Structural Dynamic Techniques, Autonomy, and Laser Doppler Sensors for Environmental Testing

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Special Thanks:

- Dr. Sathya Hanagud (PhD Advisor), Aerospace Engineering, Georgia Tech
- Dr. Brian Glass (DAME Project, PI), NASA Ames Research Center
- Andy Rose (Supervisor), Environmental Test Lab, JPL

Outline

- PhD Research
  - Motivations and background
  - Thesis objectives and approach
  - Formulation and integration
  - Field tests and validation
- Relevance to environmental testing
- Future work

Motivation

- Planetary exploration
  - Search for life on Mars
  - Space drills aboard unmanned vehicles
- Space drilling is complex & unpredictable
  - Rugged operating environment
  - Hard to predict subsurface conditions
  - Low available power (~100 W)
  - Earth-based direction not practical
- Autonomous fault diagnostic system
  - Structural health monitoring techniques

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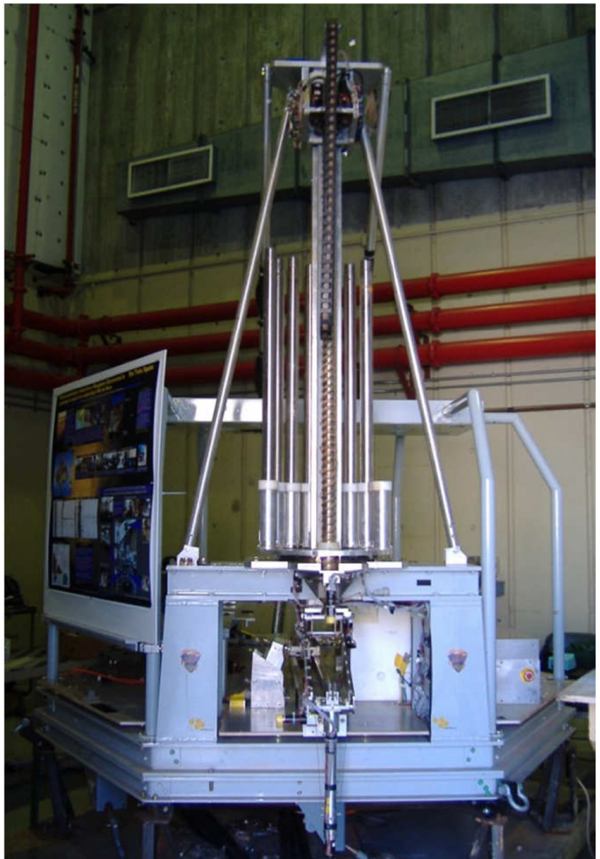
Drill Prototypes for Mars Exploration



MARTE Drill

DAME Drill

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Thesis Outline

- What is SHM?
- Design Requirements
  - Little to no interference with drilling operation
  - Continuous monitoring of the drilling condition
  - Complete autonomous operation
- Thesis Objectives
  - Design, develop, and field test automated SHM technique for rotating structures with specific application to space drilling

Thesis Approach

- Complete modal analysis experiments
- Develop harmonic excitation signal filter
- Formulate structural dynamic models
- Train and implement Neural Networks
- Formulate automation procedure
- Field test and validate SHM method

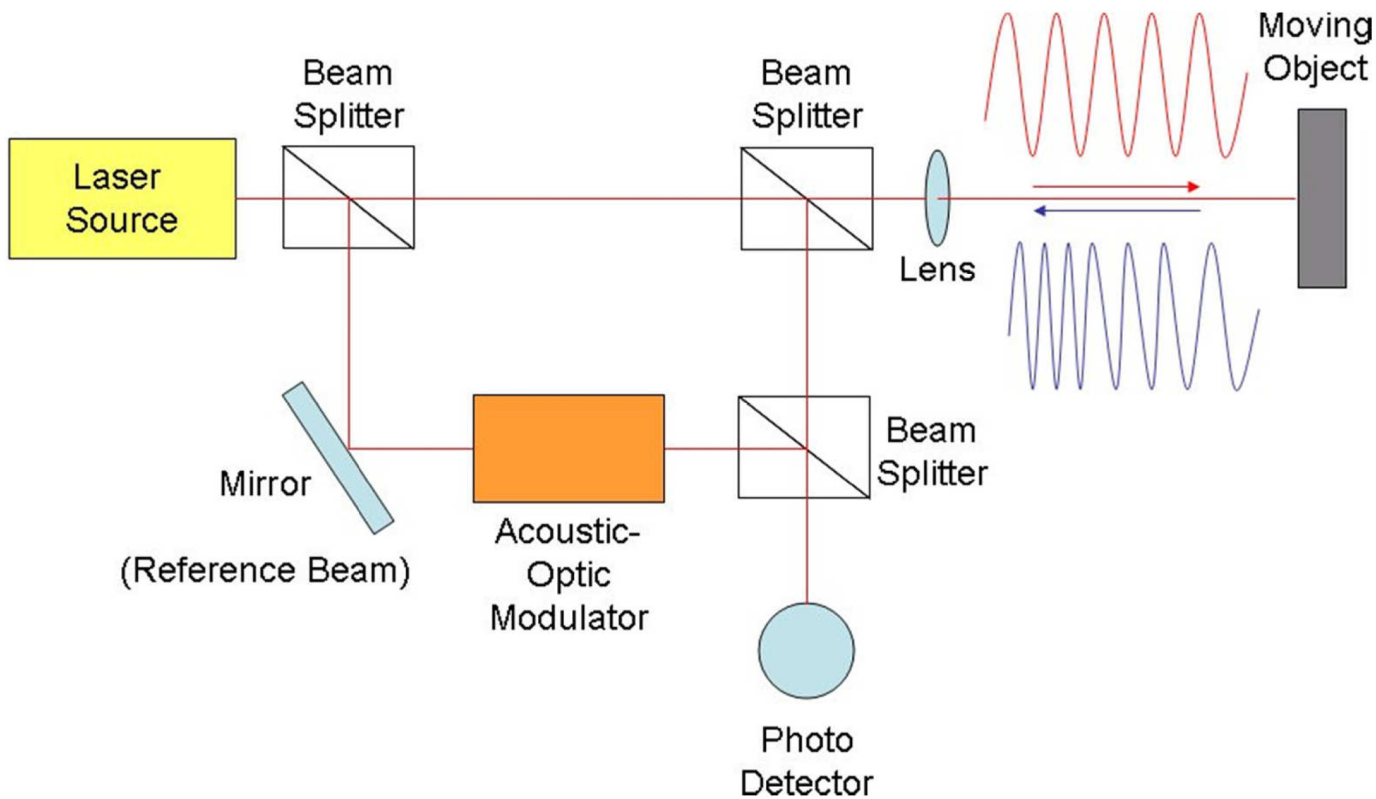
Modal Analysis Experiments

- Purpose
  - Understand dynamics of drill system
  - Base-line for analytical models
  - Validate use of LDV sensors
  - Validate drill motor system as internal exciter
- Experiments completed
  - Stationary (no operation)
  - Rotating in place
  - Nominal drilling

