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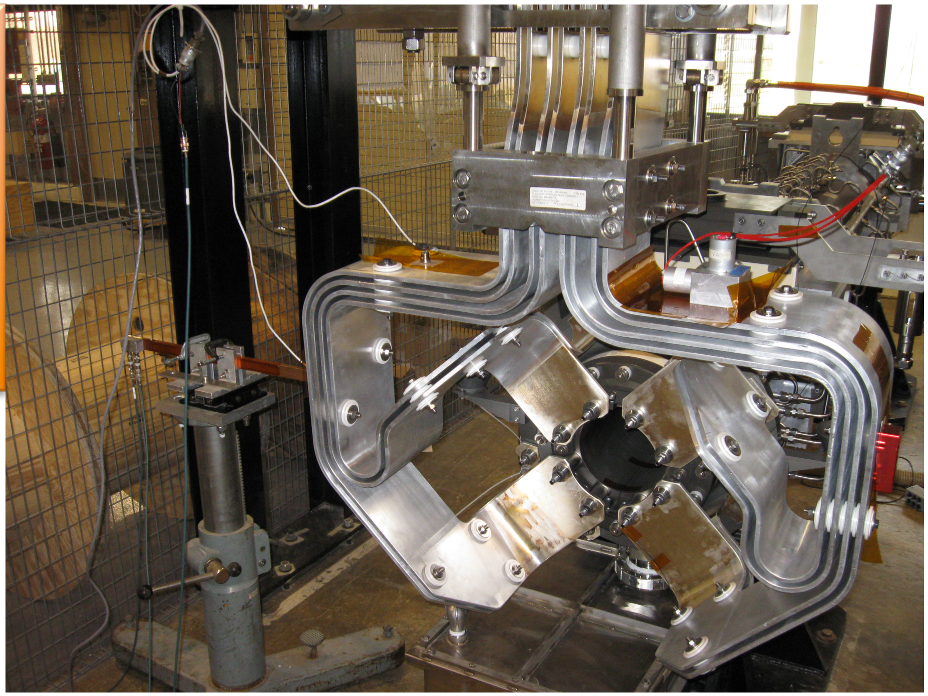
NuMI/NOvA Horn 1 Stripline Vibration Measurements



Kris Anderson

Fermi National Accelerator Lab

25-September-2014

NBI Workshop 2014

Overview

- **Some Background Information Regarding Horn 1 Stripline Analysis 400kW >> 700kW Operation**
- **Design Upgrades for 700kW NOvA Operation**
- **Motivation for Modal Characterization and Pulsed Operation Vibration Measurements**
- **Summary of Modal and Operational Vibration Results**

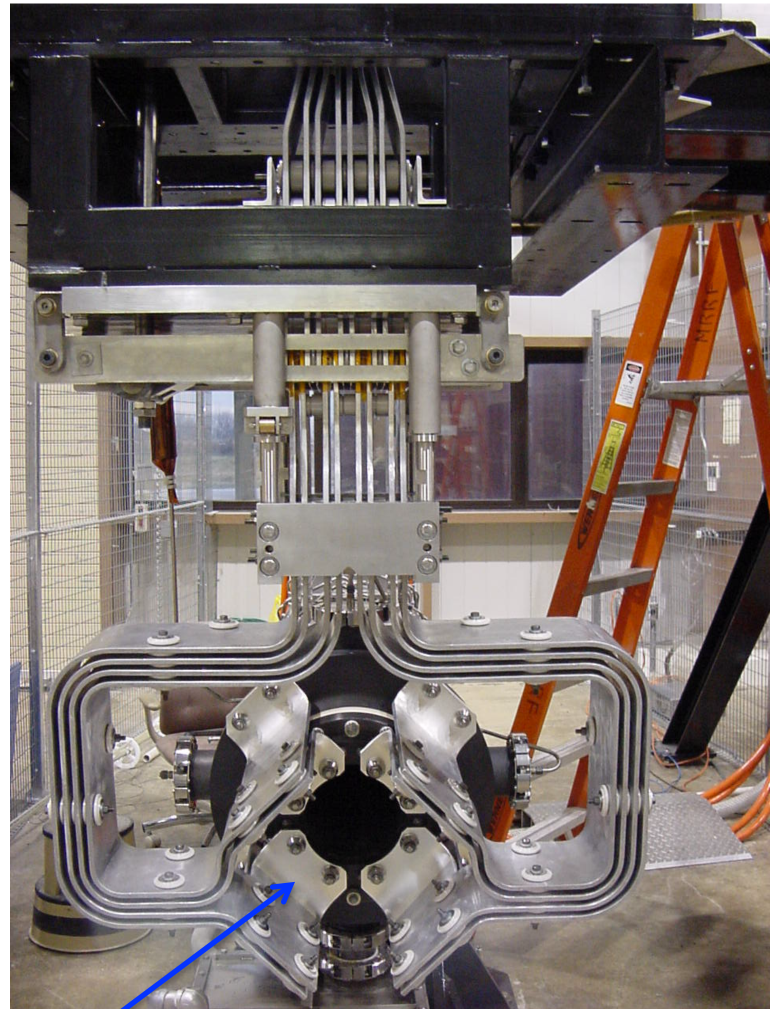
•Modal and Vibration Measurements and Data Reduction Conducted Under Contract with S&V Solutions, Sycamore, IL Principal, David Larson

• ANSYS Analysis Results Conducted by Yun He, Fermilab

400kW NuMI Horn 1

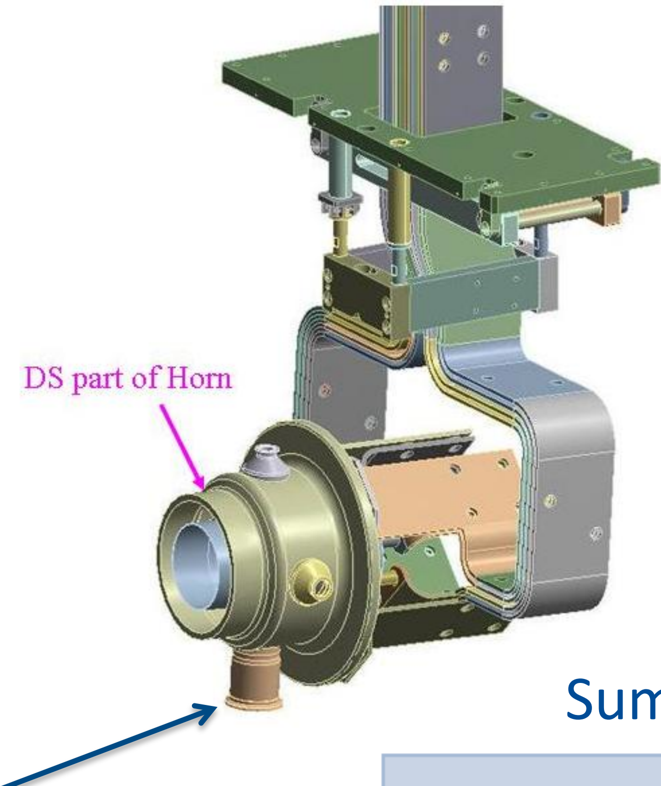
400kW Horn Stripline Features

- Designed for 4E13 protons/pulse
- Cycle time 1.86 sec
- 10μsec beam spill
- 200kA peak current pulse
- Originally 5.2 msec pulse width for resonant extraction
- Later changed for 2.3 msec pulse width for fast extraction
- Design allows conductor “flex” for horn motion relative to positioning module for beam-based alignment
- ***Reliable operation from 2005 thru 2012 NOvA reconfiguration***



Compact Routing @ Horn DS Face

Analyze 400kW Stripline @ 700kW Operation



Model of NuMI Style 400kW Beam Stripline Configuration Used for Generating ANSYS Mesh

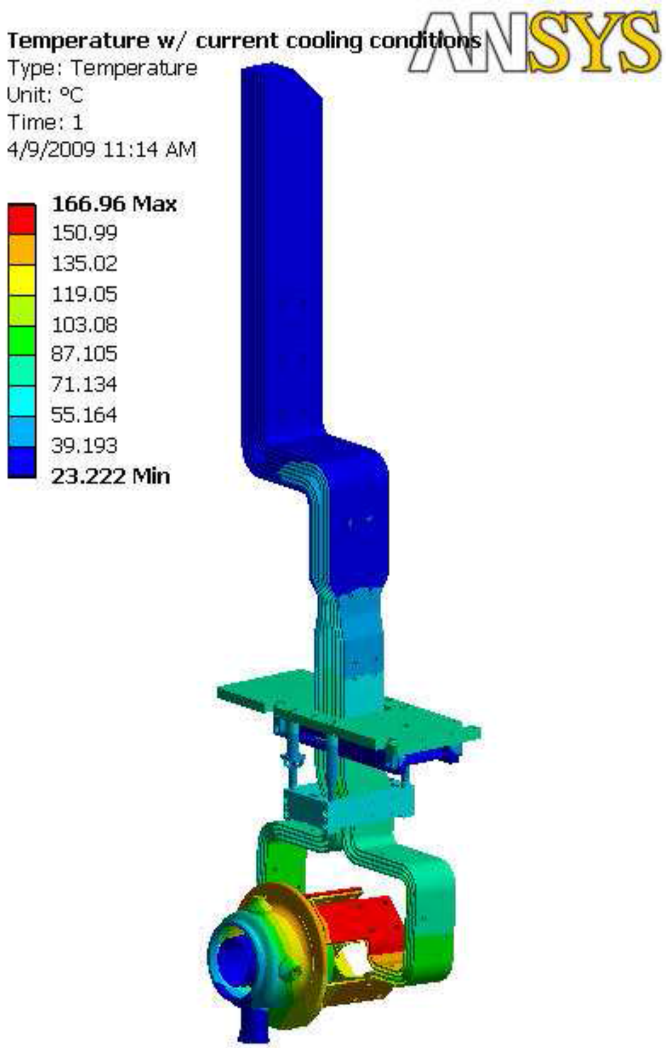
-Included thermal boundary conditions at downstream end of horn

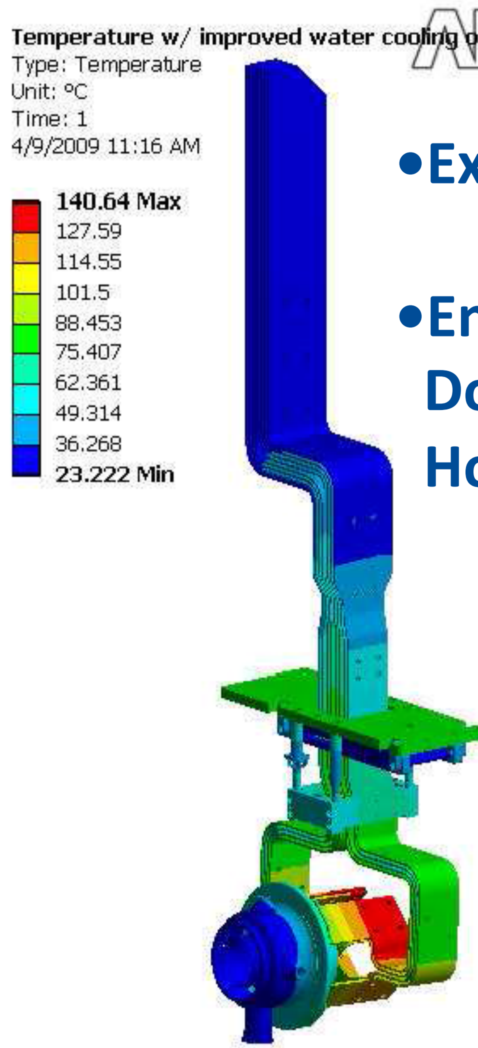
Air Cooling And Beam Direction

Summary of 700 kW Operation Heat Loads

Parts	Beam Heating	Joule Heating	Thermal Radiation Heating	Total
Stripline	3330	1340	310	4980
Horn DS End	6080	1540	320	7940
Clamp	240			240
Ceramic Spacers	50			50

Analyze 400kW Stripline @ 700kW Operation





- **Existing 400kW Design**
  T_{max} = 167°C
- **Enhanced Cooling on Downstream End of Horn**
  T_{max} = 141°C

Problems:
- Aluminum creep
- Increased Electrical Resistivity f(T)

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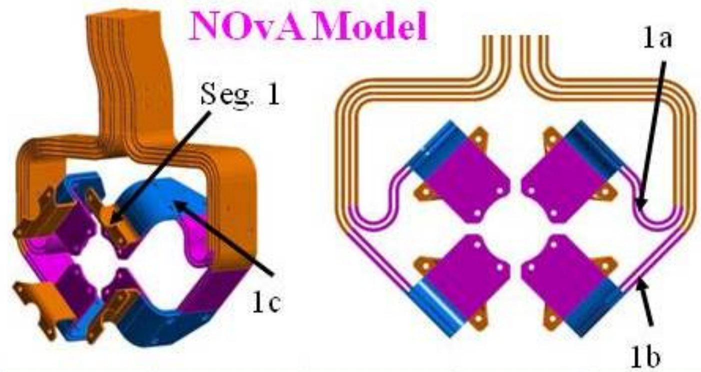
Proposed Design for 700kW Operation

