylinder

NMSBA Program: Vibrant Corporation

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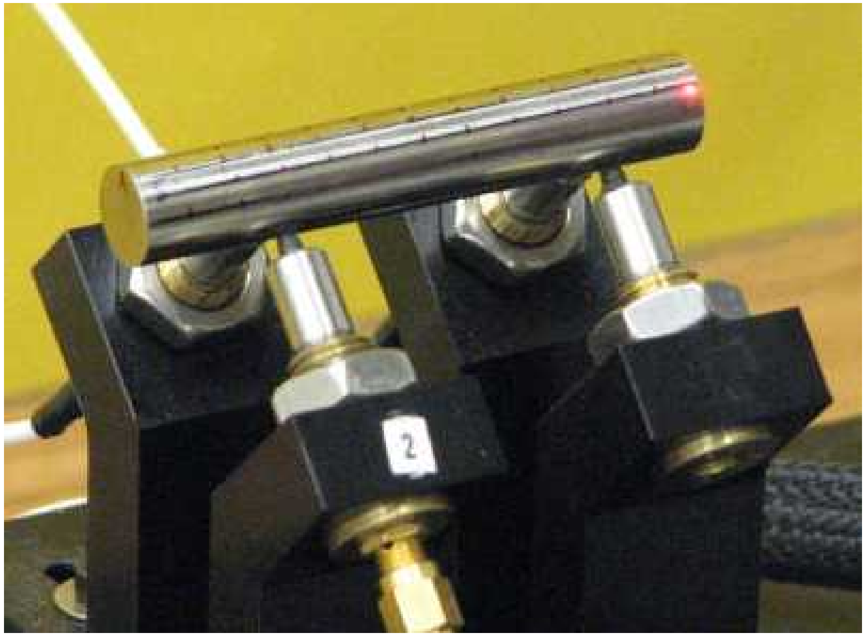
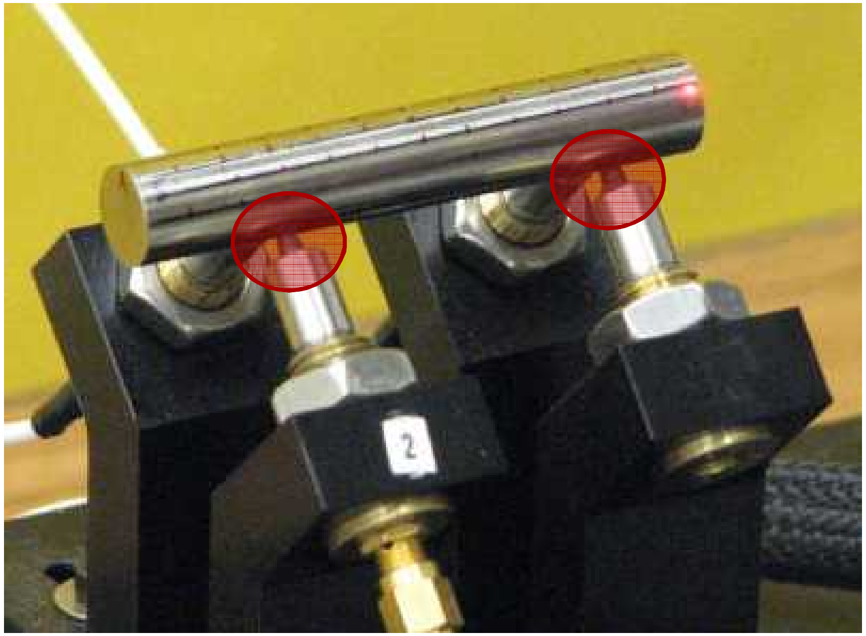
Problem Statement

- Experimentally measure mode shapes of the test unit as high in frequency as achievable with a Polytec PSV-400 scanning laser Doppler vibrometer.
- Test unit is a solid metal cylinder (TE_P_05_110068/71A1G)
  - Length: 3.0 inches
  - Diameter: 0.5 inches
  - Weight: 3 oz.



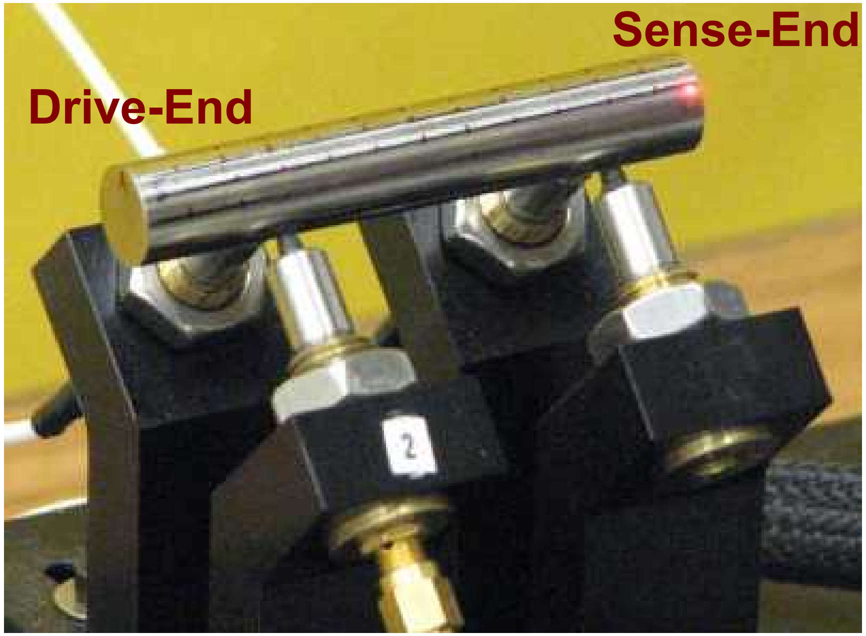
Test Fixture Description

- Test fixture provided by Vibrant Corporation
- Nominally, the test unit is simply placed upon 4 piezoelectric point locations at 45 degrees below horizontal
- Piezoelectric devices can be used for both actuation and sensing
- 1 drive point
- 2 sensing locations
- 4th point holds test unit in place