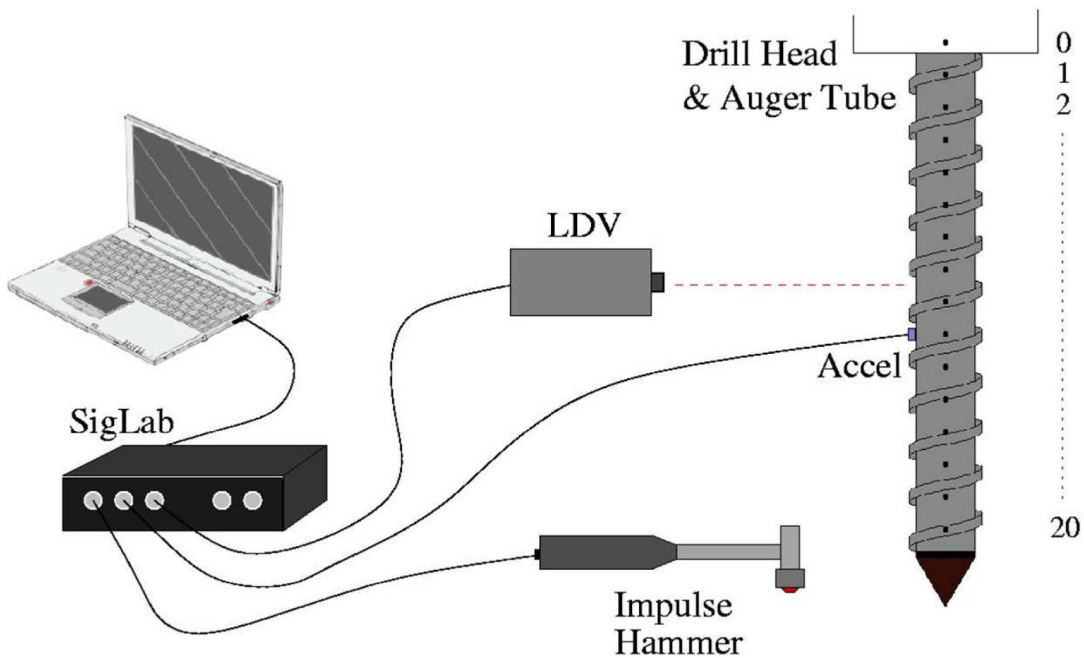
Laser Doppler Vibrometer Sensors

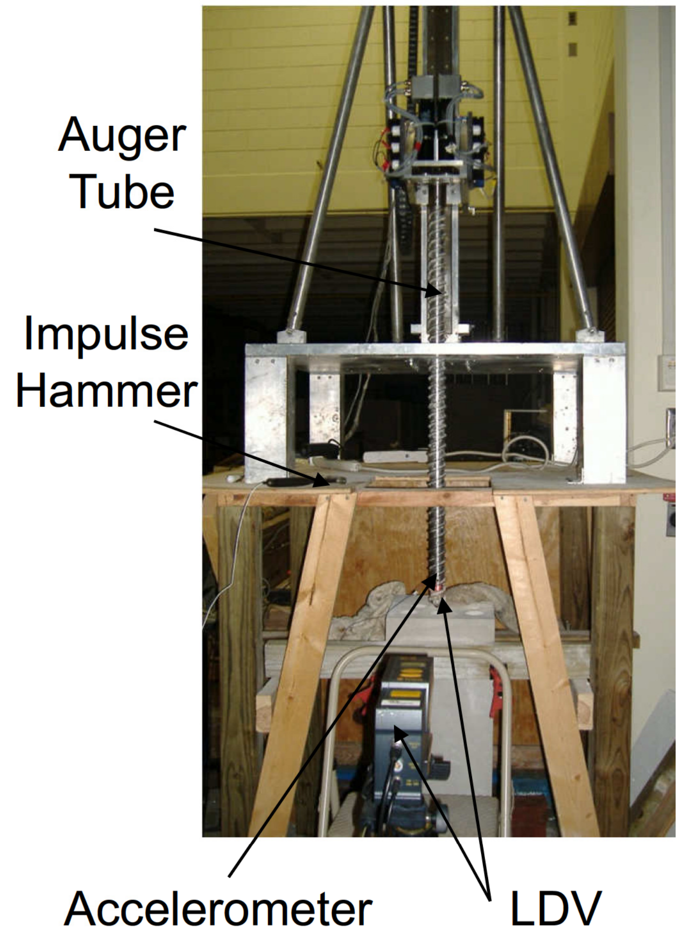
- Laser Doppler Velocimetry (LDV)
  - Measure velocity along laser line-of-sight
  - Doppler effect
- Significance for drilling application
  - “Remote” measuring device
  - Position flexibility
  - Do not require internal bus-lines
  - No added mass effects

Laser Doppler Vibrometer Sensors

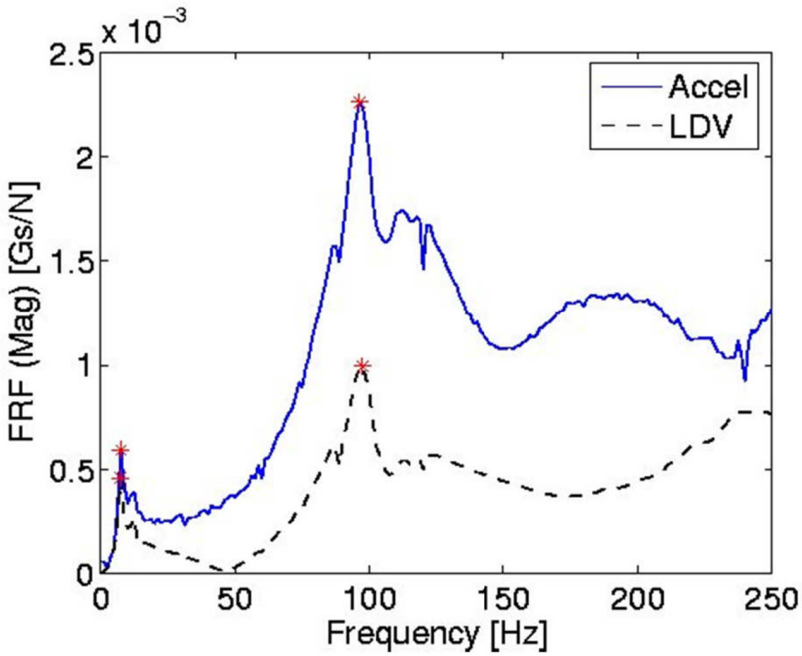


Experimental Setup

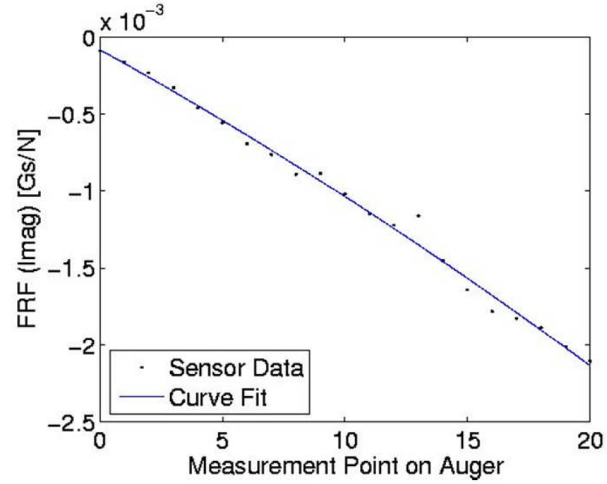




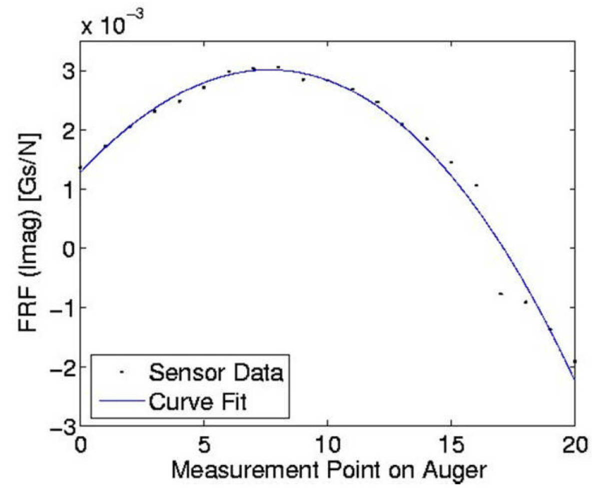
Stationary Experiments



Sample FRF of
Stationary Drill Response



First Mode Shape



Second Mode Shape

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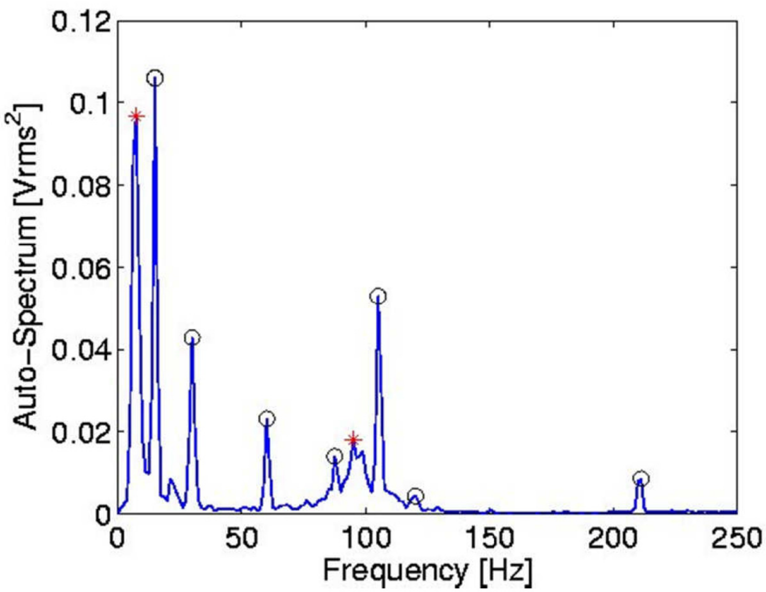
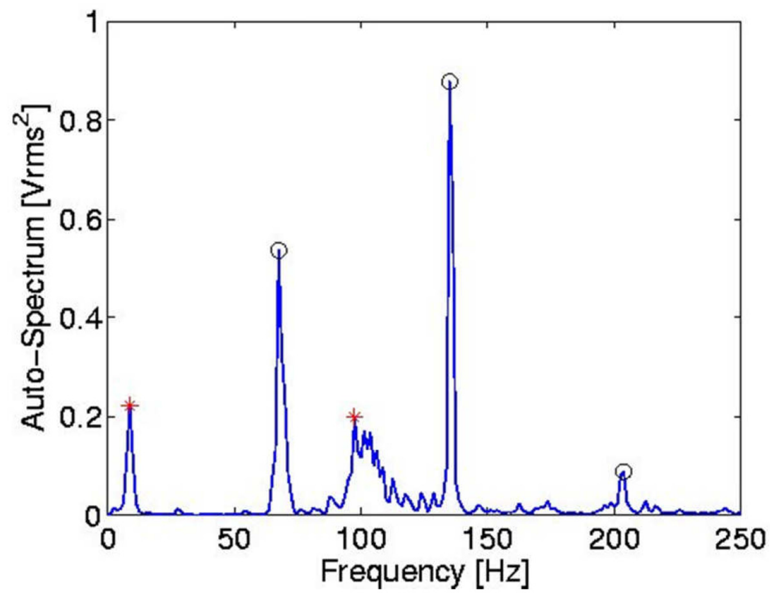
Rotating Experiments