- *"Fan out" conductors to better locate into target chase airflow stream and place material farther from beam centerline for reduced beam heating*
- *Design proposed and generated by David Tinsley of Fermilab*



(W/m3)	Beam Heating	Joule Heating	Therma l Rad. Heating	Total
Segment 1	9.02E+04	3.60E-08	1.14E+04	1.16E+05
Segment 2	4.28E+04	3.48E-08	1.14E+04	6.83E+04
Inner ear	9.10E+04	1.39E+04		1.05E+05
Outer ear	5.96E+04	1.38E+04		7.33E+04

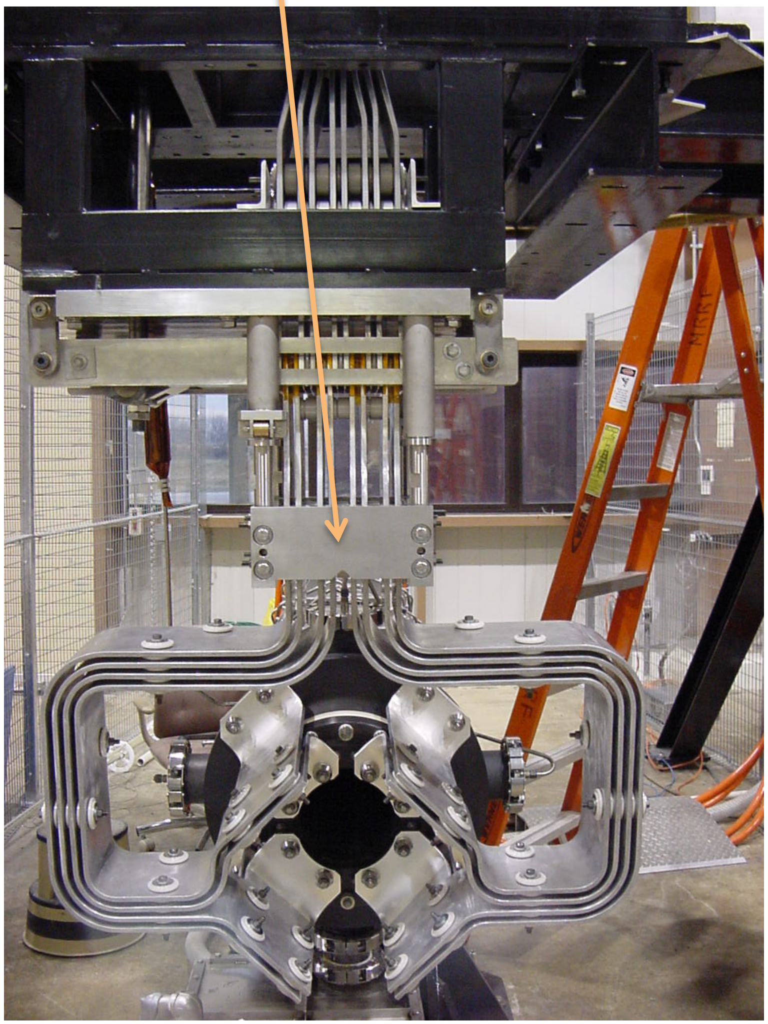
(W/m3)	Beam Heating	Joule Heating	Thermal Rad. Heating	Total
Segment 1a	7.65E+04	2.01E+04	2.67E+04	1.23E+05
Segment 1b	7.01E+04	2.01E+04	2.67E+04	1.17E+05
Segment 1	2.28E+05	1.89E+04	2.67E+04	2.73E+05
Segment 1c	1.08E+05	2.05E+04	2.67E+04	1.55E+05
Inner ear	1.39E+05	1.96E+04	2.67E+04	1.58E+05
Outer ear	3.03E+04	1.77E+04	2.67E+04	4.80E+04

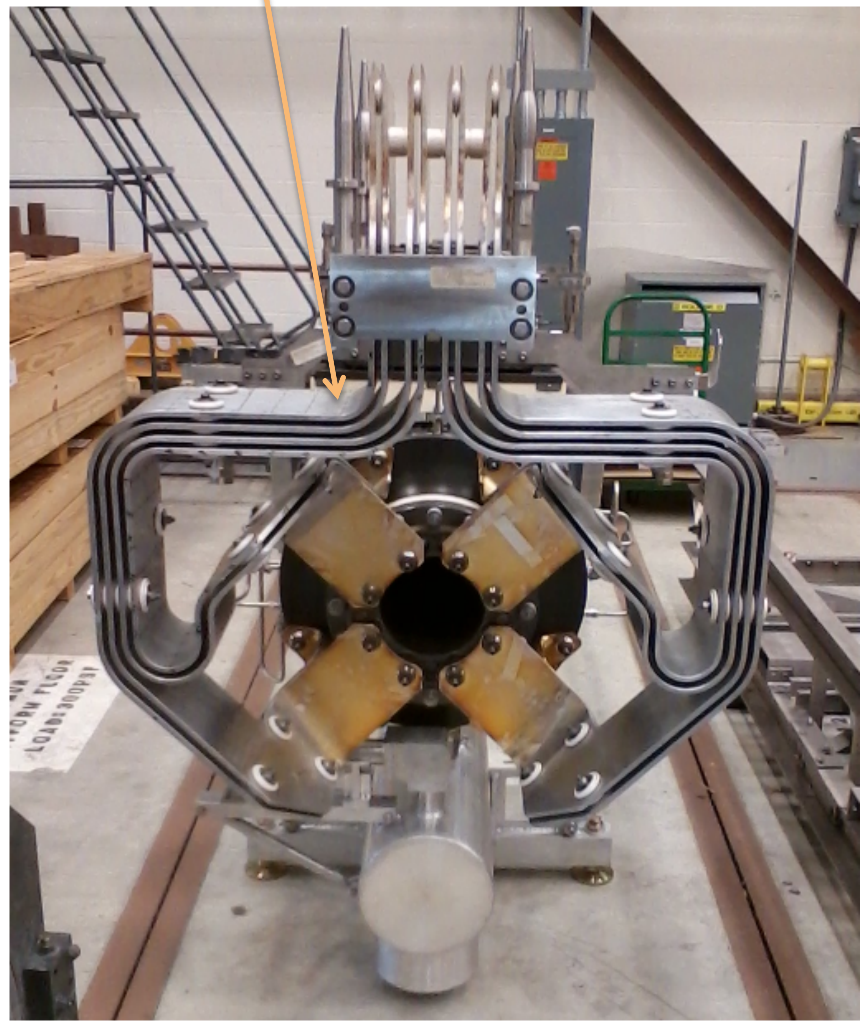
Analytical estimation, if same cooling condition:

$$\Delta T_{NOvA} = \Delta T_{NuMI} \frac{1.55E+5}{1.16E+5} = 1.34 \Delta T_{NuMI}$$

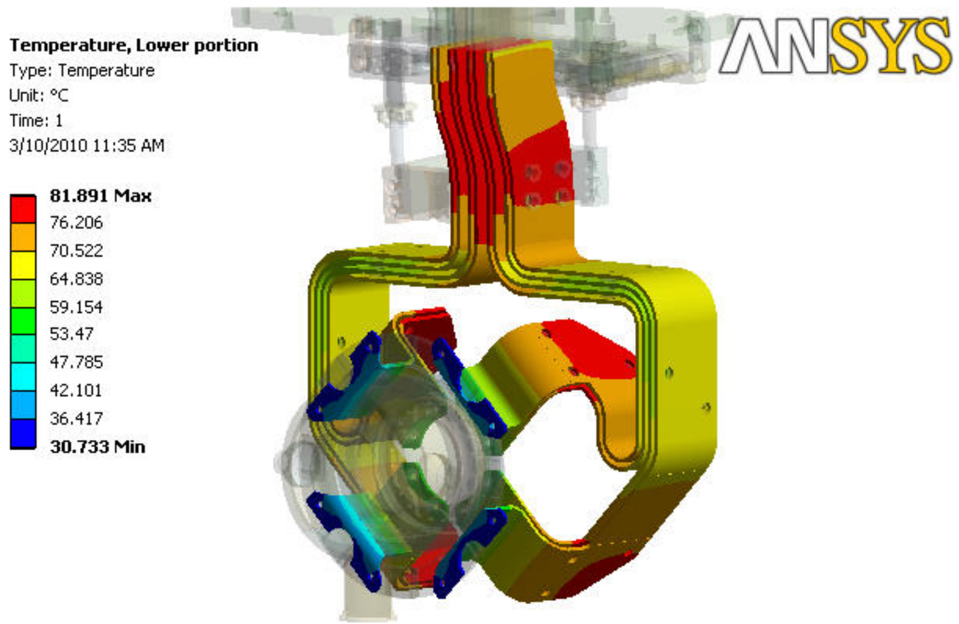
If ΔT_{NuMI}=50 °C, then ΔT_{NOvA}=68 °C, good agreement with FEA results

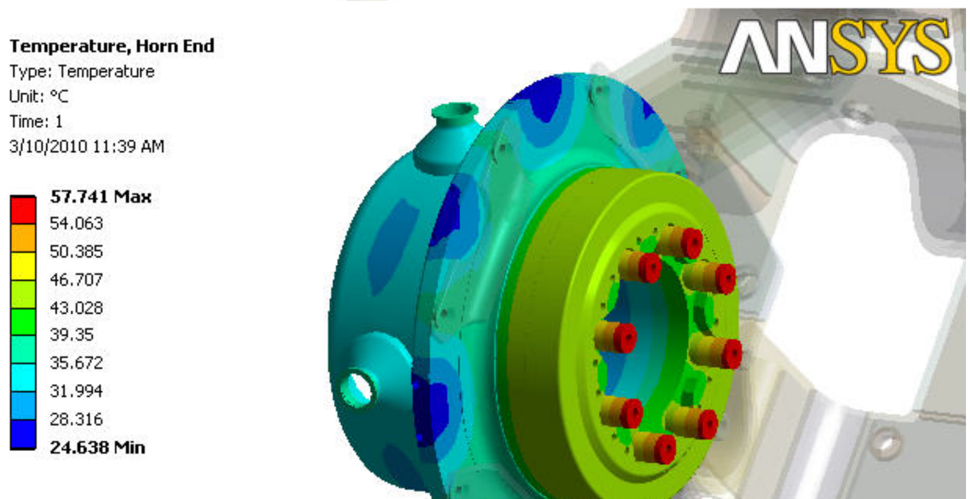
400kW Stripline vs. 700kW Stripline





ANSYS Results New 700kW Beam Stripline





- T_{max} now 82°C (higher heat transfer coefficient in direct air stream, ~ factor 2x)
- Fatigue analysis for 10M cycles reveals acceptable safety factor (*Electrical pulse heating + Electromagnetic force + Beam Heating*)
- Small magnitude of alternating stress

Dynamic Effects -- Vibration

- ***What about dynamic effects not captured in ANSYS models?***

- **Can run ANSYS modal analysis to obtain mode shapes and corresponding natural frequencies of structure**
  - *Typically a linear analysis and does not account for complex boundary conditions or reveal damping*

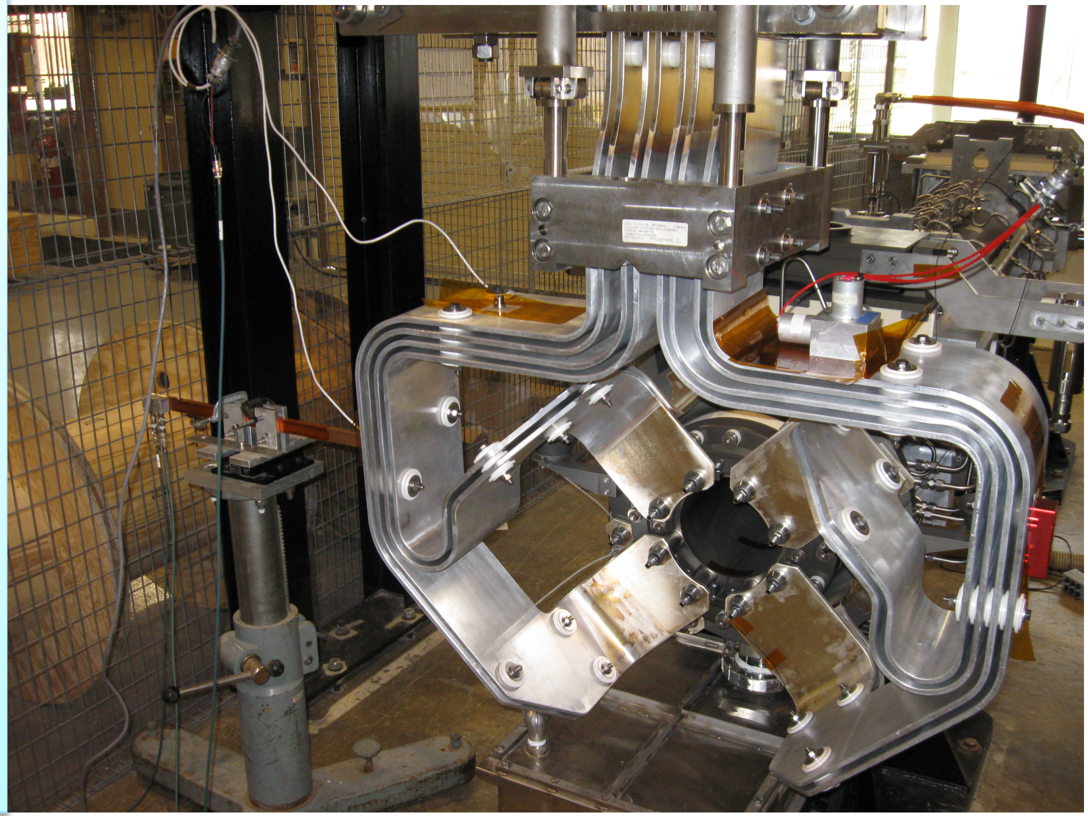
- **Can run ANSYS harmonic and/or transient dynamic analysis but these can be complicated by localized damping, complicated restraint boundary conditions, and modal participation relative to input forcing function**