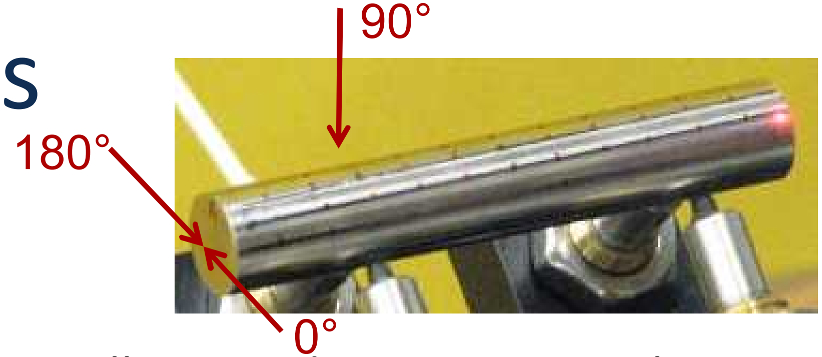
Boundary Conditions

- Small amount of super glue was placed between test unit and test fixture to reduce chatter during testing and improve coherence
- 1 drive location (Location 2)
- Unit was not placed symmetrically in the test fixture
  - 0.5 inches extending beyond the “drive-end”
  - 0.24 inches extended beyond the “sense-end”



Ideally, free-free boundary conditions would be preferable for ease of comparison to finite element results. In future tests, using a 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 would be required to excite the unit throughout the bandwidth. Achieving sufficient displacement with this type of excitation could be difficult given the stiffness of the structure.

Summary of Tests



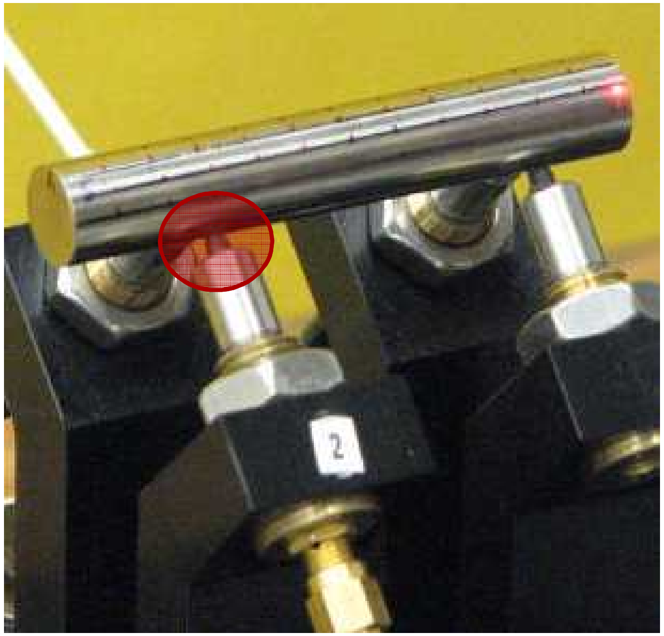
- **Radial Deflection Tests**
  - This test scans a line of 33 equally spaced measurement locations along the length of the cylinder
  - Main purpose of radial deflection tests were to extract bending some axial modes
  - The LDV only measures out-of-plane displacement, so the laser head was rotated at various angles to measure as much of the unit as possible
  - Interference of the test fixture limited laser head angles from -25 deg to 205 deg
  - Laser head angles measured (in deg): -25, -15, 0, 15, 30, …, 195, 205
  - All radial deflection scans were compiled in MATLAB and processed to produce 3D mode shapes of the test unit
  - *In the future, a special test fixture that could accurately rotate the excitation and hold the test unit instead of rotating the laser head would greatly improve efficiency of testing*.

Summary of Tests

- **Axial Tests**
  - This test scans each cylinder end face with 59 measurement locations
  - Main purpose of axial tests was to extract axial modes
  - Both axial scans were compiled in MATLAB to extract 3D mode shapes of each face
- **Full Unit Scan**
  - This test applied reflective tape to the top of the test unit and performed a scan of 315 measurement locations with a laser head angle of 90 deg
  - Reflective tape was required to diffuse laser signal such that measurement locations near the edge of the unit (0 and 180 deg) would reflect some return signal back to the laser heard
  - Main purpose of the full unit scan was to extract torsion modes
  - Also used to verify bending modes and some axial modes from radial deflection and axial tests

Excitation

- Excitation force provided at a single drive point by piezoelectric ceramic at Location 2
- Krohn-hite 7500 amplifier used to amplify the signal from the generator to the piezoelectric actuator. Voltage was limited to 14V
- Burst chirp excitation signal
  - Bandwidth: 10kHz-200kHz
  - Burst Length: 25%
- Frequency response coherence allowed measurements up to approximately 155 kHz