Sample Auto-Spectrum: Auger Rotating at 10 RPM



Sample Auto-Spectrum: Auger Rotating at 45 RPM

*Natural Frequencies, °Harmonic Frequencies

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Drilling Experiments

- Nominal drilling
  - Nominal drilling parameters
  - Limestone column
  - 1 m & 2 m auger tubes
  - 70 cm final depth
- Stationary embedded auger
  - Measurements every 10 cm

Drilling Experiments

Auger Length (m)	Drill Depth (cm)	1^{st} Mode (Hz)	2^{nd} Mode (Hz)
1	0	9	95
1	10	41	111
1	20	58	119
1	30	71	131
2	30	17	60
2	40	20	61
2	50	23	62
2	60	36	81
2	70	42	94

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Thesis Approach

- Complete modal analysis experiments
- Develop harmonic excitation signal filter
- Formulate structural dynamic models
- Train and implement Neural Networks
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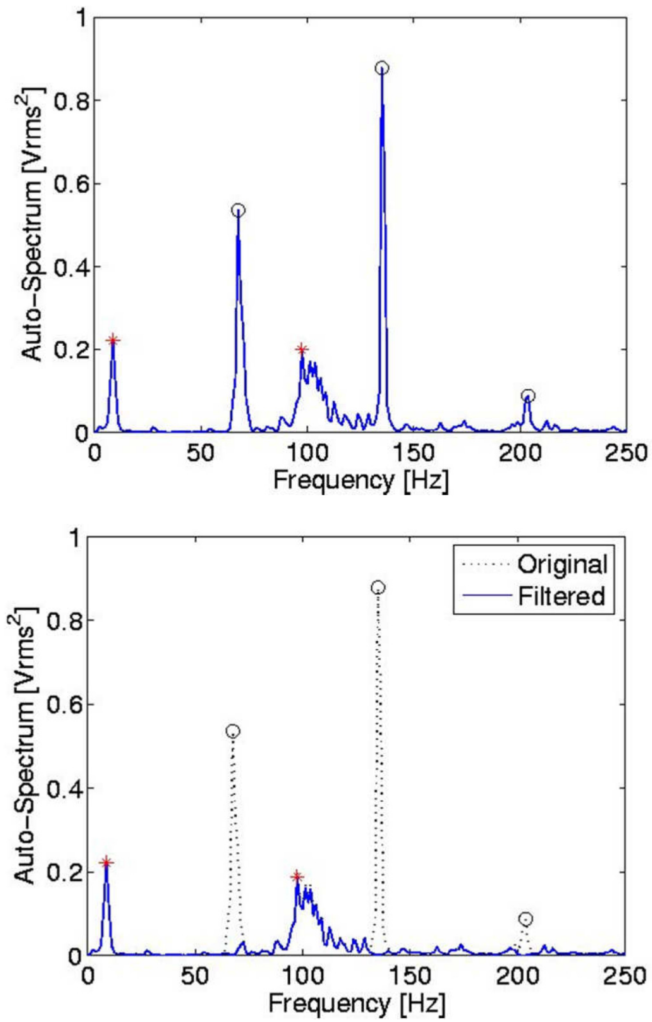
Harmonic Frequency Filter

- Harmonic frequencies
  - Rotating structure
  - Drill gear mesh system
  - Interfere with analysis
- Objectives
  - Determine frequencies
  - Filter frequencies
  - Retain useful data

Auger Rotating at 45 RPM



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Thesis Approach

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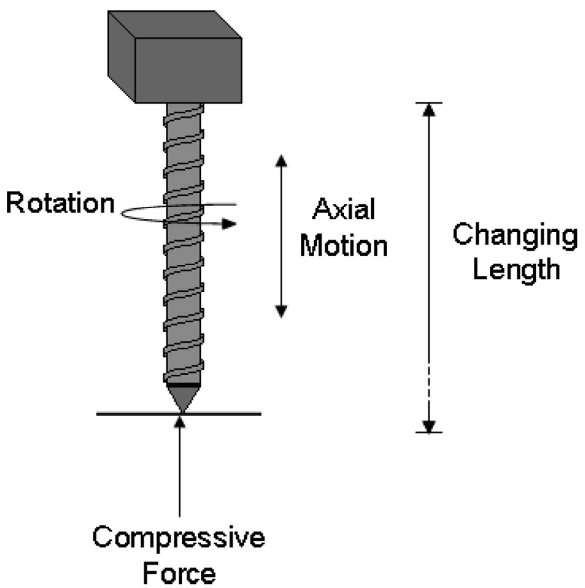
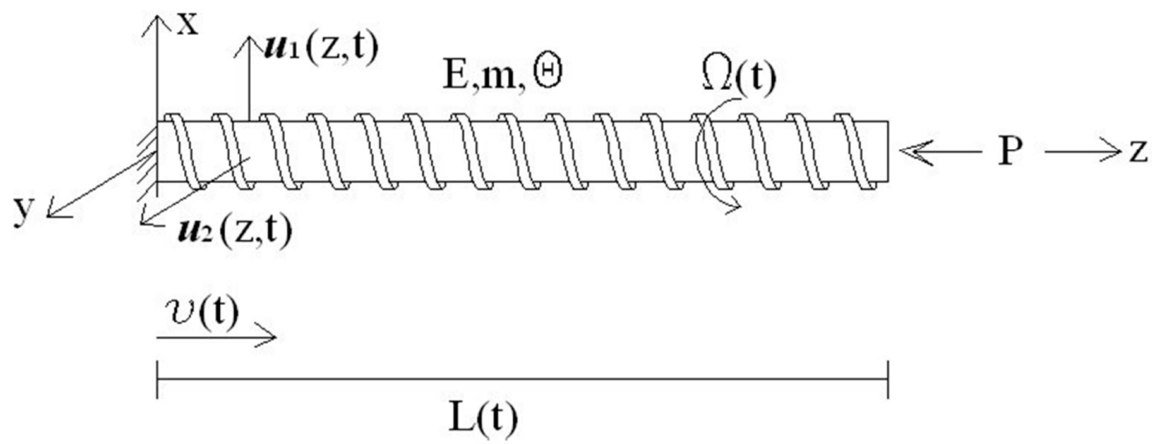
Structural Dynamic Models

- Objectives
  - Develop base model for drill system
  - Simplify through analytical analysis
  - Compare with experimental results
  - Formulate models for all expected drilling conditions
    - Nominal drilling and six drilling fault conditions

Structural Dynamic Models

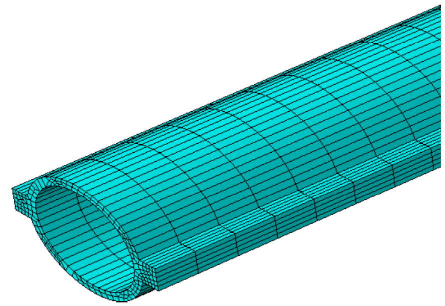




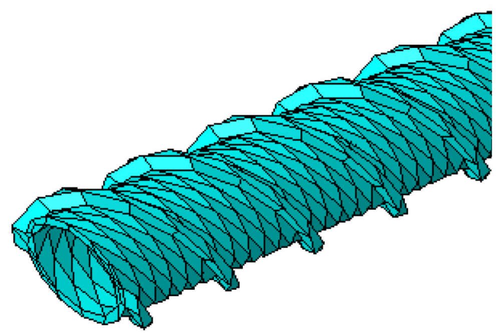
Two-Dimensional Continuum Model of Auger Tube

Structural Dynamic Models

- Analysis of drilling parameters
- Analysis methods
  - Closed-form solutions
  - Numerical methods (Galerkin's Method)
  - Finite Element Analysis (Abaqus)