Sorting Out Dynamic Effects

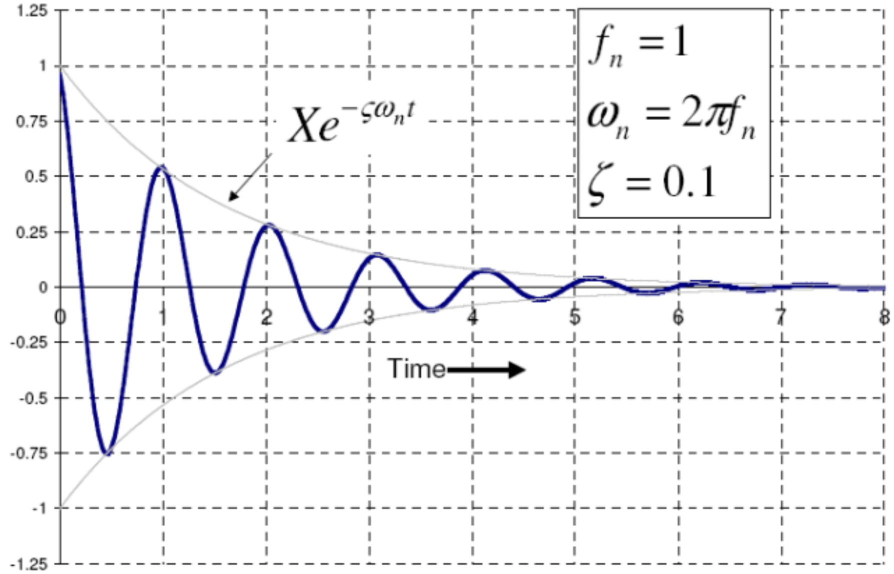
In November of 2013 S&V Solutions (David Larson) and I met and discussed the possible goals of a vibration analysis project to characterize the dynamic response of the NuMI/NOvA 700kW horn 1 (PH1-05) stripline

Measurement Objectives

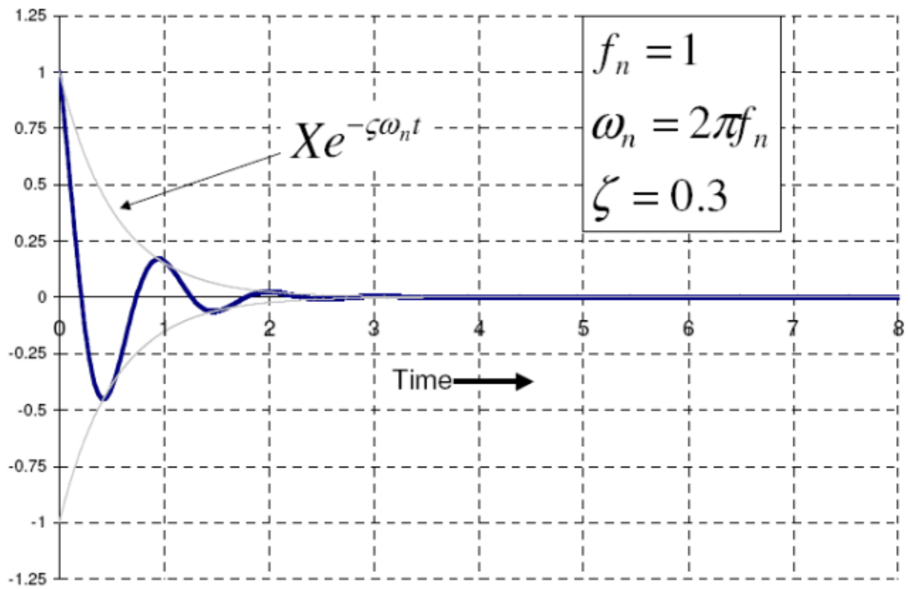
1. **Perform a full modal analysis and extract a set of modal parameters for the strip line assembly.**
2. **Measure operating vibration data on the stripline conductors under typical running conditions**
3. **Perform an analysis of operating vibration in terms of modal participations and decay rates**



Modal Damping: Time Domain Natural Response

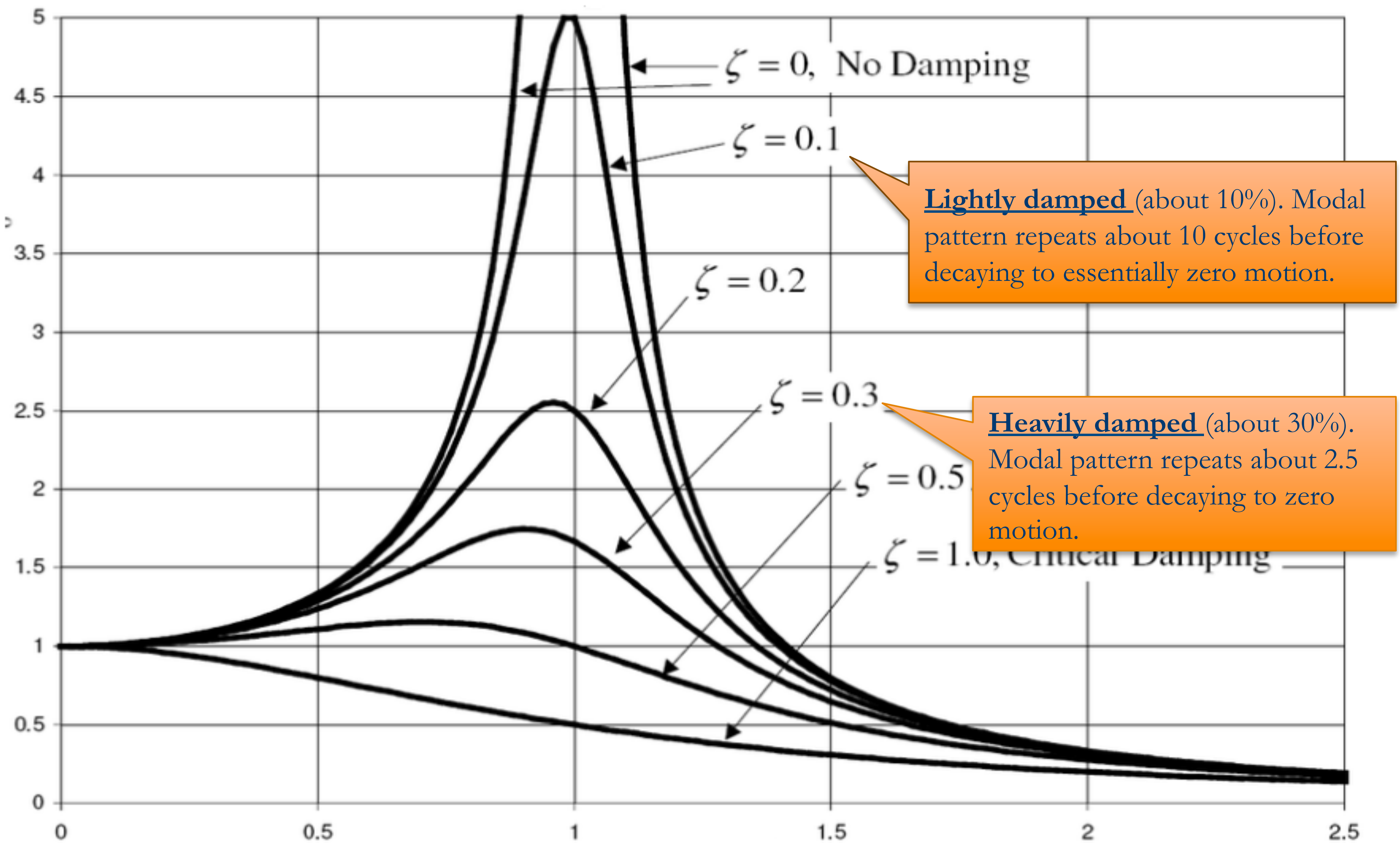


Lightly damped (about 10%). Modal pattern repeats about 10 cycles before decaying to essentially zero motion.



Heavily damped (about 30%). Modal pattern repeats about 2.5 cycles before decaying to zero motion.

Modal Damping: Frequency Domain



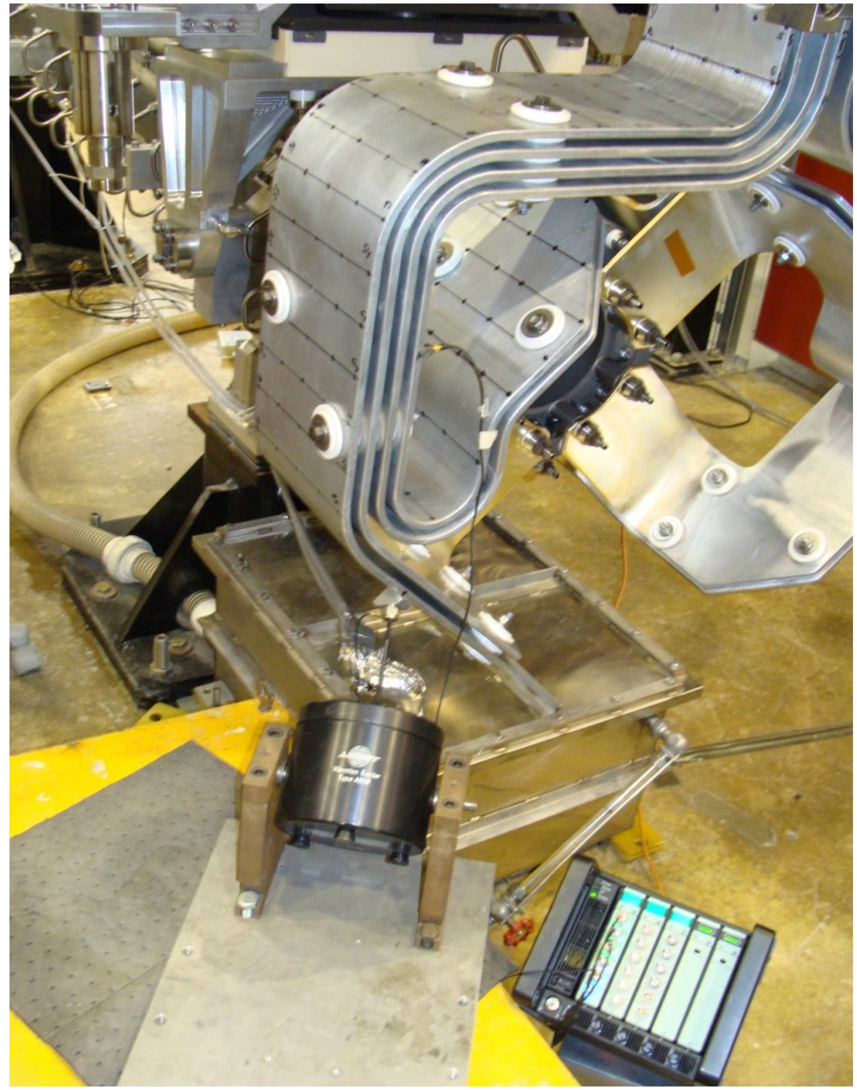
Response/Forcing

Relative Frequency (ω/ω_n)

Approach for Stripline Modal Testing

Approximately 200 points were selected from the existing FEA wireframe model and were used to create the EMA model. A 10 lbf dynamic force shaker was used with broad-band white noise forcing to excite the modes of the stripline (right).

The shaker was attached to the stripline using an oblique mounting block and a piezo-electric force transducer (below).