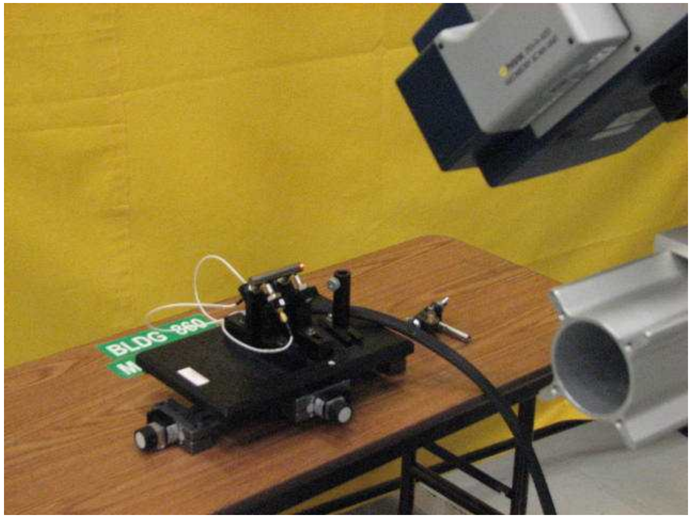


DAQ Setup

- Bandwidth: 10 kHz – 200 kHz
- Frequency Resolution: 3.9 Hz
- No windows
- 8 averages @ each measurement location
- Reference Signal: voltage input to piezoelectric driver before amplification

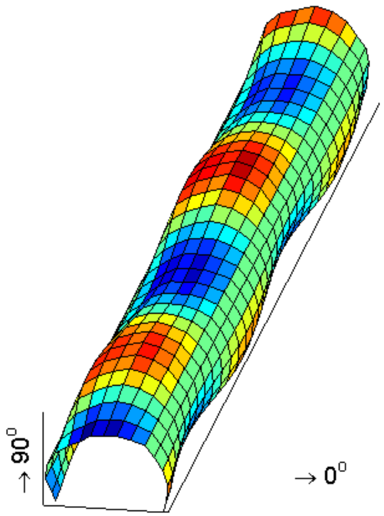
Results – Radial Deflection Tests

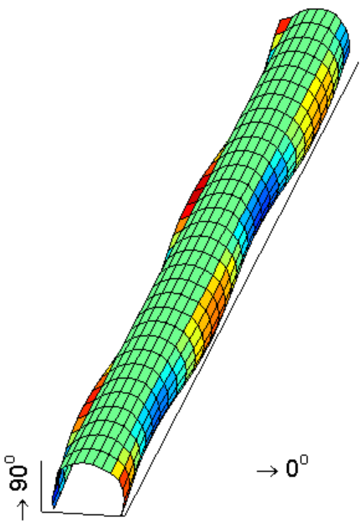
- Used to identify bending and some axial modes
- Torsion and some axial modes were not well observed in the radial deflection data
- Not all scans identified all modes
- Modes not identified in scans show up as zero deflection in the MATLAB mode shape images
- Test setup image for 45 deg laser head angle:



Results – Bending Mode Pairs

- Seven bending mode pairs observed below 155 kHz
- Each pair is orthogonal so some laser head angles observed one of the pair better than the other





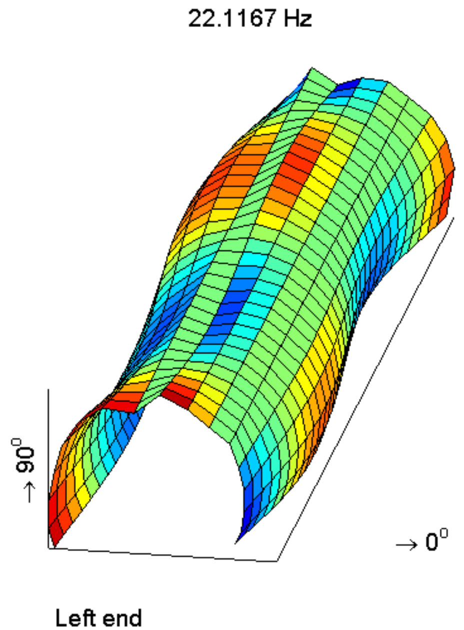
- Bending modes greater than 140 kHz contained localized effects near the boundary conditions of the test fixture attachment locations

Results – Bending Mode Pairs

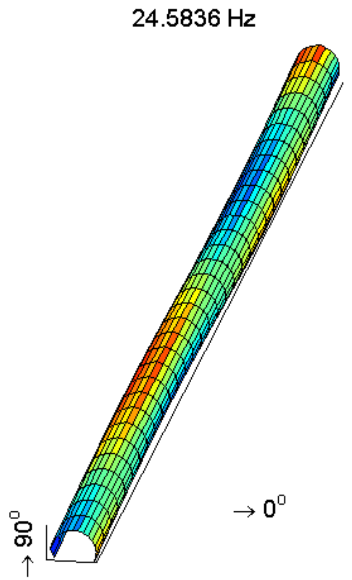
One of the bending mode pairs was also observable in the full unit scan and compared to results from the radial deflection tests.