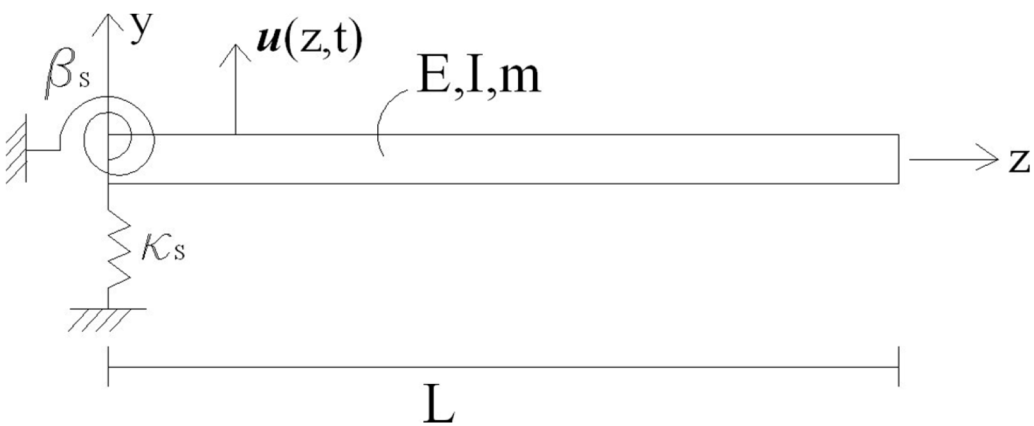
Simplified Geometry

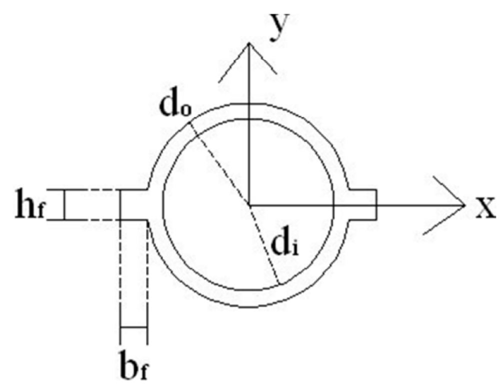


Complex Geometry

Structural Dynamic Models

- Simplified base drill model
- Comparison to experimental results





- Repeat process for all drilling modes

Thesis Approach

- Complete modal analysis experiments
- Develop harmonic excitation signal filter
- Formulate structural dynamic models
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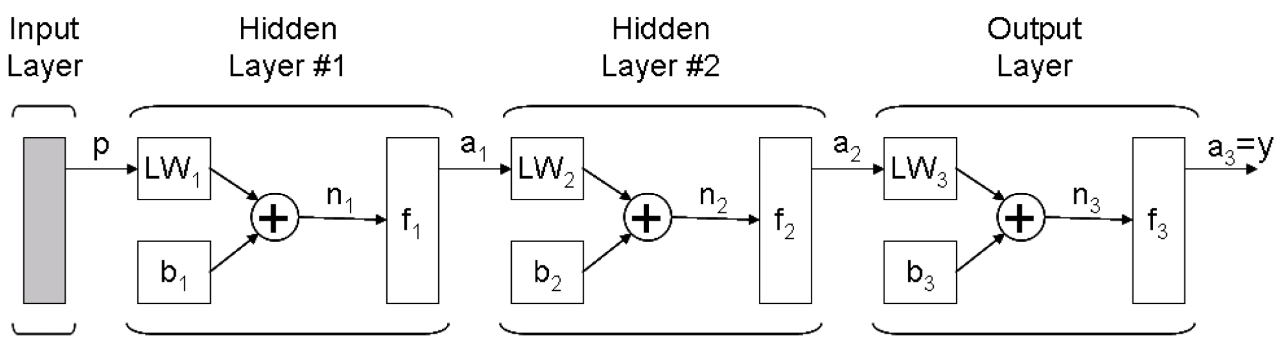
Neural Networks

- Require quick-response diagnostics system
  - Difficult to implement complex models on-line
- Why Neural Networks (NN)?
  - Pattern recognition and function approximation
  - Trained for input → output
  - Use model results to train individual NNs

Neural Networks

- Feed-forward, backpropogation NN
  - *newff* in Neural Network MATLAB toolbox
  - Training database from fault models
  - Trained NNs produce diagnostic results



p = input values

LW_i = weights for layer *i*

b_i = biases for layer *i*

n_i = net input vector for layer *i*

f_i = transfer function for layer *i*

a_i = outputs for layer *i*

y = network output

Thesis Approach

- Complete modal analysis experiments
- Develop harmonic excitation signal filter
- Formulate structural dynamic models
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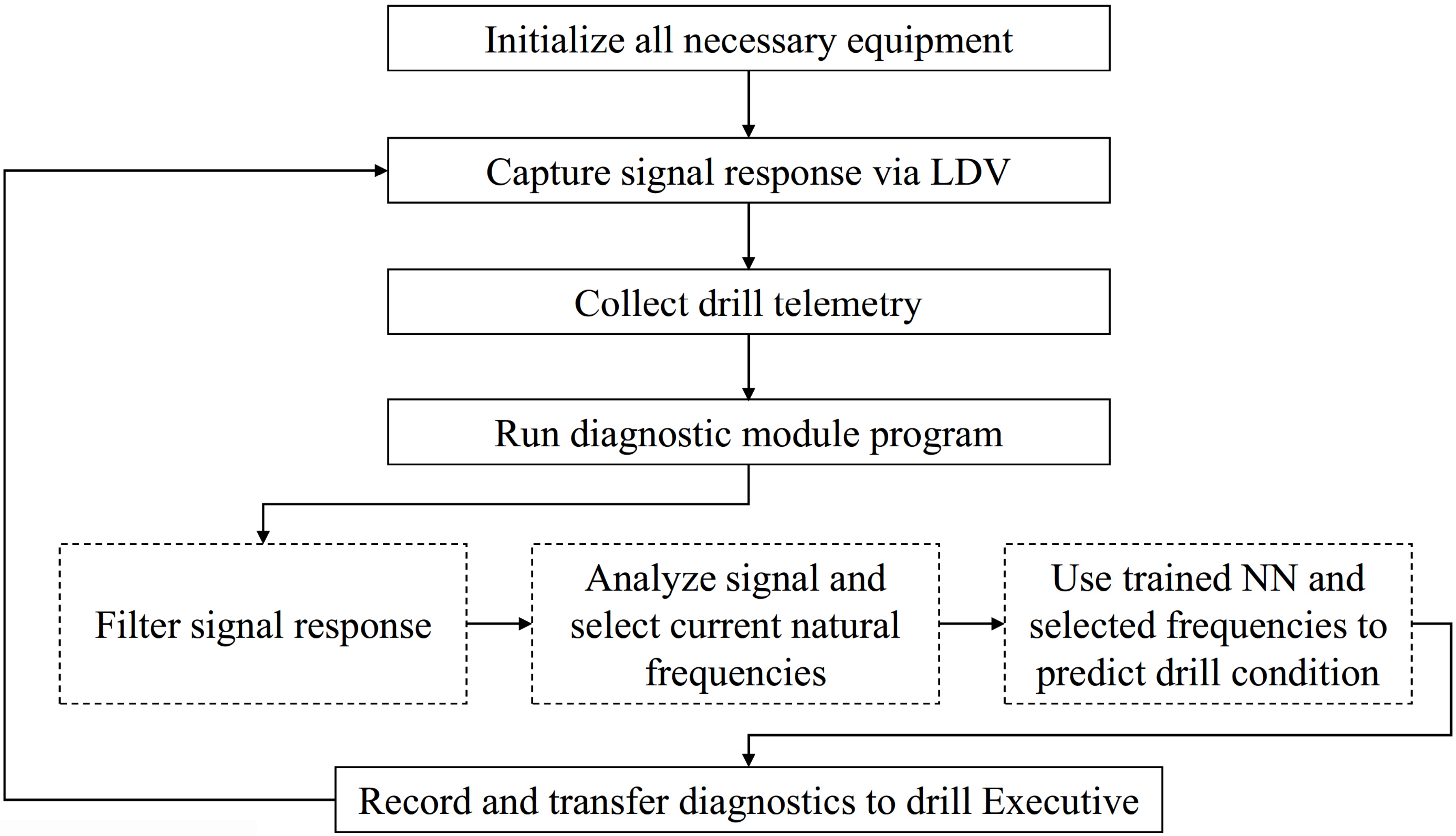
- Formulate automation procedure
- Field test and validate SHM method

Automation Procedure & Integration



Thesis Approach

- Complete modal analysis experiments
- Develop harmonic excitation signal filter
- Formulate structural dynamic models
- Train and implement Neural Networks
- Develop automated signal analysis algorithm
- Integrate and automate components
- Field test and validate SHM method

Field Testing & Validation

- Haughton Crater, Devon Island
  - Mars-analog site
  - Subsurface ice and permafrost
  - July 2006, July 2008
- JPL, California
  - Blind drilling tests
  - Demonstrate repeatability
  - October 2007