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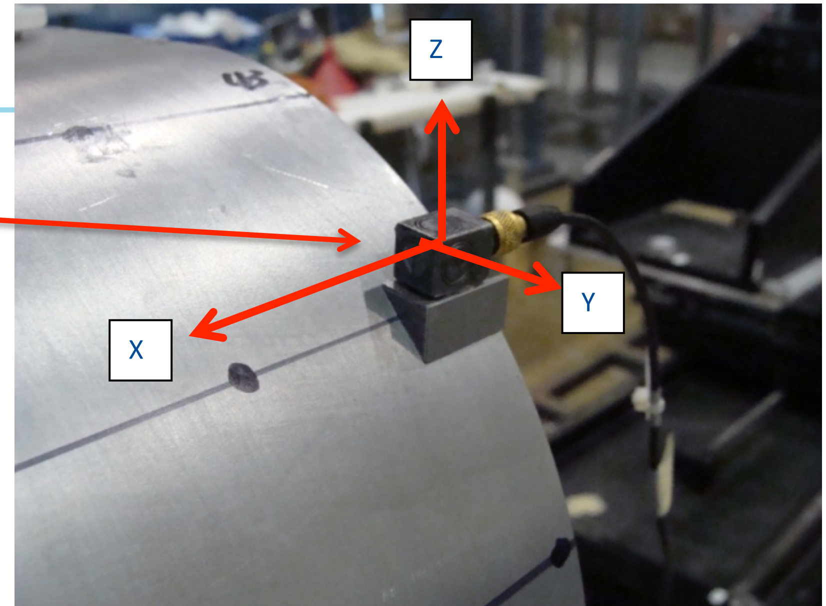
Measurement Transducers:
Force and Acceleration

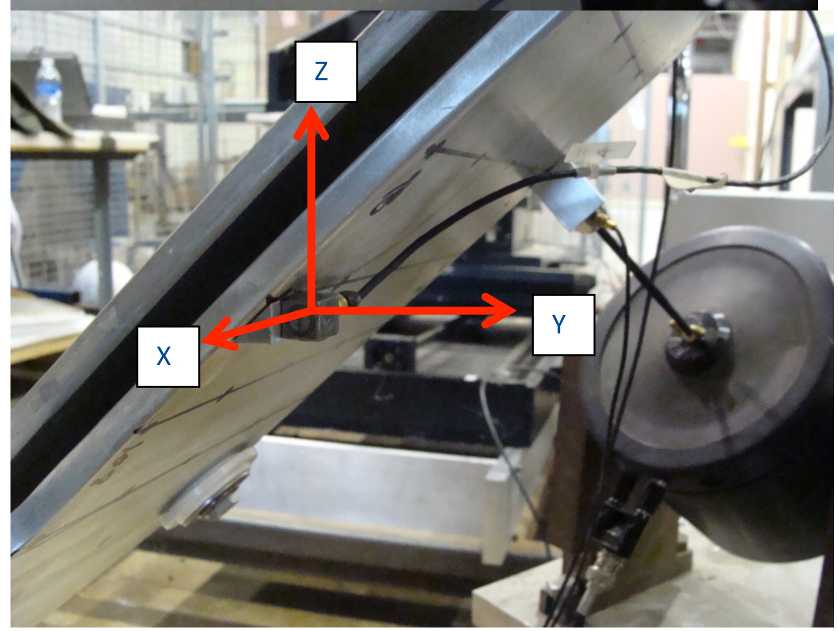
For modal data acquisition a global coordinate frame of reference preserving directionality was used (photos to right).

For live firing data acquisition a local coordinate system was used (z-axis normal to stripline conductor surface).

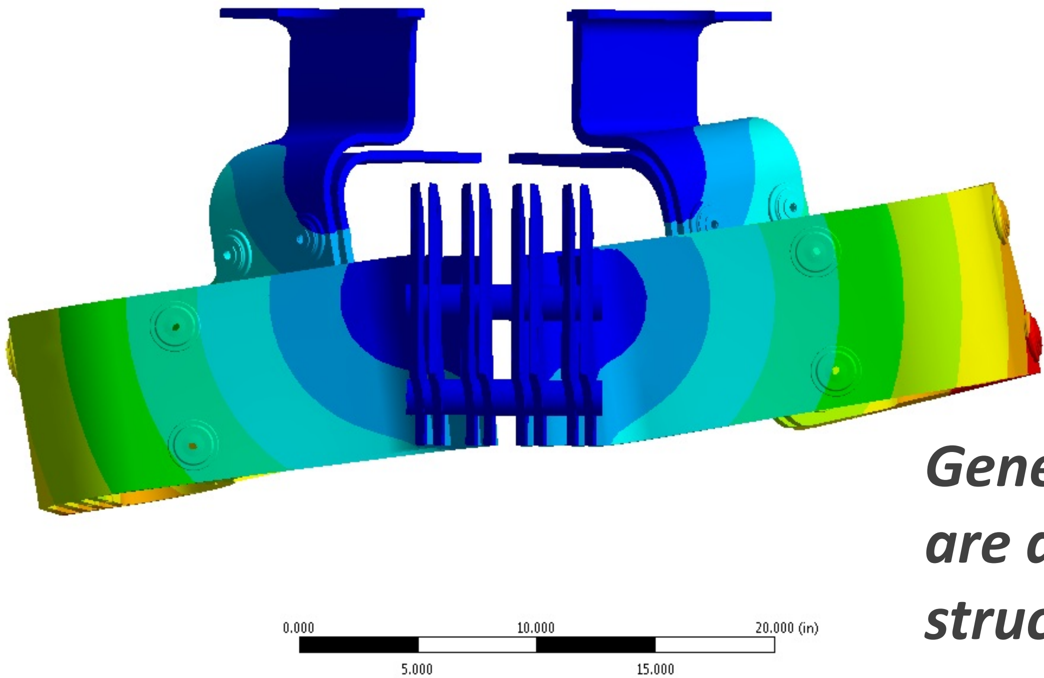
In all cases the response transducers were oriented to an orthogonal coordinate system so that directional information in the resulting mode shape functions was preserved.

The force transducer remained fixed in one location during the 200 triaxial measurements.





Example of Sorting Out Dynamic Effects

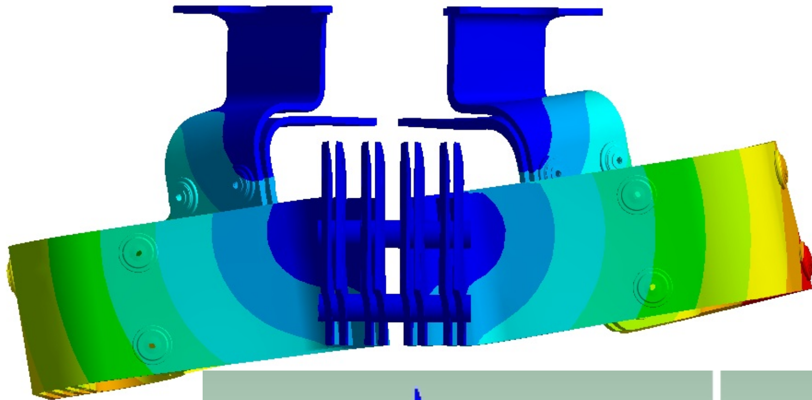


This is a 35 Hz Mode Simulated Using ANSYS

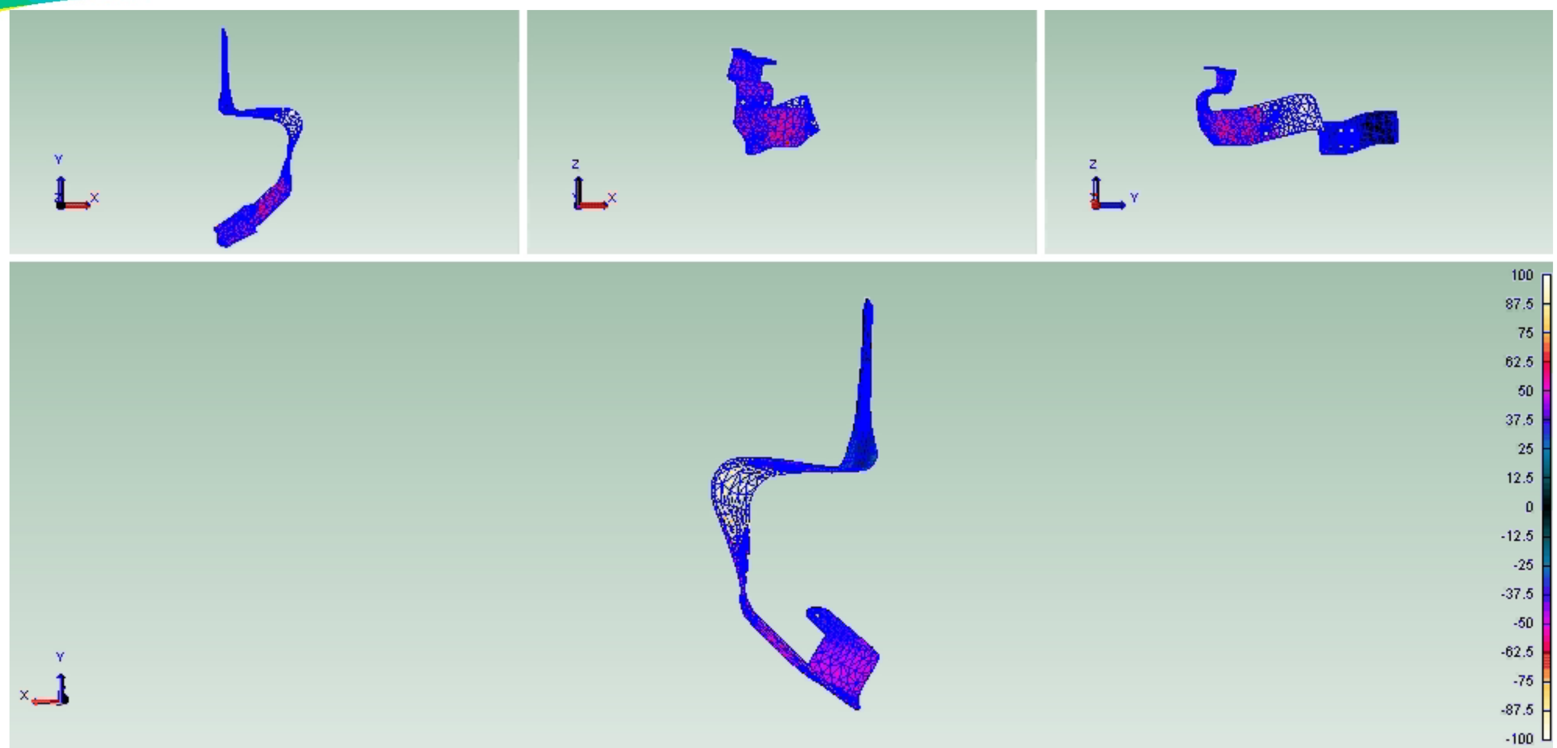
Generally lower frequency modes are accompanied by larger structural deflections that correspond to larger stresses

- Just FYI- This mode was confirmed with real modal measurement along with calculating corresponding damping coefficient
- ***Question: Will this mode participate in real horn-pulse operation?***

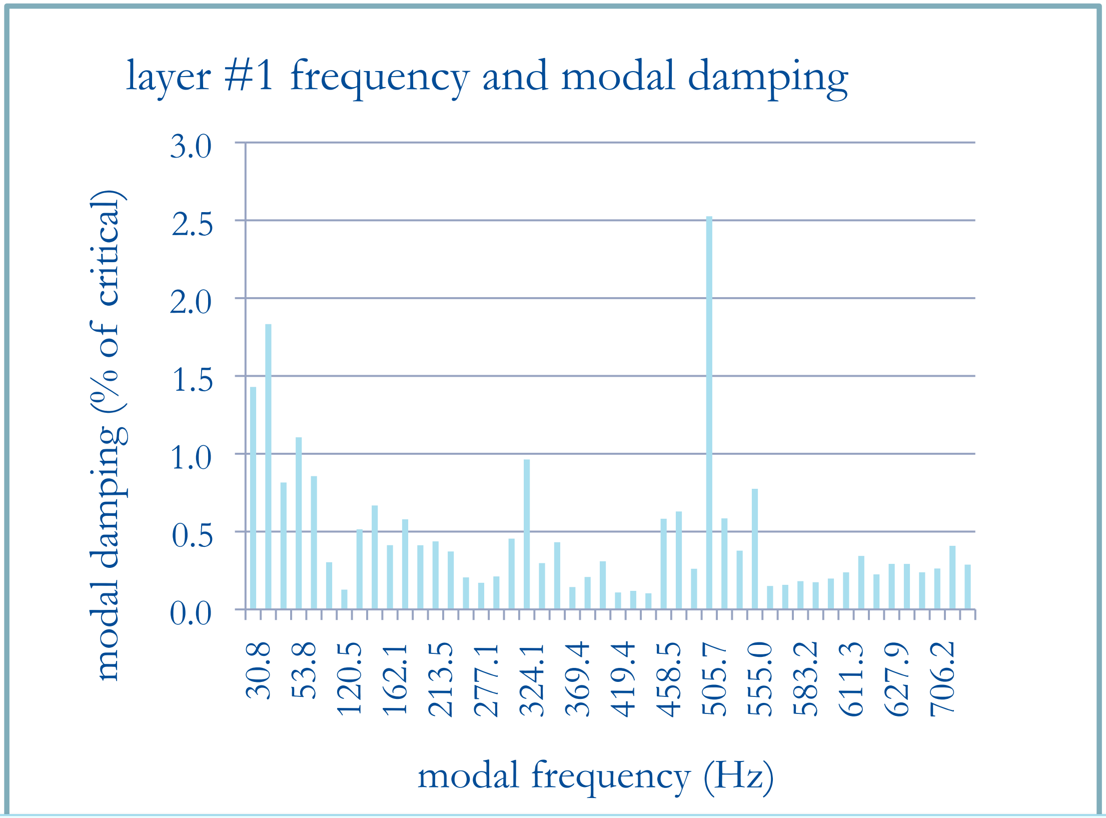
Sorting Out Dynamic Effects



35 Hz Mode Animation from Modal Testing



Results of modal testing: resonant frequencies & modal damping: layer #1 (Outer-most conductor layer, beam left)



Note: Are lightly damped modes of concern (e.g., 120 Hz, 424Hz)?