Bending Mode Pair	Frequency from Radial Deflection Tests (kHz)		Frequency from Full Unit Scan (kHz)
1	22.1	24.6	22.1
2	38.9	41.8	41.5
3	58.5	58.6	58.3
4	78.78	79.2	78.9
5	98.3	100.6	99.9
6	118.4	118.8	118.5
7	136.6	137.3	136.3

Bending Mode Pair 1

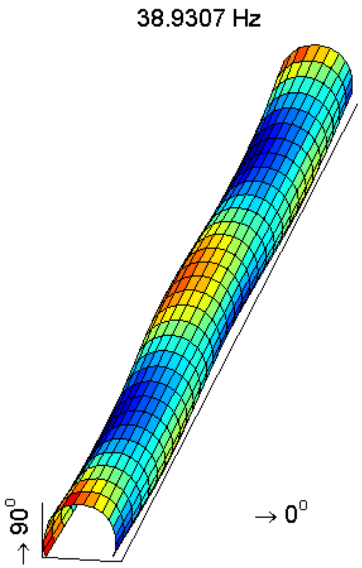


22.1 kHz

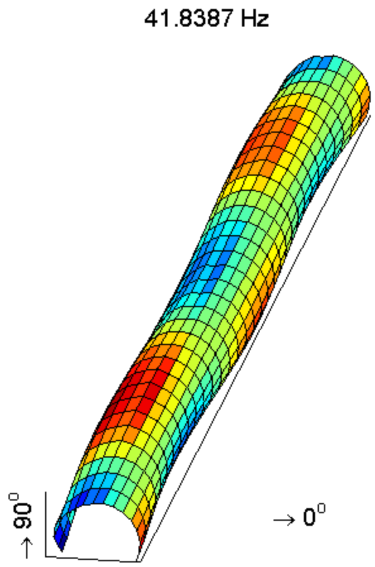


24.6 kHz

Bending Mode Pair 2

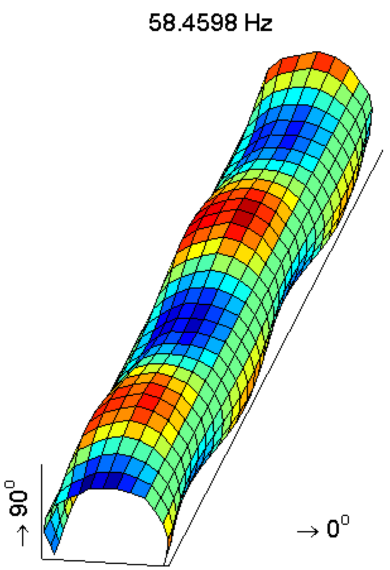


38.9 kHz

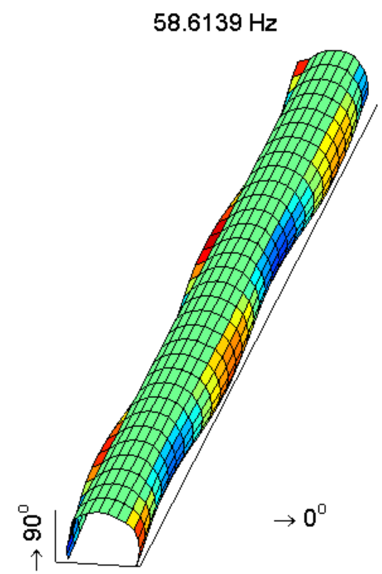


41.8 kHz

Bending Mode Pair 3

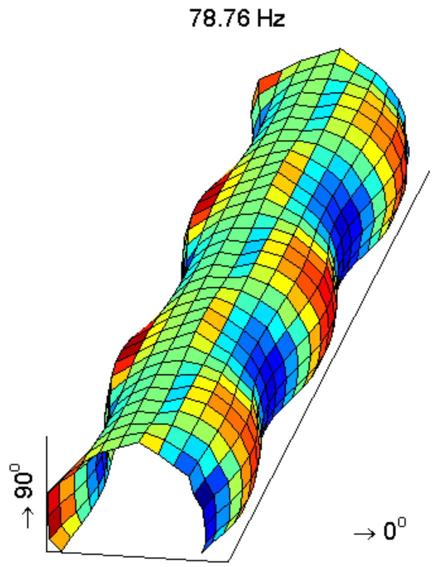


58.5 kHz

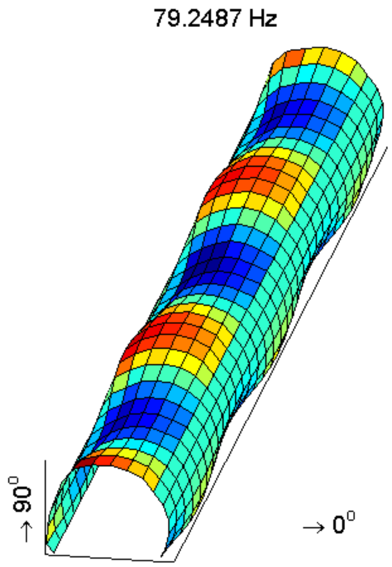


58.6 kHz

Bending Mode Pair 4

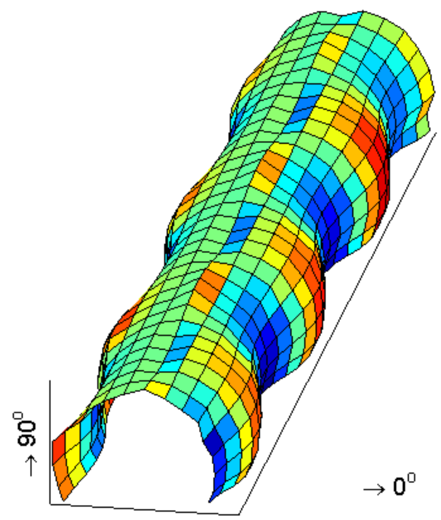


78.8 kHz

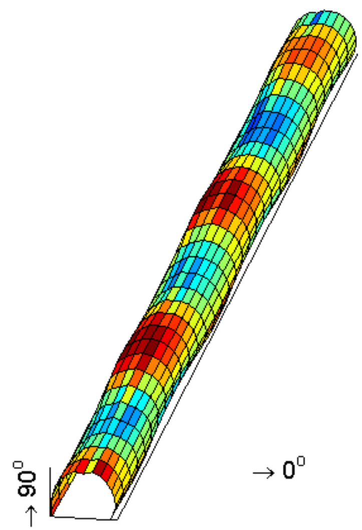


79.2 kHz