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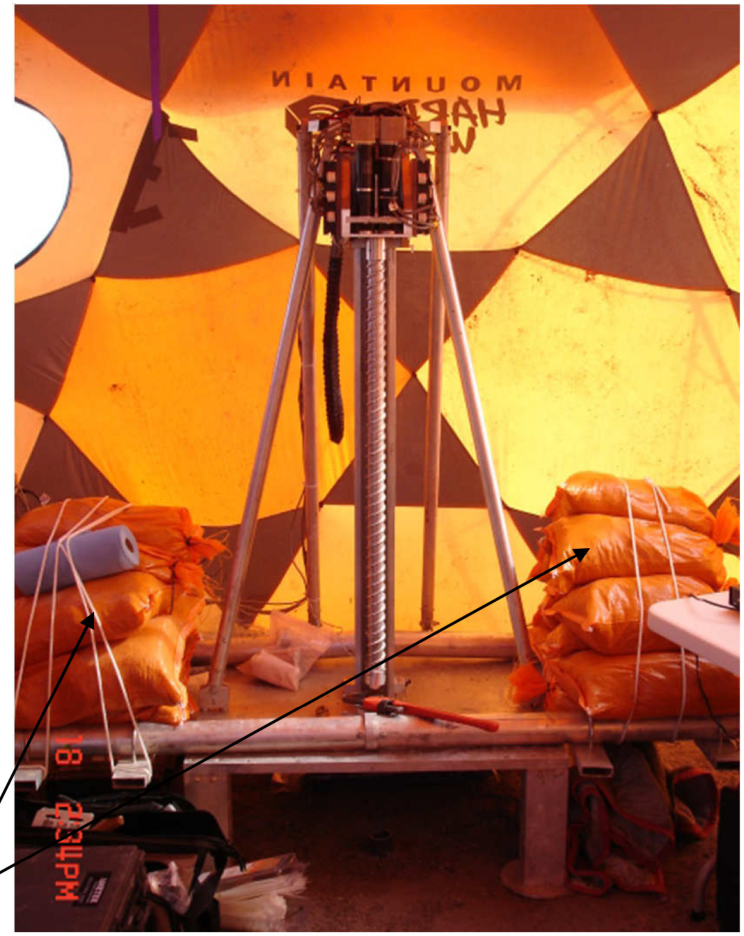
Field Testing & Validation (2006)

2006 Drill Site: Drill Hill



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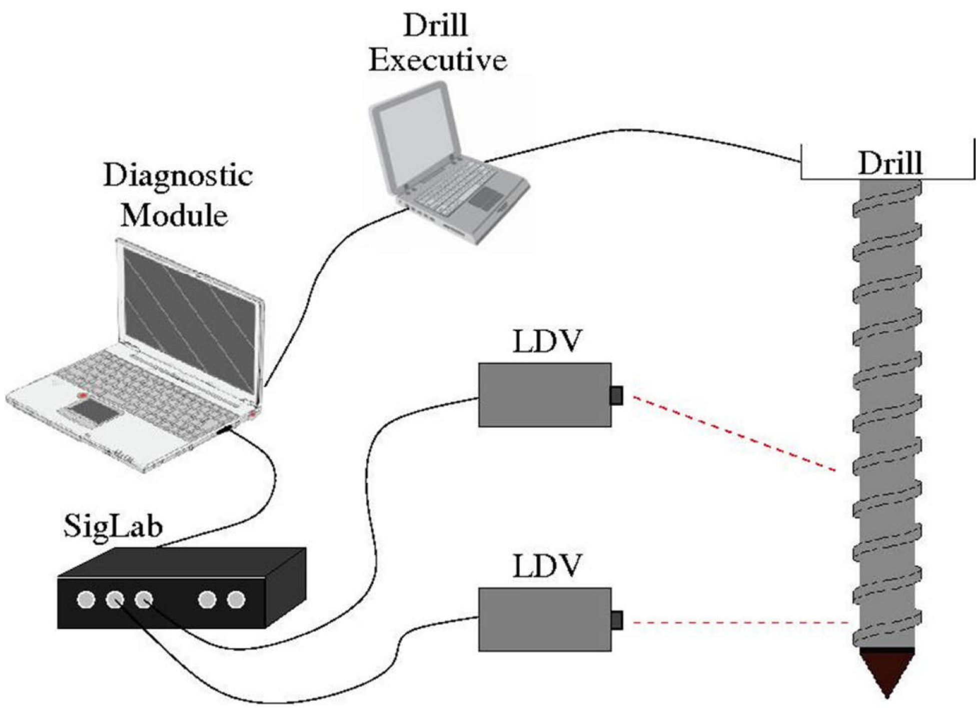
Field Testing & Validation (2006)



LDV Set-up for

2006 Field Test

Field Testing & Validation

- Results
  - All field test objectives were met & exceeded
  - Demonstrated over 100 hours of continuous hands-off drilling
  - 3.22 m depth on Devon Island (2006)
  - SHM system accurately detected drilling faults

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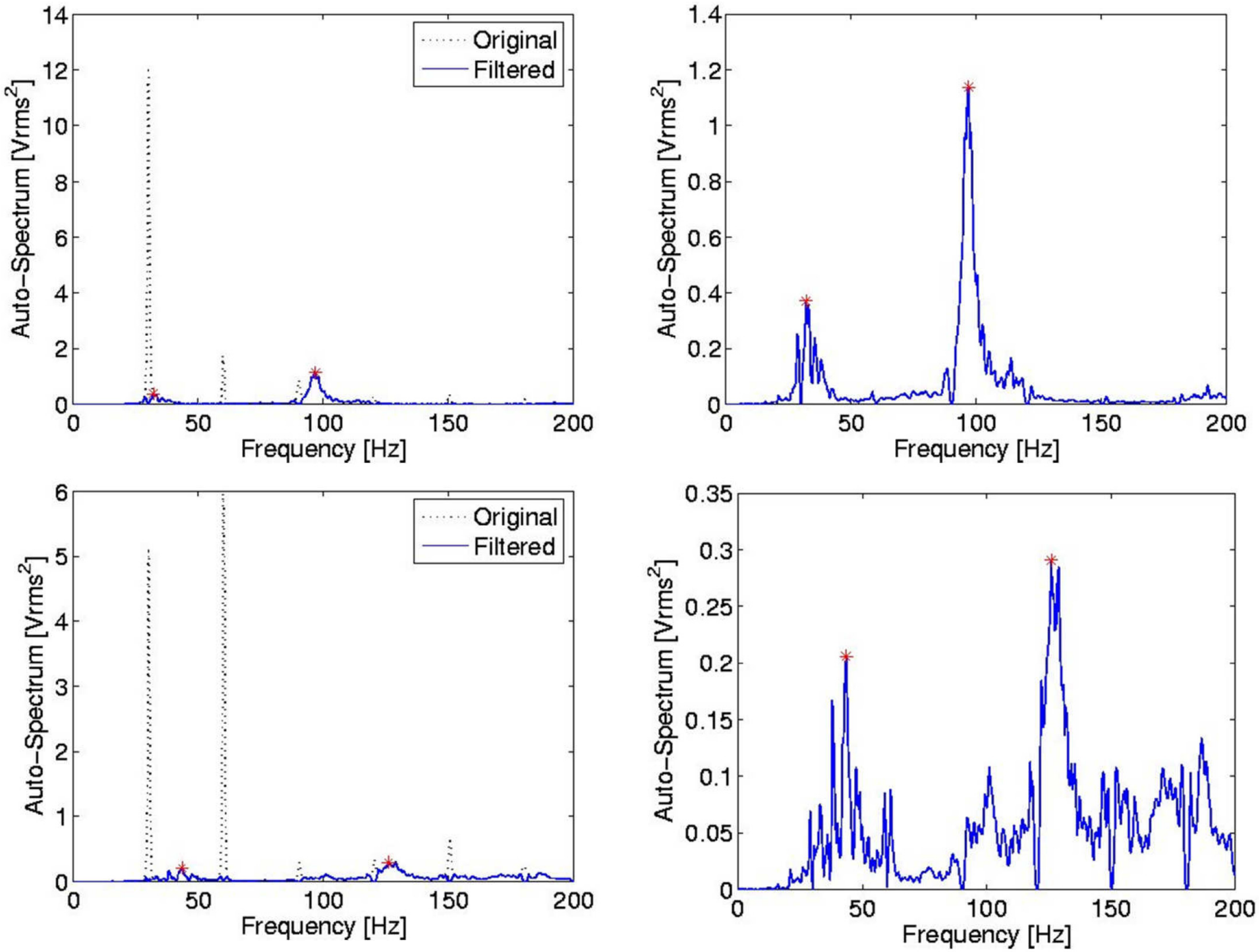
Field Testing & Validation (2006)

Nominal Drilling

Jamming 60%



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Contributions & Significance

- Automated Dynamics-Based SHM Technique
  - Advantages of LDV sensors
  - Autonomous signal analysis and integration
  - "Real-time," quick-response diagnostics
  - Field tested and validated
- Advancements to SHM field
- SHM applications
  - Interplanetary exploration missions
  - Other Earth-based functions