Need to acquire real horn pulse operation data

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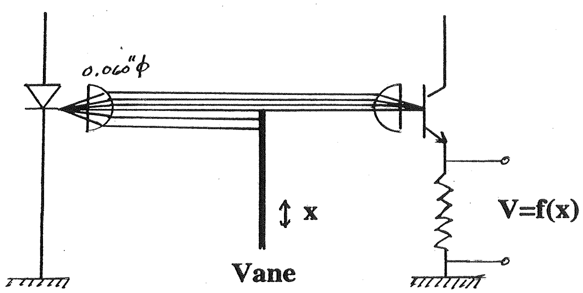
Accelerometer __Cross Check__ with Direct Displacement Non-Contact Transducer -- the Eclipsometer – a dynamic displacement pickup direct measurement of displacement = f(t)

2. Eclipseometer

Non-contact absolute position sensor developed by David Blair (U Western Australia). Further development at CalTech, MIT & Fermilab. (Notes 877-16, 877-37)

Light from a photodiode is detected by a photo-transistor. If the light path is eclipsed by an opaque vane, then the photo-transistor current is a function of the amount of eclipsing by the vane, i.e. the position of the vane in the light path.

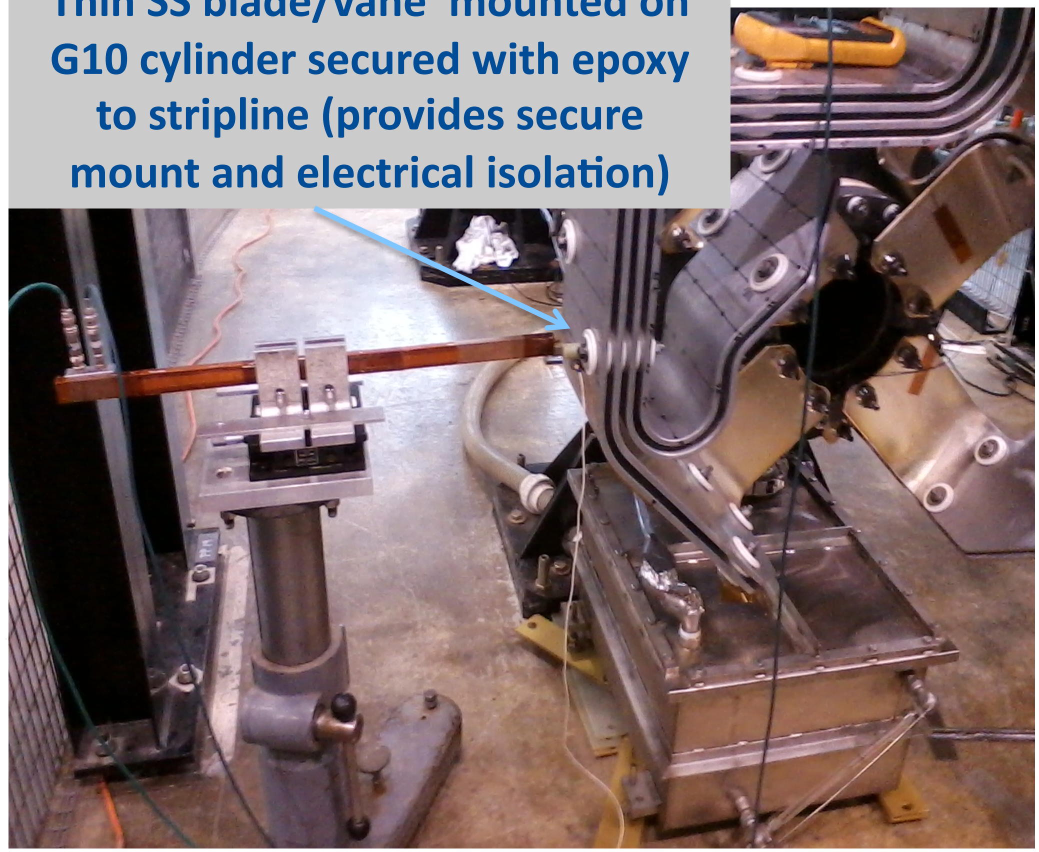


8506
GaAs
IR Photodiode

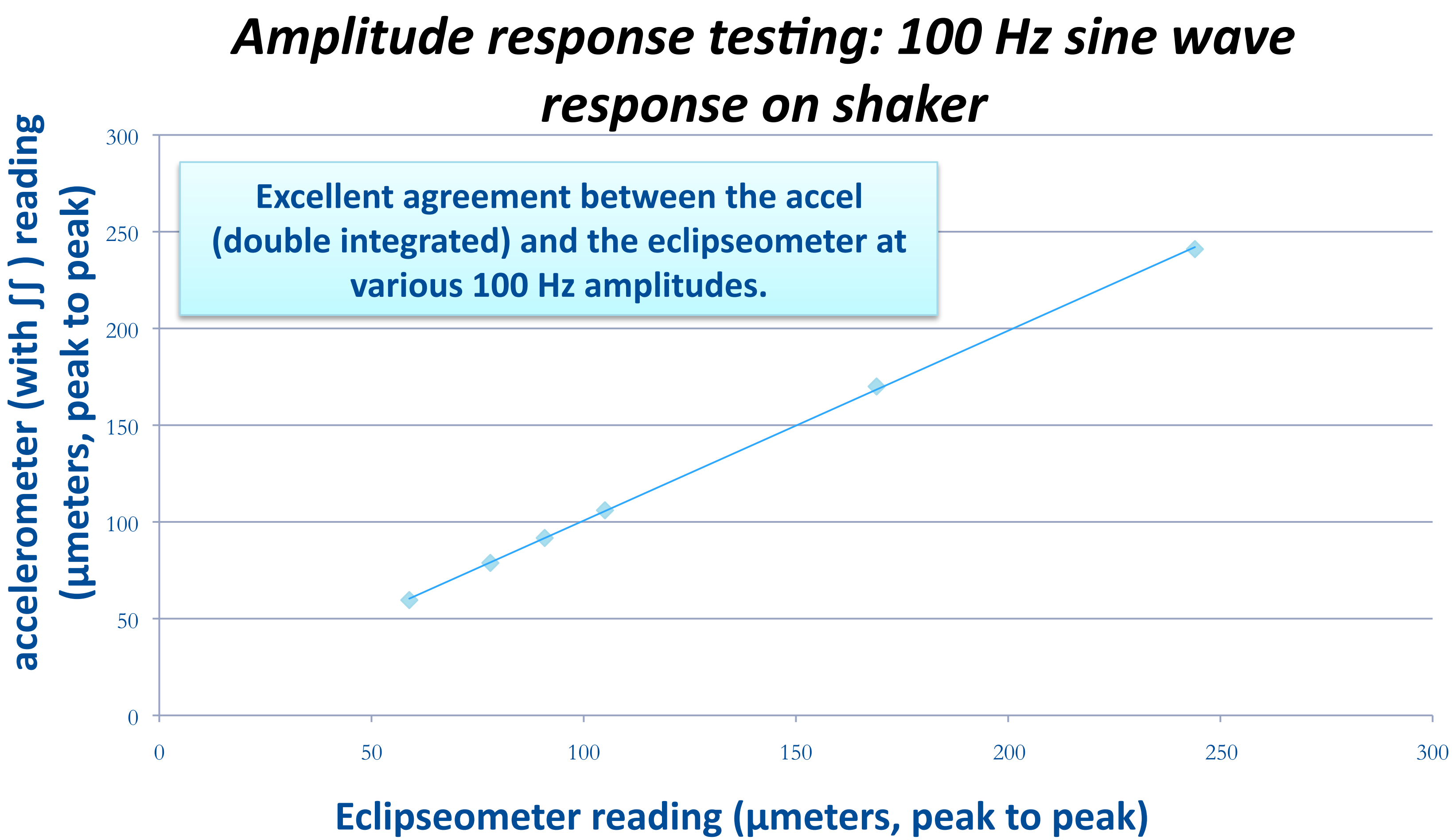
8406
matched
Photo-transistor

__Courtesy of Dr. Frank Nezrick__

Thin SS blade/vane mounted on G10 cylinder secured with epoxy to stripline (provides secure mount and electrical isolation)



Performance Benchmark of Eclipseometer with the Calibrated Electrodynamic Shaker/Amplitude Response



Typical Test Setup for Accelerometers: Used for Live Horn Pulse Comparison of ∫∫Accel vs. Eclipseometer

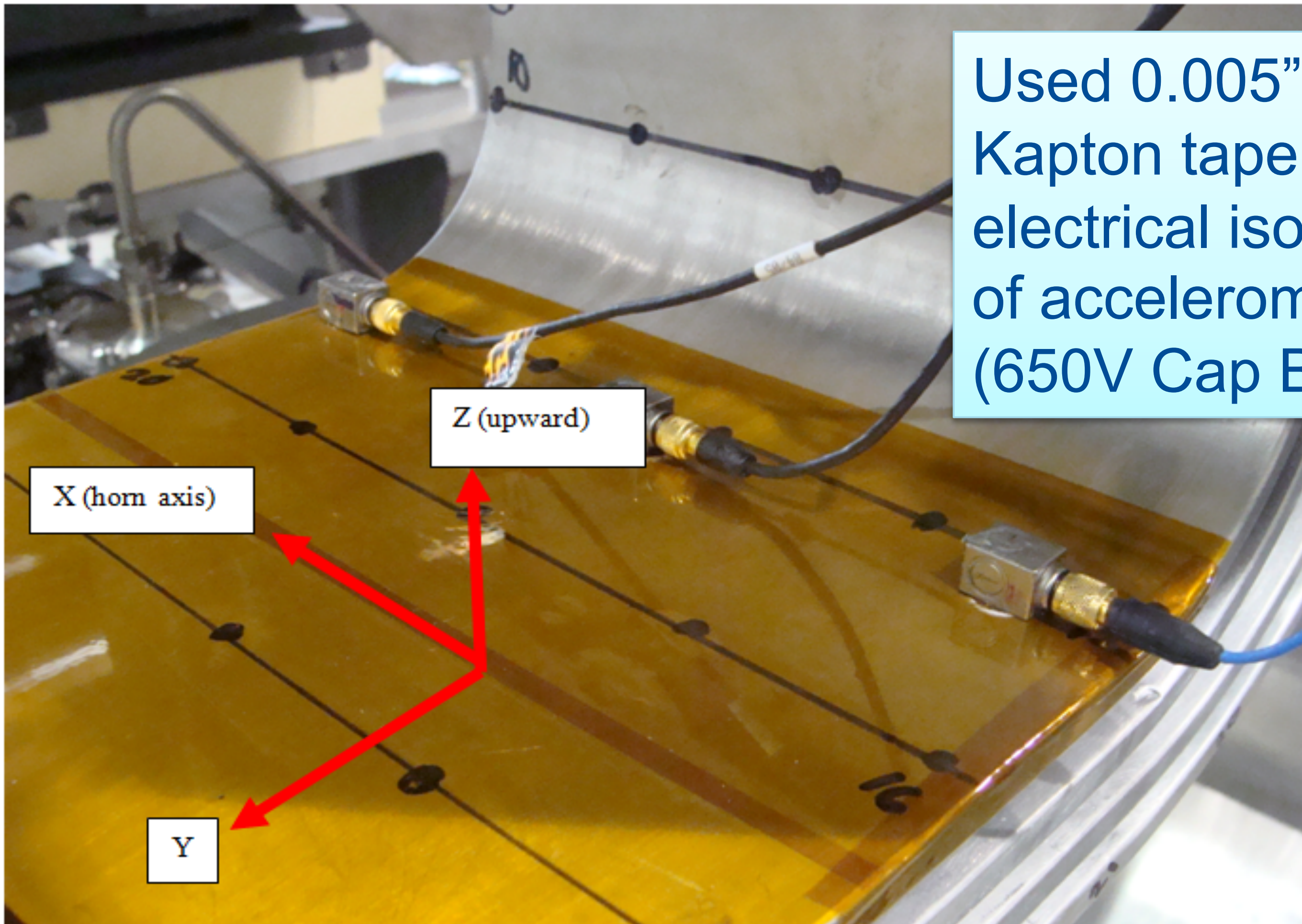
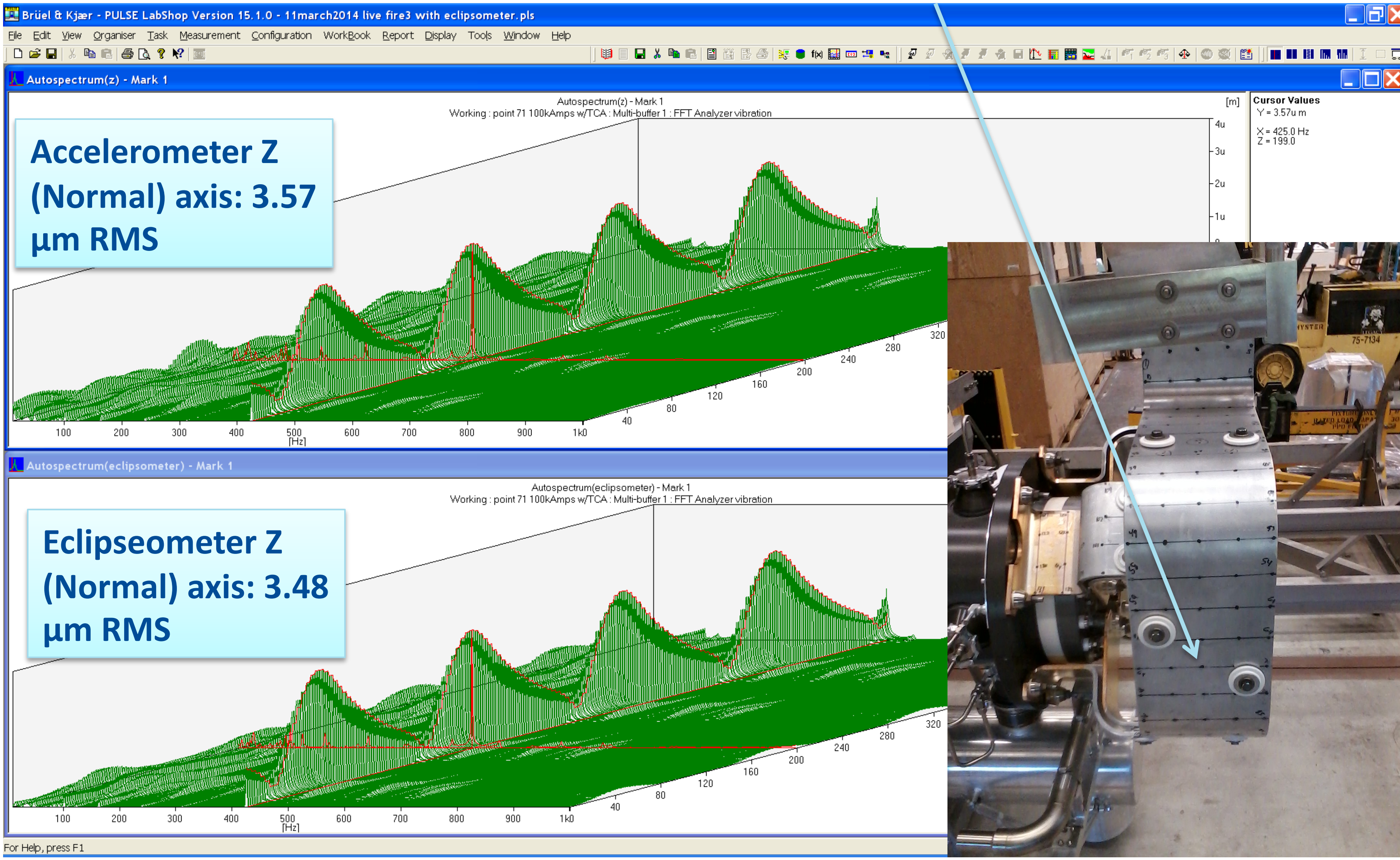