Bending Mode Pair 5

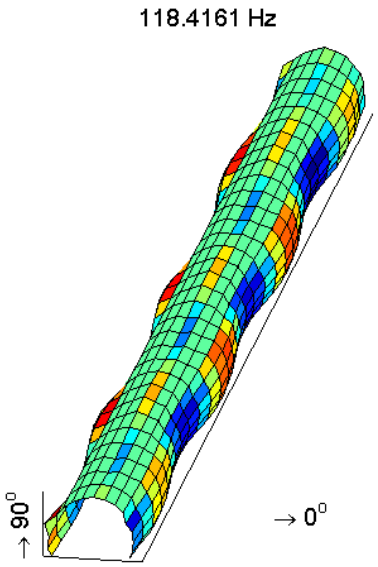


98.3 kHz

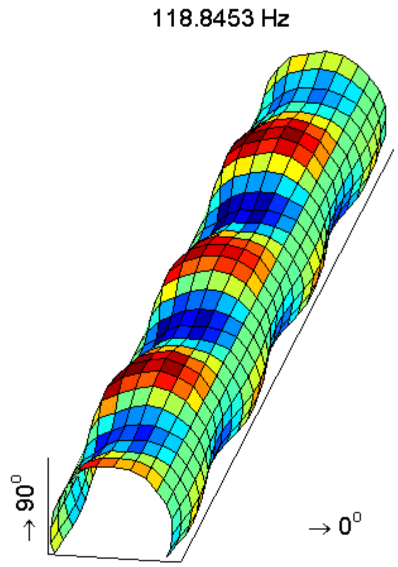


100.6 kHz

Bending Mode Pair 6

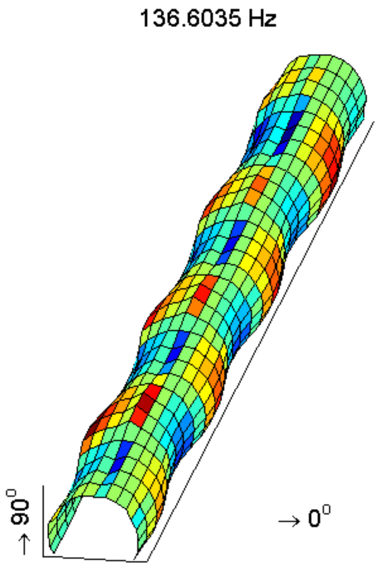


118.4 kHz

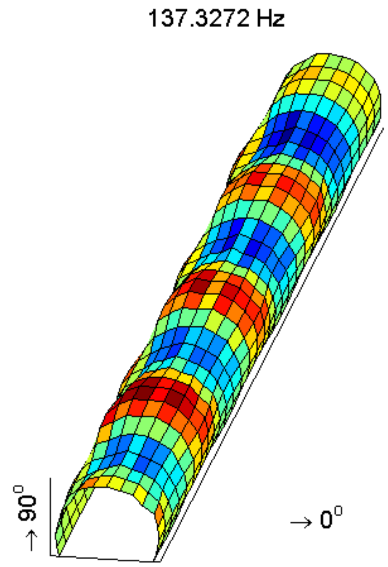


118.8 kHz

Bending Mode Pair 7



136.6 kHz



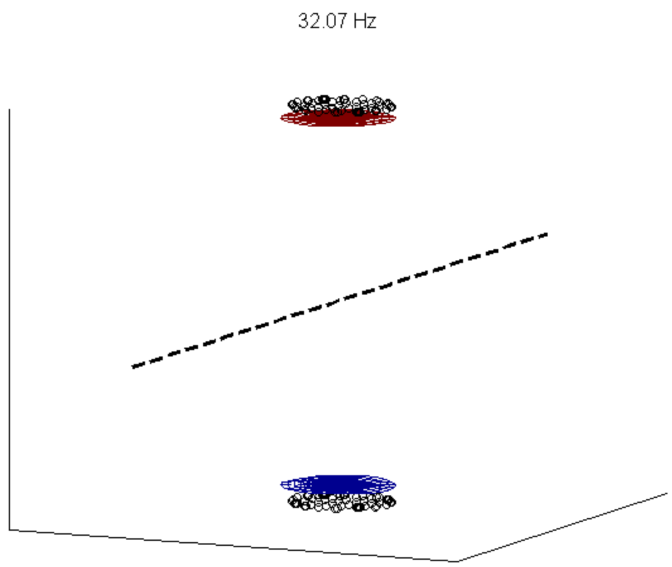
137.3 kHz

Results – Axial Modes

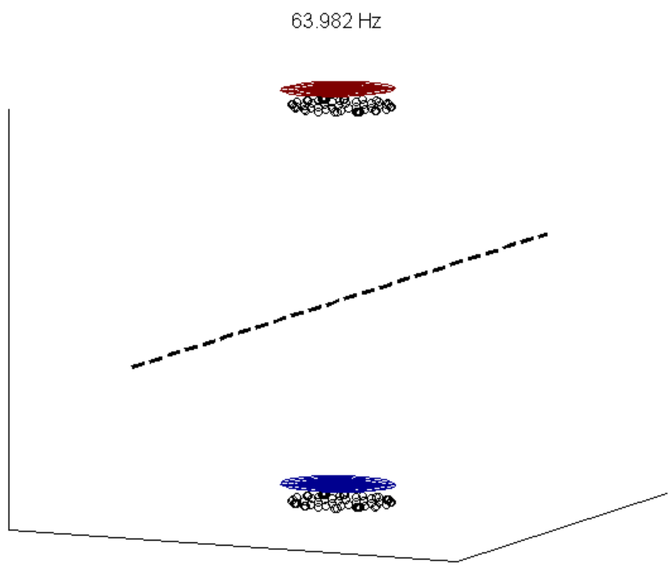
Five axial modes were observed using data from all types of scans

Axial Mode	Frequency from Radial Deflection Tests (kHz)	Frequency from Full Unit Scan (kHz)	Frequency from Axial Tests (kHz)
1	*Not observable*	*Not observable*	32.1
2	64.0	*Not observable*	64.0
3	94.9	94.7	94.9
4	124.6	124.4	124.6
5	153.0	152.8	153.0