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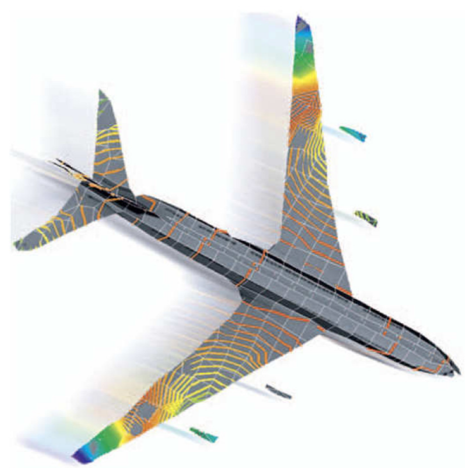
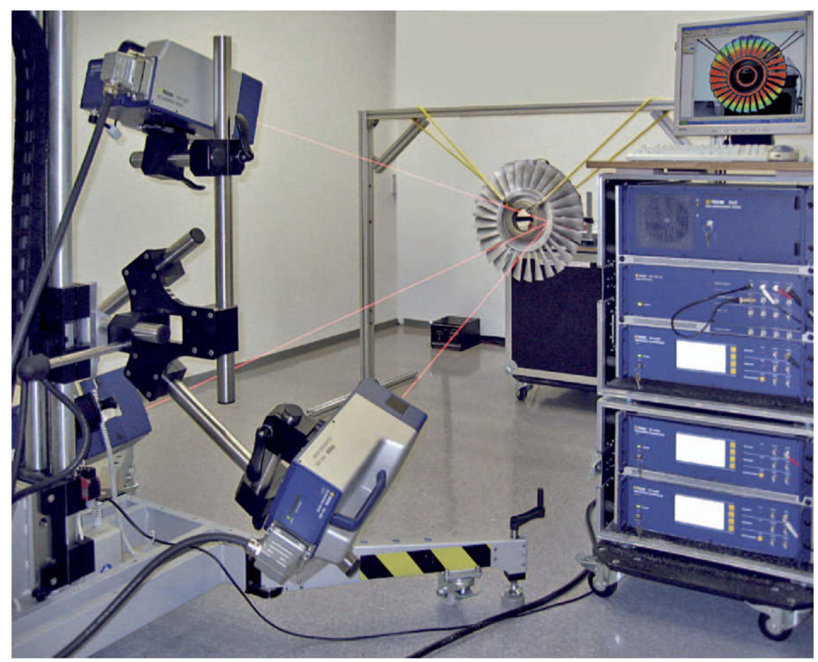
Relevance to Environmental Testing

- Laser Doppler Vibrometer Sensors
  - Non-contact, optical sensors
  - Control and response sensors
  - Scanning LDV: multiple points, one sensor
- Analytical Modeling
  - Model dynamic test environment
  - Compliment experiments and tests
- Automation

Relevance to Environmental Testing (cont.)

- Modal Testing
  - 1D, 2D, 3D dynamic response measurements
  - Characterize modal parameters
  - Compare with analytical models





Pictures borrowed from www.polytec.com

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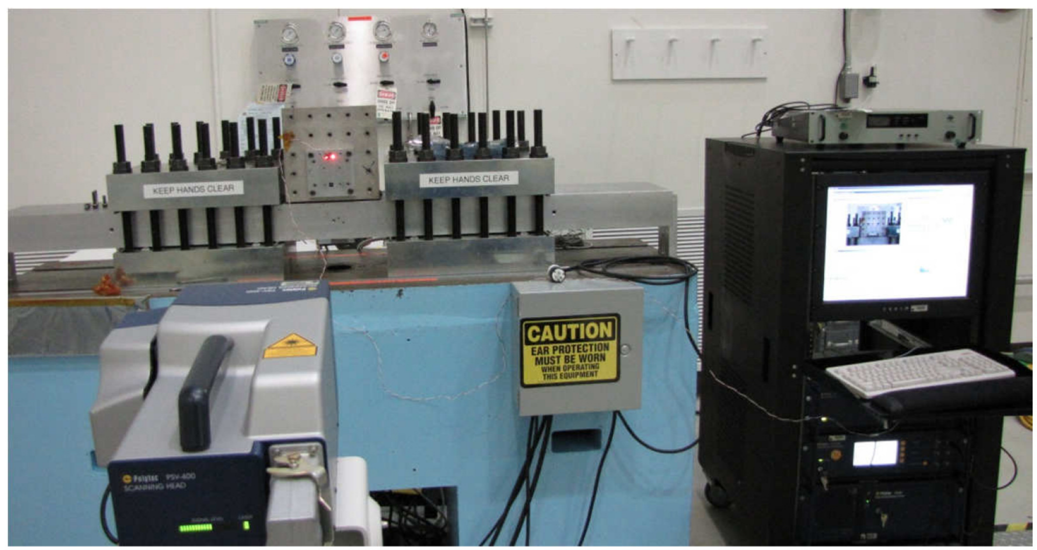
Future Work at ETL

- Profile dynamic test environments
  - Reverberant chamber
  - Tunable beam shock bench
- Introduce LDV sensors to ETL tests
  - Shock tests
  - Vibration tests
  - Modal analysis



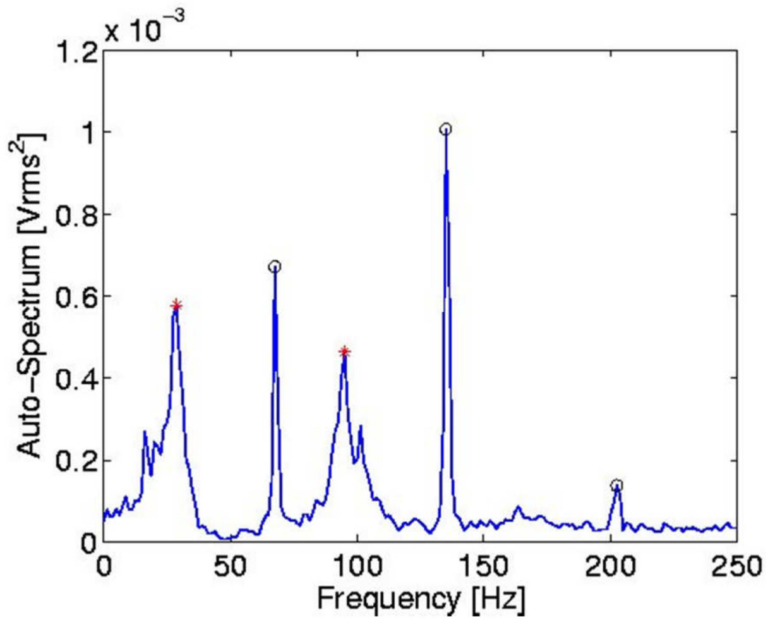
Questions?

Back Up Slides

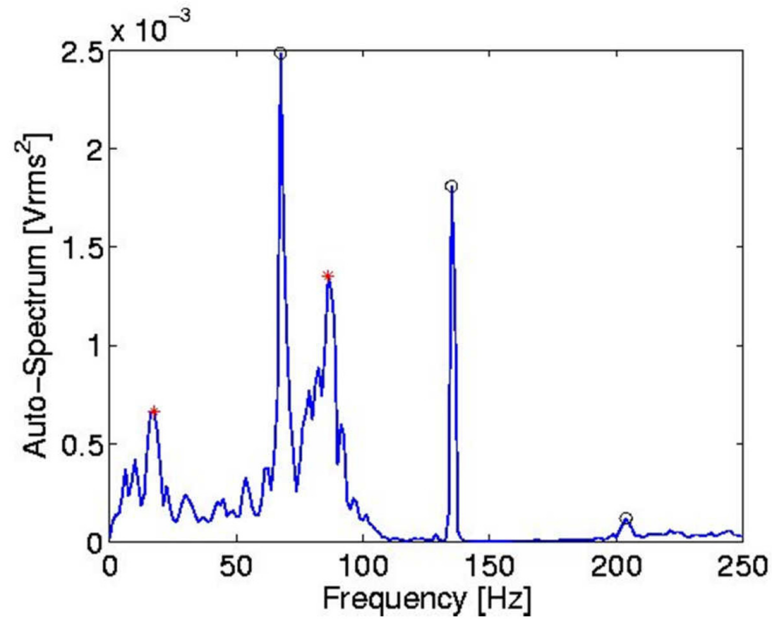
Drill Prototypes for Mars Exploration

- MARTE
  - "Mars Astrobiology Research and Technology Experiment"
  - Automated core handling and auger tube change-outs
  - Remote sensing device & life detection instruments
  - Field test: 2005 in Rio Tinto, Spain
- DAME
  - "Drilling Automation for Mars Exploration"
  - Automated drilling and recovery procedures
  - On-board diagnostics modules
  - Field tests: 2006 & 2008 in Devon Island, Canada

Drilling Experiments



Sample Auto-Spectrum:
1m Auger, 14cm Depth



Sample Auto-Spectrum:
2m Auger, 43cm Depth

*Natural Frequencies, °Harmonic Frequencies

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Harmonic Frequency Filter

- Harmonic frequencies of gear mesh system*

$$\xi_{\text{perfect}}(t) = \sum_{n=0}^{\infty} \Xi_n \cos(n\omega t + \Phi_n) + w(t)\,, \quad \omega = 2\pi f_r Q$$

$$\boxed{f_n = Q f_r n}$$

- DAME drill harmonic frequencies
  - 90-gear tooth system (Q=90)
  - 45 RPM (0.75 Hz) → 67.5 Hz, 135 Hz, 202.5 Hz, …

*McFadden, P., "Examination of a technique for the early detection of failure in gears by signal processing of the time domain average of the meshing vibration," *Mechanical Systems and Signal Processing*, vol. 1, pp. 173-183, 1987.