Figure 1 - typical triax mounting and reference directions.

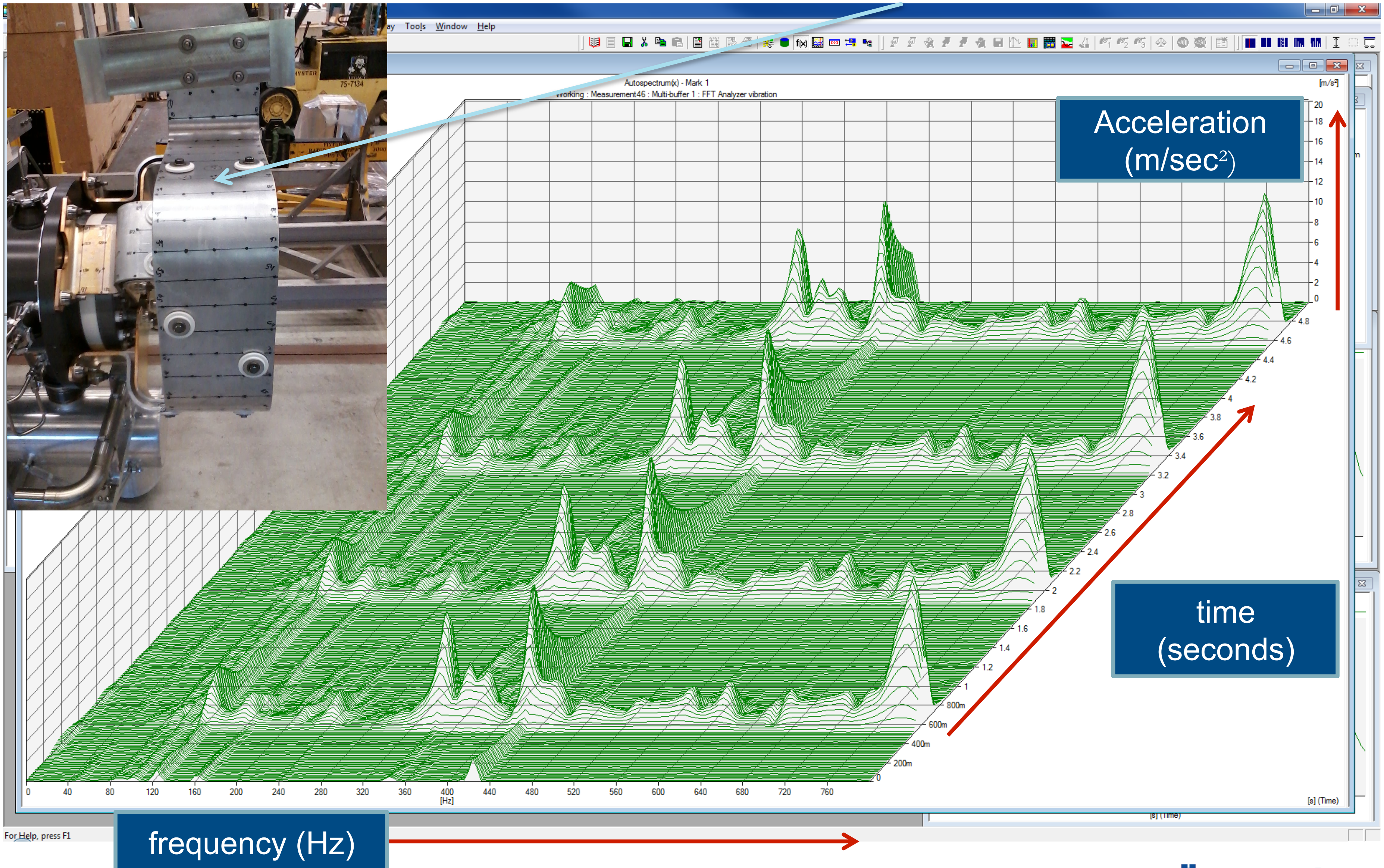
Used 0.005” thick Kapton tape for electrical isolation of accelerometers (650V Cap Bank)

Live fire comparison of ∫∫accel vs. Eclipseometer- 100 kA

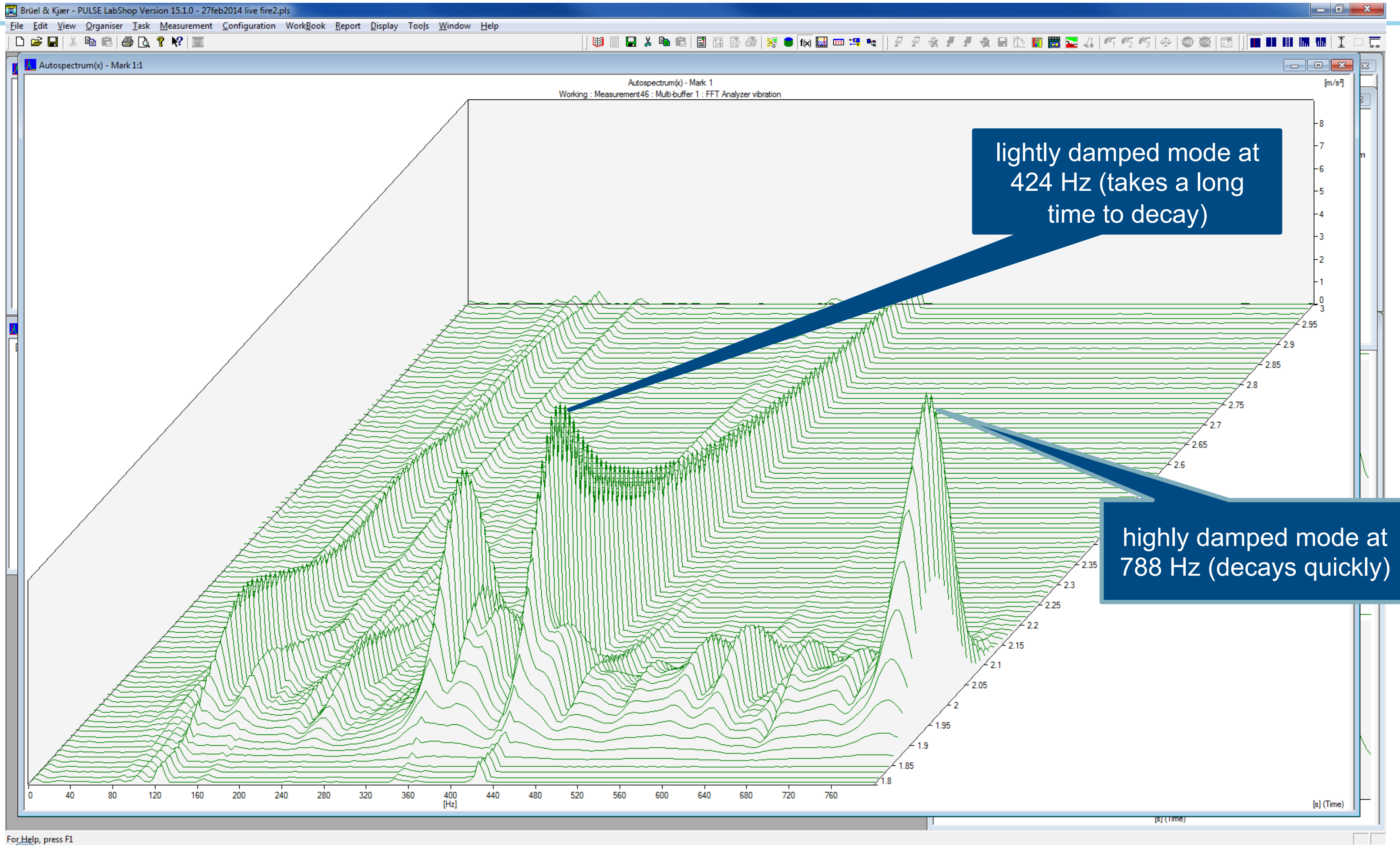
Plot Slice at 424 Hz - (Measurement location 71)



Live Fire Operating Motion –Typical data – 200 kAmps, 1.33 Hz repetiton rate, modal measurement location 46



Live Operating Motion –Expanded time scale – 200 kA, 1.33 Hz repetition rate, Modal measurement location 46



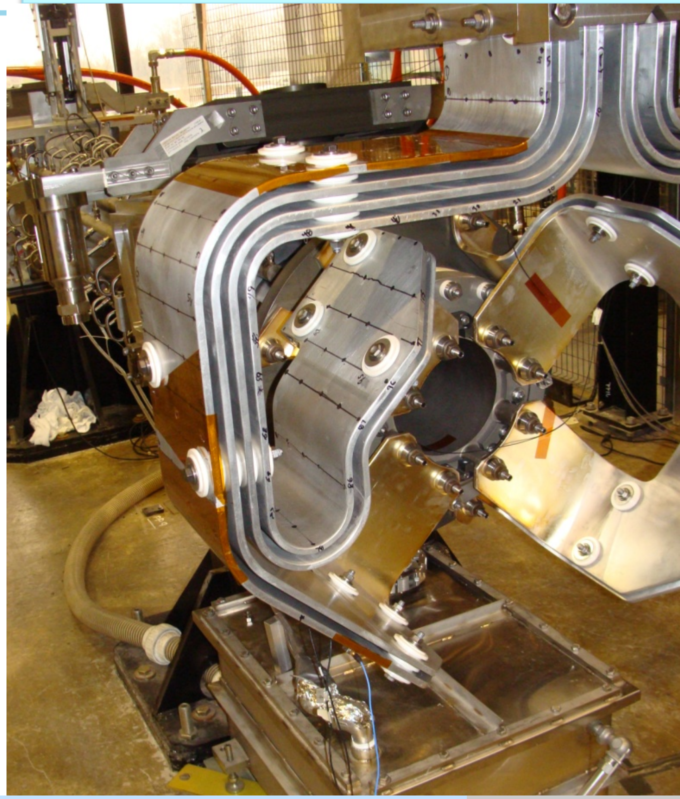
Time axis expanded to show t=1.8 sec to t=3.0 sec. One can see that some modes of vibration "ring down" faster than others. This is due to the variation in modal damping for the modes.