Axial Mode 1 & 2

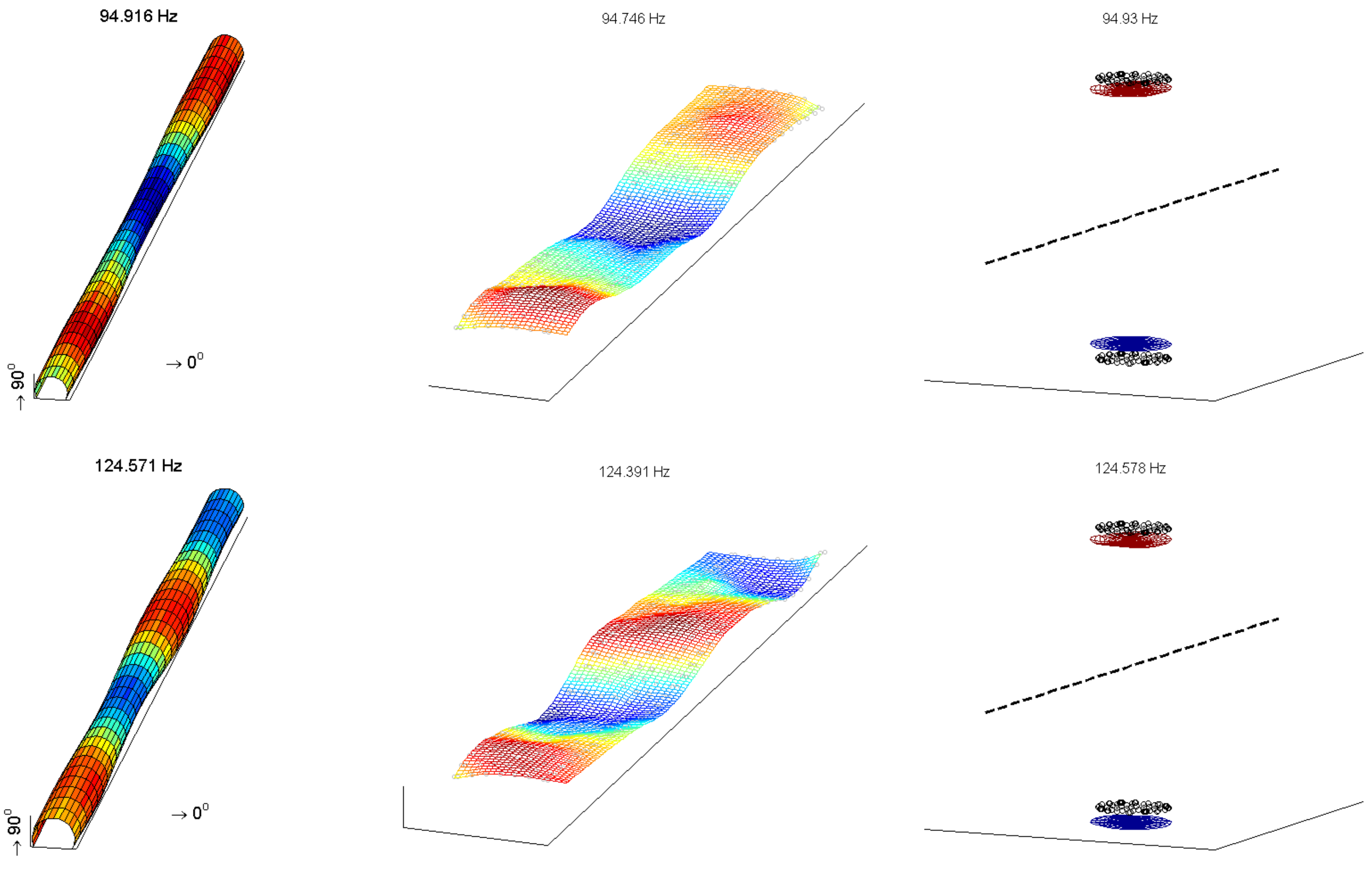


32.1 kHz

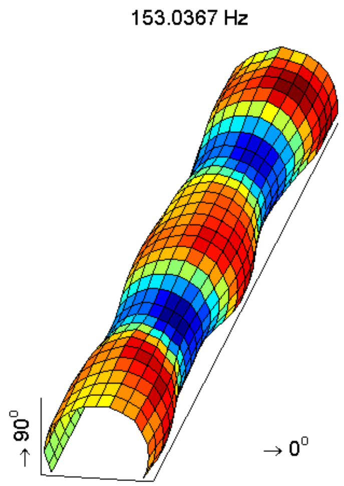


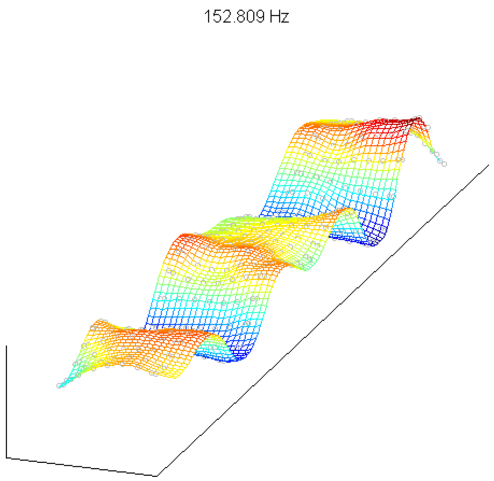
64.0 kHz

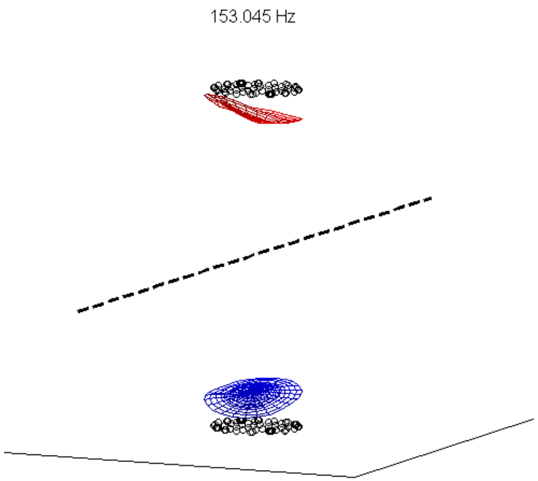
Axial Mode 3 & 4



Axial Mode 5