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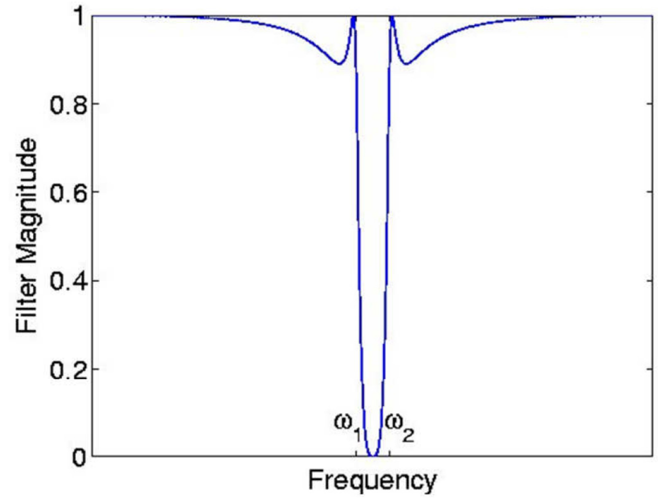
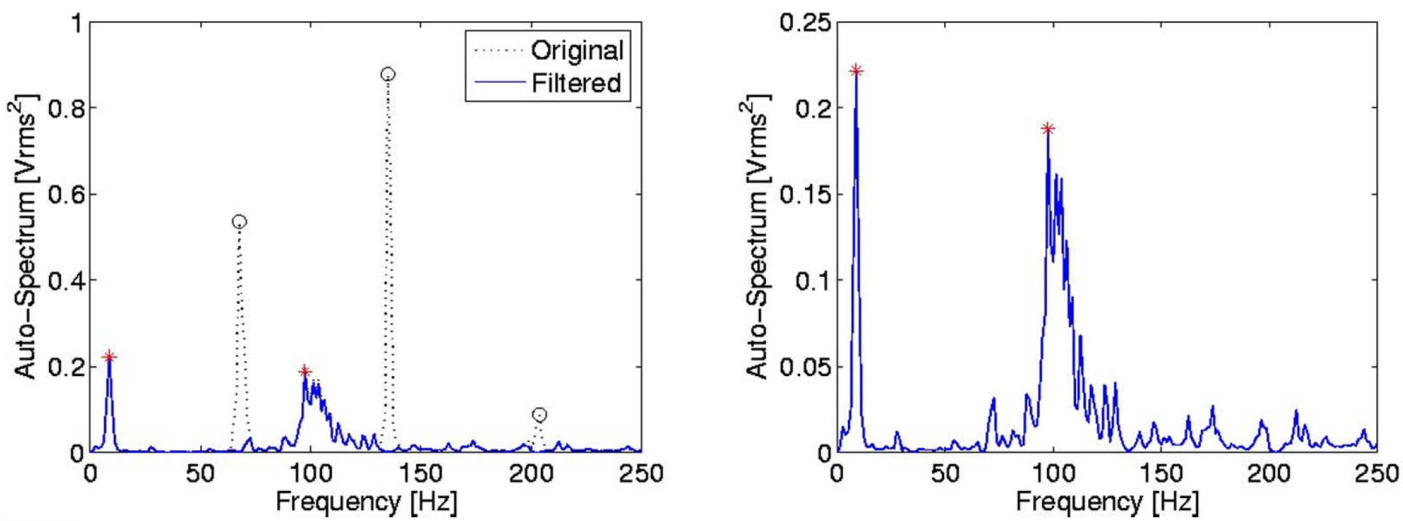
Harmonic Frequency Filter

- Chebyshev Type I Filter
  - Bandstop, $\omega_1 < \omega < \omega_2$
- Model + Cheby Filter





Structural Dynamic Models

- Equations of Motion (0<z<L)

$$\frac{\partial^2}{\partial z^2}\left(EI_{yy}\frac{\partial^2 u_1}{\partial z^2}+EI_{xy}\frac{\partial^2 u_2}{\partial z^2}\right)-\frac{\partial}{\partial z}\left(\rho I_{yy}\frac{\partial^3 u_1}{\partial z\partial t^2}+\rho I_{xy}\frac{\partial^3 u_2}{\partial z\partial t^2}\right)-\frac{\partial}{\partial z}\left(J_p\Omega\frac{\partial^2 u_2}{\partial z\partial t}\right)$$
$$+P\frac{\partial^2 u_1}{\partial z^2}+m\left(\frac{\partial^2 u_1}{\partial t^2}+\upsilon^2\frac{\partial^2 u_1}{\partial z^2}-\Omega^2 u_1+2\upsilon\frac{\partial^2 u_1}{\partial z\partial t}-2\Omega\frac{\partial u_2}{\partial t}-2\Omega\upsilon\frac{\partial u_2}{\partial z}\right)=0$$

$$\frac{\partial^2}{\partial z^2}\left(EI_{xx}\frac{\partial^2 u_2}{\partial z^2}+EI_{xy}\frac{\partial^2 u_1}{\partial z^2}\right)-\frac{\partial}{\partial z}\left(\rho I_{xx}\frac{\partial^3 u_2}{\partial z\partial t^2}+\rho I_{xy}\frac{\partial^3 u_1}{\partial z\partial t^2}\right)+\frac{\partial}{\partial z}\left(J_p\Omega\frac{\partial^2 u_1}{\partial z\partial t}\right)$$
$$+P\frac{\partial^2 u_2}{\partial z^2}+m\left(\frac{\partial^2 u_2}{\partial t^2}+\upsilon^2\frac{\partial^2 u_2}{\partial z^2}-\Omega^2 u_2+2\upsilon\frac{\partial^2 u_2}{\partial z\partial t}+2\Omega\frac{\partial u_1}{\partial t}+2\Omega\upsilon\frac{\partial u_1}{\partial z}\right)=0$$

Structural Dynamic Models

- Boundary Conditions (z=0,L)

$$u_1 = 0 \quad \text{or} \quad \left[-\frac{\partial}{\partial z}\left(EI_{yy}\frac{\partial^2 u_1}{\partial z^2} + EI_{xy}\frac{\partial^2 u_2}{\partial z^2} \right) + \rho I_{yy}\frac{\partial^3 u_1}{\partial z \partial t^2} + \rho I_{xy}\frac{\partial^3 u_2}{\partial z \partial t^2} - P\frac{\partial u_1}{\partial z} - m\left(\upsilon^2 \frac{\partial u_1}{\partial z} - 2\Omega \upsilon u_2 \right) \right] = 0$$

and

$$\frac{\partial u_1}{\partial z} = 0 \quad \text{or} \quad \left(EI_{yy}\frac{\partial^2 u_1}{\partial z^2} + EI_{xy}\frac{\partial^2 u_2}{\partial z^2} \right) = 0$$

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Structural Dynamic Models

- Drilling dynamic studies

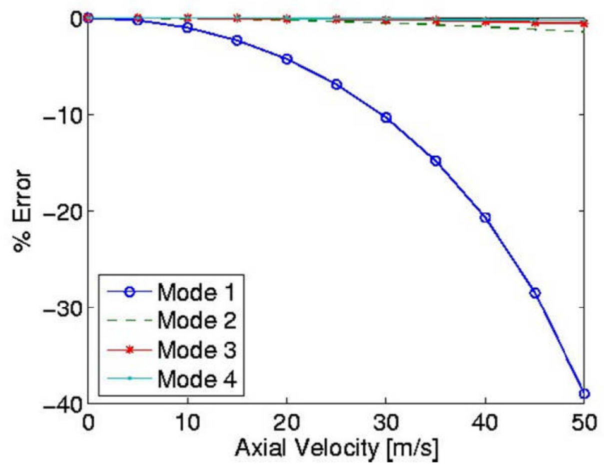
Rotating, Tip Load, Complex Geometry

Gyroscopic Effects

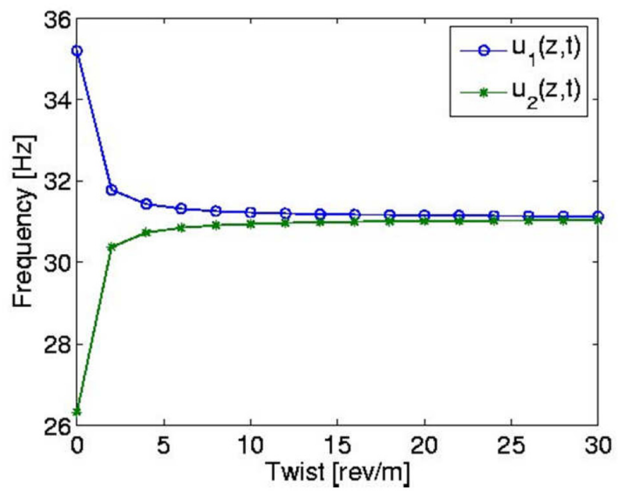
Axial Velocity

1. Liao, C. L. and Dang, Y. H., "Structural characteristics of spinning pretwisted orthotropic beams," *Computers & Structures*, vol. 45, no. 4, pp. 715-731, 1992.
2. Huang, B. W., "Dynamic characteristics of a drill in the drilling process," *Journal of Engineering Manufacture*, vol. 217, no. 2, pp. 161-167, 2003.
3. Rincon, D. M. and Ulsoy, A. G., "Complex geometry, rotary inertia and gyroscopic moment effects on drill vibrations," *Journal of Sound and Vibrations*, vol. 188, no. 5, pp. 701-715, 1995.
4. Akulenko, L. and Nesterov, S., "Flexural vibrations of a moving rod," *Journal of Applied Mathematics and Mechanics*, vol. 72, pp. 550-560, 2008.