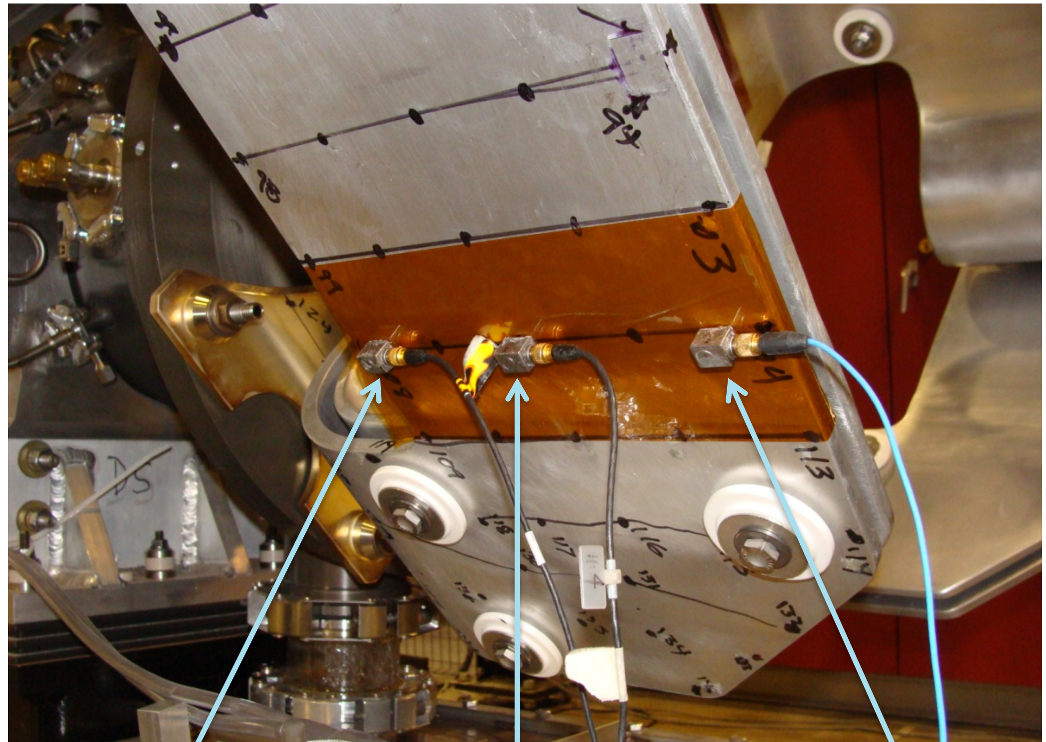
Sample data reduction to calculate total displacement

- Double integrate acceleration in all three directions
- Calculation a vector sum of the 3 orthogonal directions
- Convert from RMS to peak to peak by multiplying by (2*√2), assumes sinusoidal motion
- Use resulting total max displacement of 30.21μm for stress/strain calculations

	RMS displacement	P to P displacement
X1	*3.30*	*9.31*
Y1	*5.00*	*14.10*
Z1	*8.88*	*25.04*
vector total	***10.71***	***30.21***

Test #6: Accelerometer locations @ position of maximum measured displacement

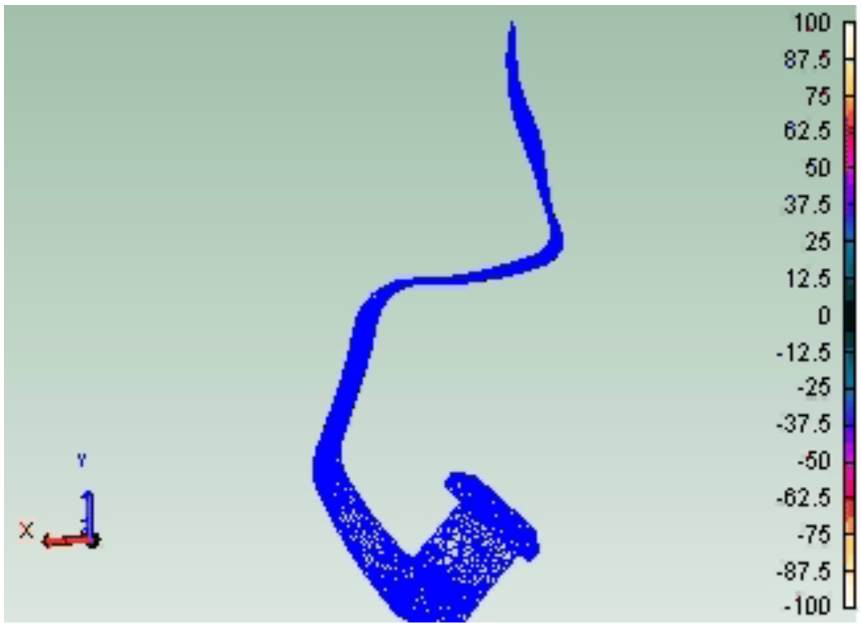


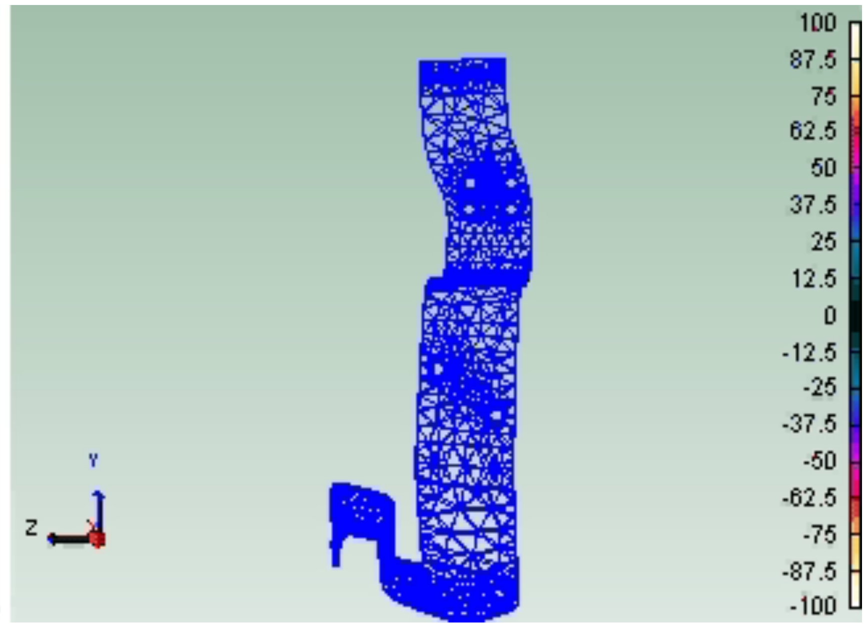


These values are the 20 Hz to 1600 Hz total peak to peak displacement in milli-inches

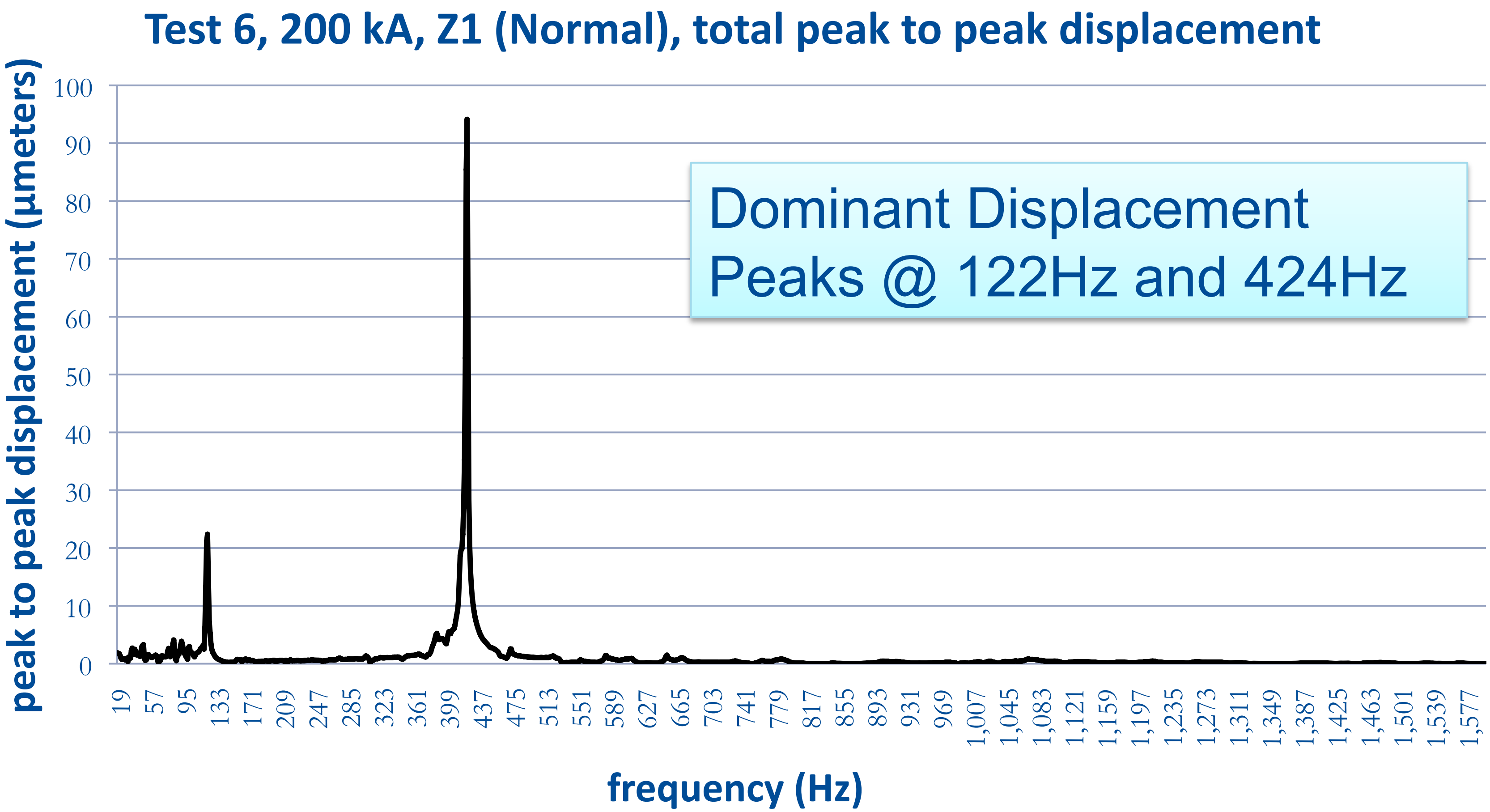
		vector sum X1, Y1, & Z1	vector sum X2, Y2, & Z2	vector sum X3, Y3, & Z3
test6	50 kA	***0.597***	***0.623***	***0.562***
	100 kA	***1.845***	***2.032***	***1.583***
	200 kA	***5.869***	***6.462***	***5.002***