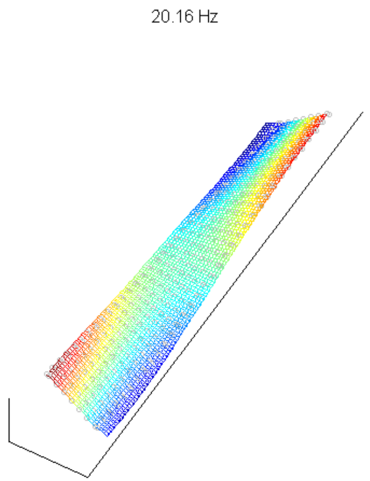




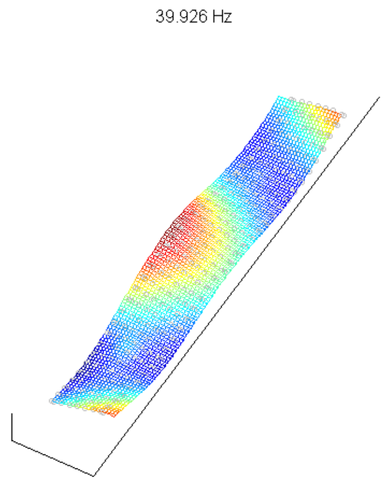
153.0 kHz | 152.8 kHz | 153.0 kHz

Results – Torsion Modes

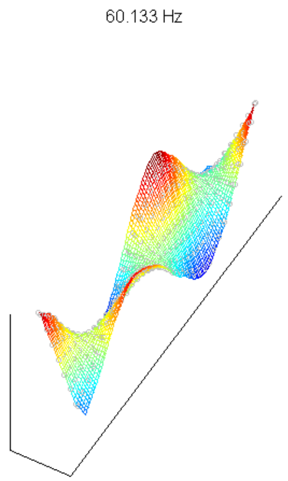
Six torsion modes were observable with the full unit scan