Mode Shape Animation Stripline layer #1 Mode Shape 424 Hz

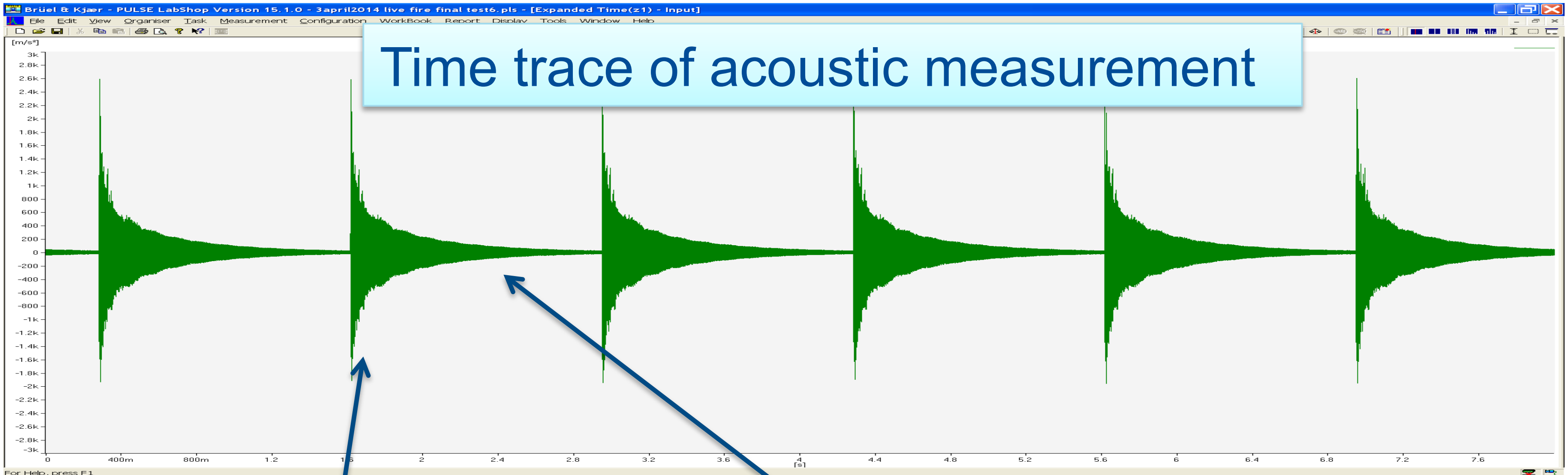




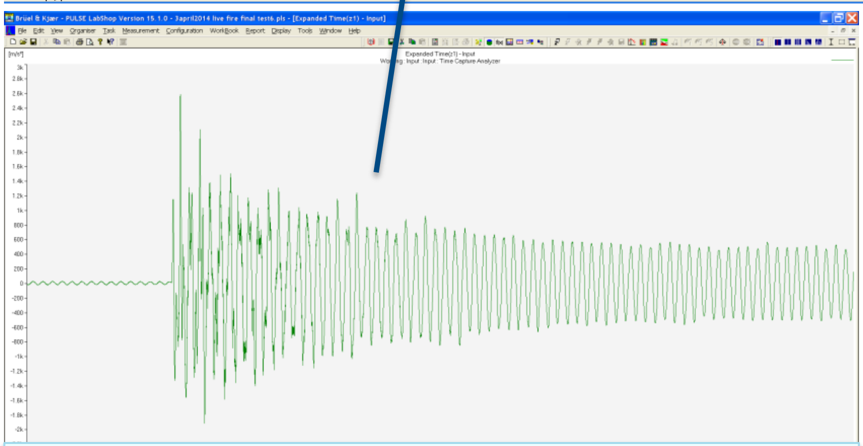
Spectrum of Motion @ test #6 locations



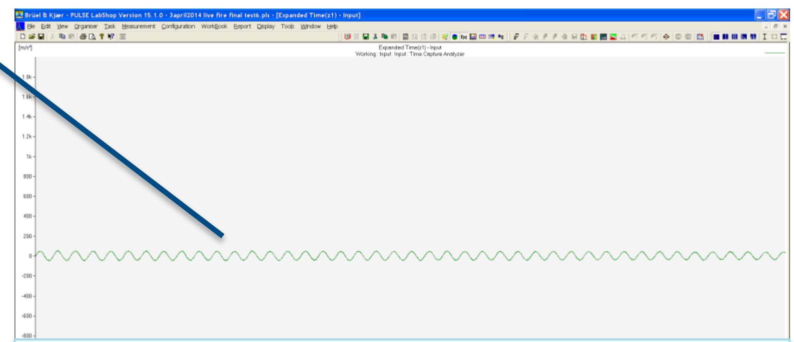
Acoustic Signature Cross-Check



Time trace of acoustic measurement



Expansion of initial portion of ring-down showing contribution of highly damped modes



Expansion of final portion of ring-down showing contribution of a single lightly mode (424Hz)

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Conclusions

- The stripline is a complex structure with multiple unique boundary conditions and large variations in modal damping
- Under pulsed operation, conductor motion generally increases with current level but does not closely follow the Lorentz force relationship for the simple case of parallel current carrying conductors, i.e. displacement ≠ $f(I^2)$
- The modal analysis results identified low frequency modes in the range of 30 to 80 Hz
  - These modes were of concern due to their potential to cause large deflections
  - It was found that the 850µsec MI-8 horn test stand pulse is too short to "wake-up" the low frequency modes
  - Longer pulse widths may result in more low frequency modal participation; determination requires testing and/or detailed modeling
- NOvA 700kW horn 1 pulsed operation displacements tend to be dominated by two lightly damped modes at 122 and 424 Hz.

Conclusions

- **Largest motion measured during pulse operation roving with 3 triaxial accelerometers across conductor was measured during pulsed operation Test #6 in the vicinity of modal test points 70 thru 74 (*lower beam-right stripline flag*) and is normal to stripline with peak to peak displacements of 140 to 160 µm**

- **Acoustic measurements support the previous conclusions**

- **Since the 424 Hz mode is very lightly damped it requires further investigation if cycle time is decreased from 1.33 sec to 0.8 sec as proposed for LBNF operation**

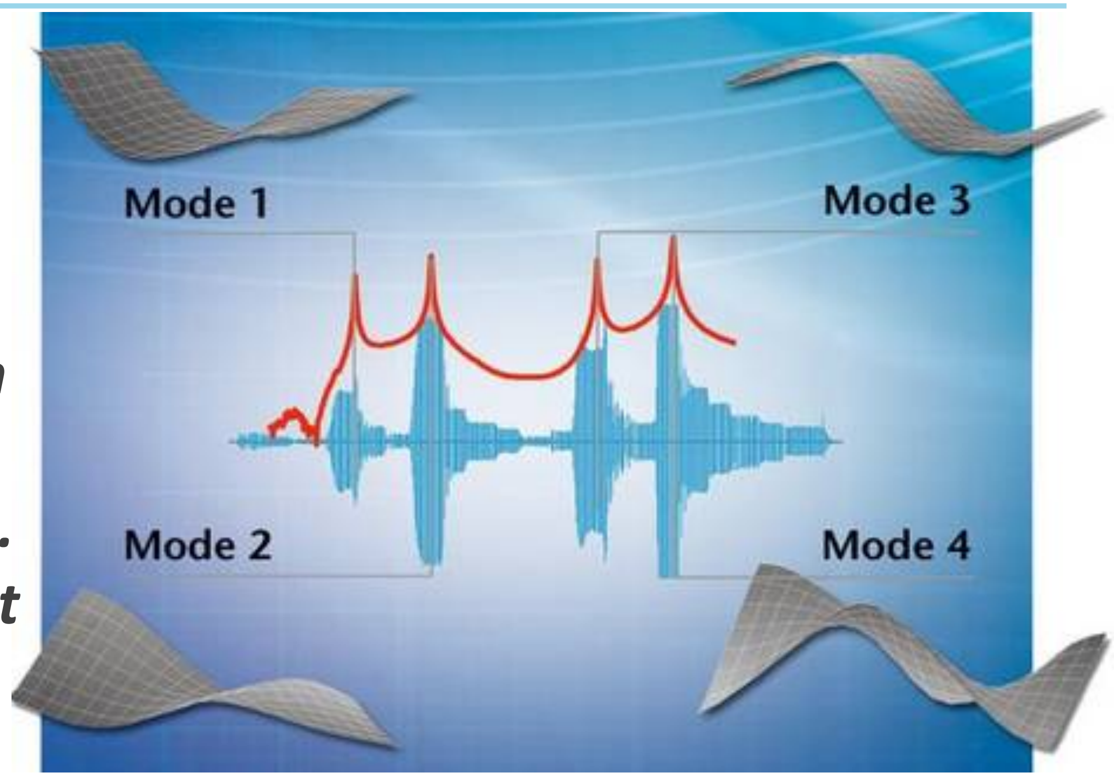
Future Work

- Make an assessment of stress and resulting fatigue life based on the measured displacement data.

- Continue investigation of the relationship between pulse width and cycle time and stripline dynamic response.
  - *Narrow pulse width does not appear to excite low frequency modes*
  - Lightly damped modes coupled with short cycle time would tend to result in larger response due to building of response
  - Investigate Laplace transform model to further understand pulse width effect on stripline motion

- An extensive amount of data was acquired in addition to the subset presented herein. Raw time series have been archived for all measurements and are useful for further detailed analysis. These series are available in UFF and MATLAB formats.

Fundamentals of Normal Mode Testing



A swept sine forcing is applied to the rectangular plate. The plate response is presented in the time domain (blue trace) and in the frequency domain (red trace). If the response is measured at a number of points on the plate (i.e., a grid) one can easily extract the 4 modes shown above by comparing magnitude and phase of the response functions.

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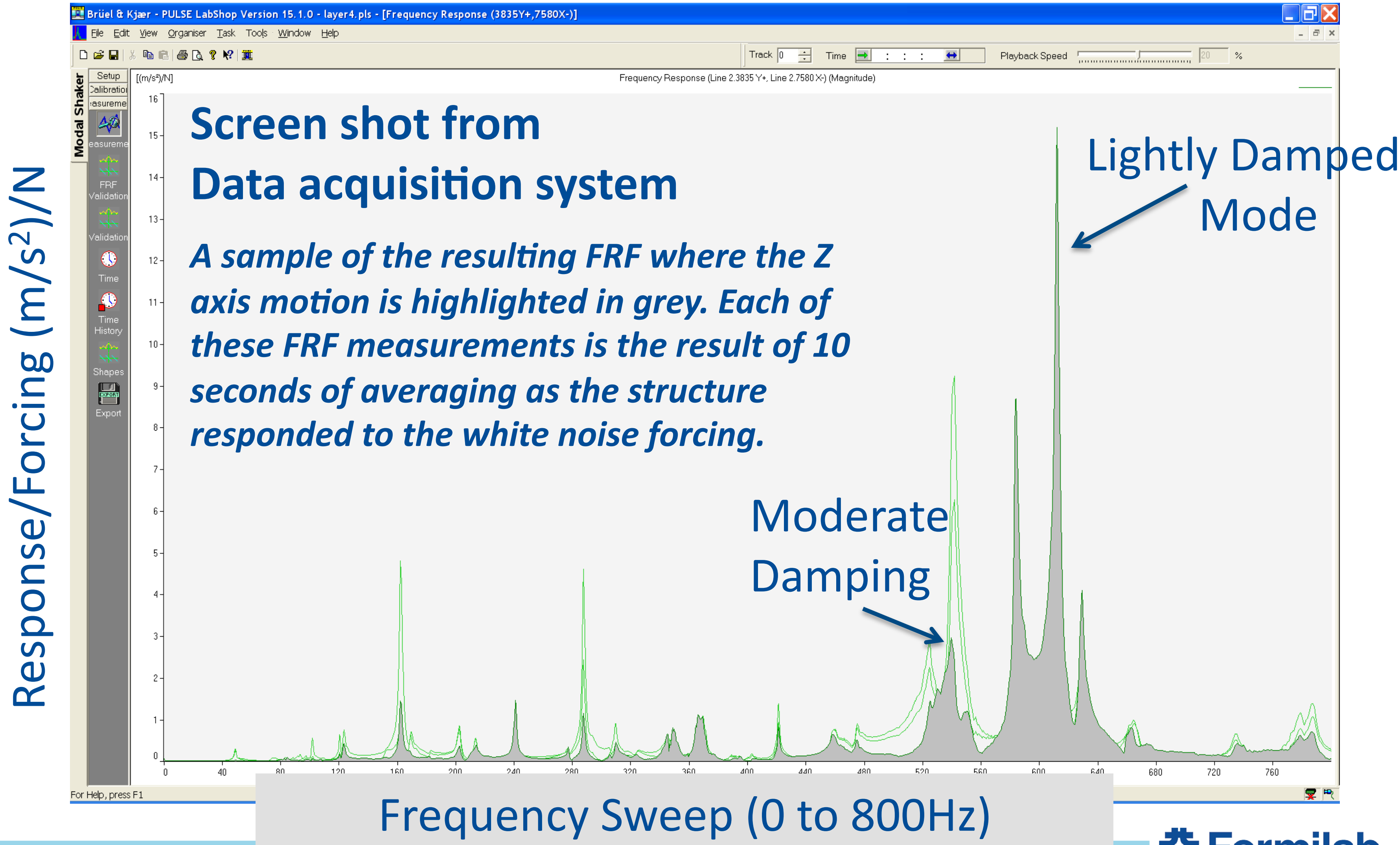
Typical Output of Modal Frequency Response Function

Screen shot from Data acquisition system

A sample of the resulting FRF where the Z axis motion is highlighted in grey. Each of these FRF measurements is the result of 10 seconds of averaging as the structure responded to the white noise forcing.



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Backup: Live Operating Motion- Displacement data by test#

		vector sum X1, Y1, & Z1	vector sum X2, Y2, & Z2	vector sum X3, Y3, & Z3
test1	50 kA	2.6	2.7	3.8
	100 kA	7.8	8.4	8.7
	200 kA	29.1	31.5	31.9
test2	50 kA	5.1	4.6	6.1
	100 kA	11.6	12.0	13.9
	200 kA	40.3	42.1	51.8
test3	50 kA	5.4	4.9	6.5
	100 kA	10.1	10.4	11.5
	200 kA	30.1	33.3	33.8
test4	50 kA	4.9	5.7	6.4
	100 kA	11.5	15.5	12.6
	200 kA	28.0	47.6	29.9
test5	50 kA	6.7	7.4	7.3
	100 kA	14.7	19.5	13.2
	200 kA	43.7	62.9	36.0
test6	50 kA	15.2	15.9	14.3
	100 kA	46.9	51.7	40.3
	200 kA	149.3	164.4	127.3
test7	50 kA	5.6	5.7	6.4
	100 kA	13.5	13.8	14.2
	200 kA	48.9	49.7	55.2
test8	50 kA	3.5	3.6	3.9
	100 kA	9.6	11.1	19.3
	200 kA	34.4	46.2	40.7

these values are the 20 Hz to 1600 Hz **total peak to peak** displacement in micro-meters, by direction, with vector sums added. Red values are the largest motion seen.

164.43 micro meters peak to peak = about 6.4 milli-inches peak to peak

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