20.2 kHz



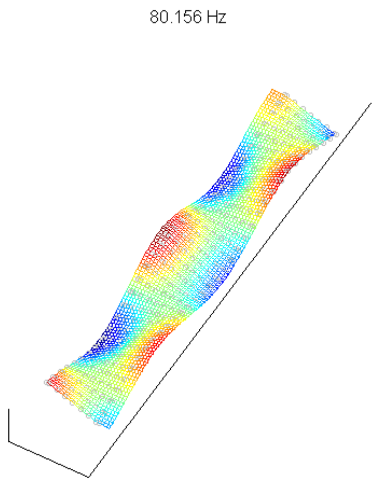
39.9 kHz



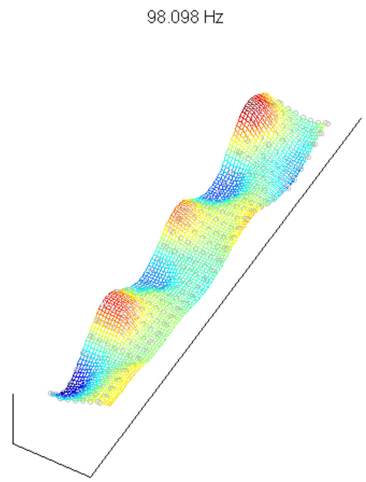
60.1 kHz

Results – Full Unit Scan

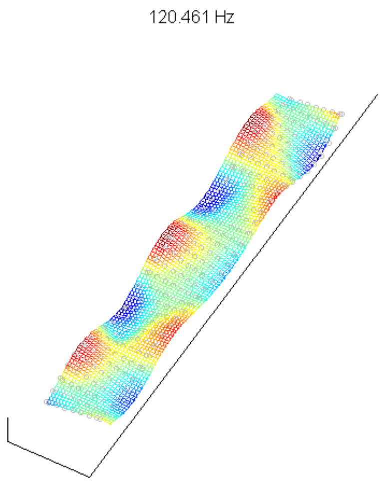
Six torsion modes were observable with the full unit scan



80.2 kHz



98.1 kHz



120.5 kHz

Comparison to Calculated Values

- **Hand Calculations**
  - Bending frequencies computed using Timoshenko beam formula (Blevins, RD, 1995, *formulas for Natural Frequencies and Mode Shapes*, Van Nostrand, p 108 and 181)
  - Axial frequencies computed using approximate formula for axial modes of a beam (Blevins p 183)
  - Torsion frequencies computed using approximate formula for torsion modes of a beam (Blevins p 193)
- **FEM**
  - Computed eigensolution for 510 modes using SIERRA/SD
  - Mesh generated using CUBIT (approximately 40k HEX8 elements)
- **Material properties**
  - Density: 8.8103 kg/m^3
  - Young's Modulus: 203 Gpa
  - Poisson Ratio: 0.33

Comparison to Hand Calculations

Mode Shape Description	Average Measured Frequency (kHz)	Calculated Frequency (kHz)	% Difference
Bending	*Out of Bandwidth*	9.0	--
Torsion	20.2	19.5	3.6%
Bending	22.9	23.0	0.4%
Axial	32.1	31.5	1.9%
Torsion	39.9	39.1	2.0%
Bending	40.7	40.4	0.7%
Bending	58.5	59.5	1.7%
Torsion	60.1	58.6	2.6%
Axial	64.0	63.0	1.6%
Torsion	80.2	78.1	2.7%
Bending	79.0	79.4	0.5%
Axial	94.8	94.5	0.3%
Torsion	98.1	97.7	0.4%
Bending	99.6	100.9	1.3%
Torsion	120.5	117.2	2.8%
Bending	118.6	121.3	2.2%
Axial	124.5	126.0	1.2%
Torsion	*Not Observed*	136.7	--
Bending	136.7	141.7	3.5%
Axial	152.9	157.5	2.9%

Comparison to FEM

Mode Shape Description	Average Measured Frequency (kHz)	Calculated Frequency (kHz)	% Difference
Bending	*Out of Bandwidth*	9.2	--
Torsion	20.2	20.5	1.5%
Bending	22.9	22.9	0%
Axial	32.1	32.9	2.4%
Torsion	39.9	40.9	2.4%
Bending	40.7	40.1	1.5%
Bending	58.5	59.2	1.2%
Torsion	60.1	61.4	2.1%
Axial	64.0	65.6	2.4%
Torsion	80.2	79.1	0.1%
Bending	79.0	81.9	2.1%
Axial	94.8	97.5	2.8%
Torsion	98.1	102.4	4.2%
Bending	99.6	99.2	0.4%
Torsion	120.5	118.9	0.3%
Bending	118.6	122.9	2.0%
Axial	124.5	128.2	2.9%
Torsion	*Not Observed*	143.4	--
Bending	136.7	136.9	0.1%
Axial	152.9	156.7	2.4%

Summary

- Polytec PSV-400 used to measure velocity response of a solid metal cylinder due to burst chirp excitation
- Natural frequencies & mode shapes were recorded between 10 & 155 kHz
- Variety of scans observed bending, axial and torsion modes
  - 7 bending mode shape pairs
  - 5 axial modes
  - 6 torsion modes
- MATLAB used to piece together multiple scans
- Since not all modes were observable in all runs this report is not assumed to be all-inclusive of modes within the bandwidth
- **Comparison to hand calculations, measured frequencies are within 3.5% of calculated frequencies (using estimated material properties)**
- **Comparison to FEM, measured frequencies are within 4.2% of calculated frequencies (using estimated material properties)**

Challenges/Areas of Improvement

- Free-free boundary conditions are preferable, but excitation with acceptable bandwidth could prove challenging
- Rotating the laser head angle was time consuming and introduced uncertainty into the experiment. Designing an intelligent test fixture that allowed the excitation to accurately rotate instead of the laser head could improve efficiency of testing, though could be challenging to integrate with a free-free type boundary condition.