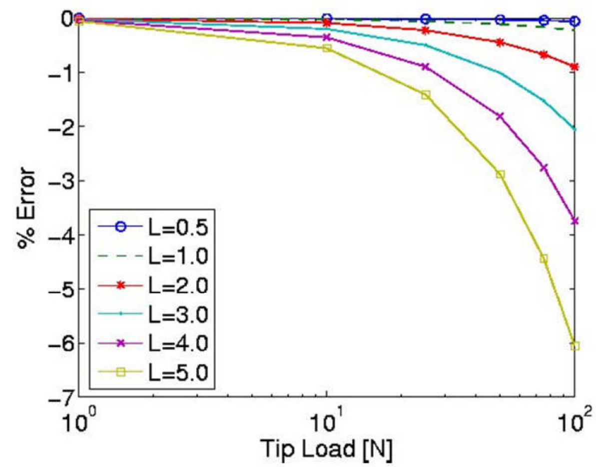
Structural Dynamic Models



Axial Velocity Effect



Flute Twist Effect



Tip Load Effect

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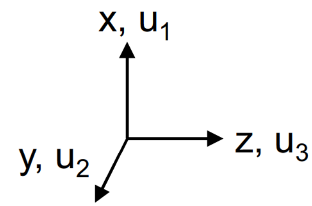
Structural Dynamic Models



Cross-Section Geometry	Mode*	Frequencies (Hz) Numerical†	FEM	Error (%)
Simple	1,2	26.32	26.38	0.20
	1,1	35.20	34.70	-1.46
	2,2	164.69	163.57	-0.68
	2,1	219.97	213.65	-2.96
Flute Twist (20 rev/m)	1,2	31.01	25.49	-21.67
	1,1	31.15	25.50	-22.18
	2,2	193.91	157.93	-22.78
	2,1	194.78	158.01	-23.27

*Mode i, j = Natural frequency of mode i for lateral deflection $u_j(z, t)$

†Closed-form solution for simple beam, Galerkin's Method for fluted beam

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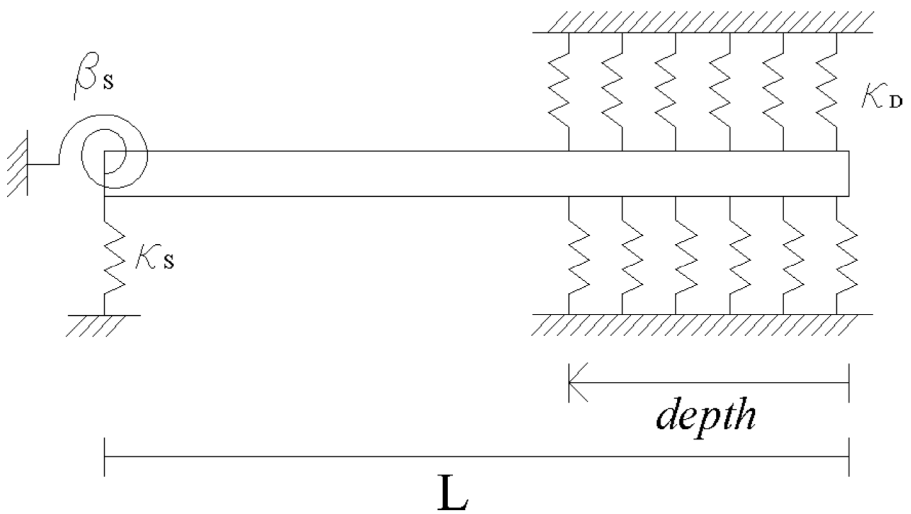
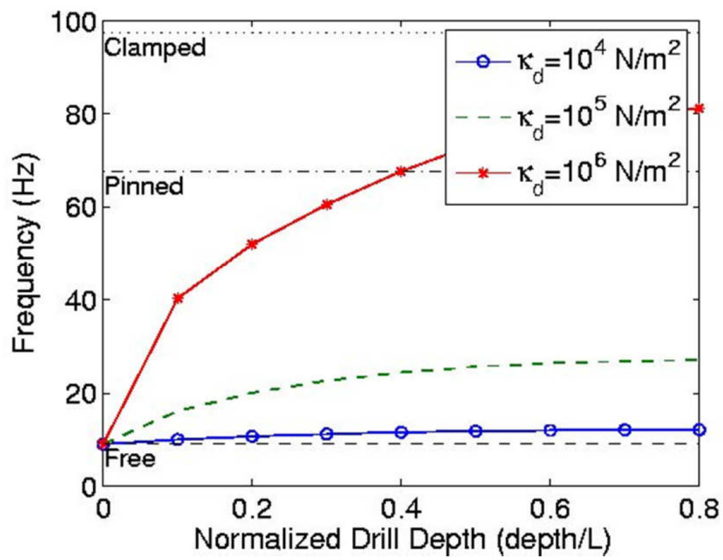
Structural Dynamic Models

- Nominal drilling model
- Comparison to experimental results
  - Evaluate spring constant (κ_D)

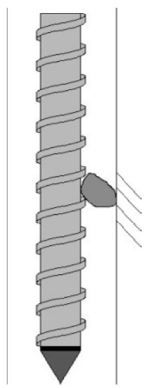




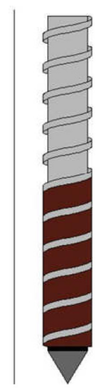
Structural Dynamic Models

- Drilling fault models

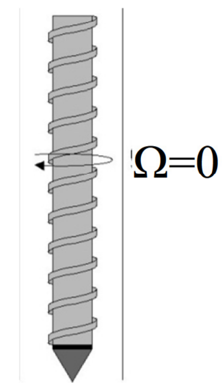
1. Auger Binding



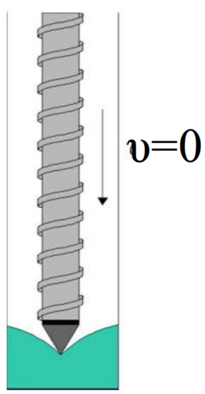
2. Auger Choking



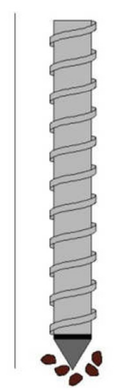
3. Bit Jamming



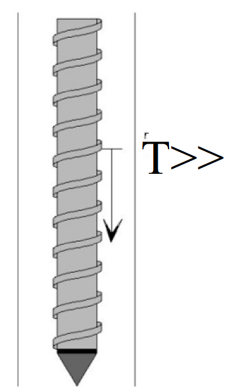
4. Hard Material



5. Bit Inclusion



6. Cork-screwing



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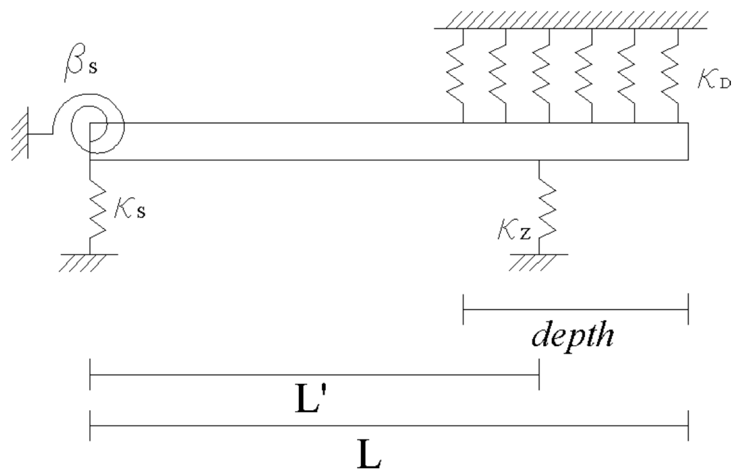
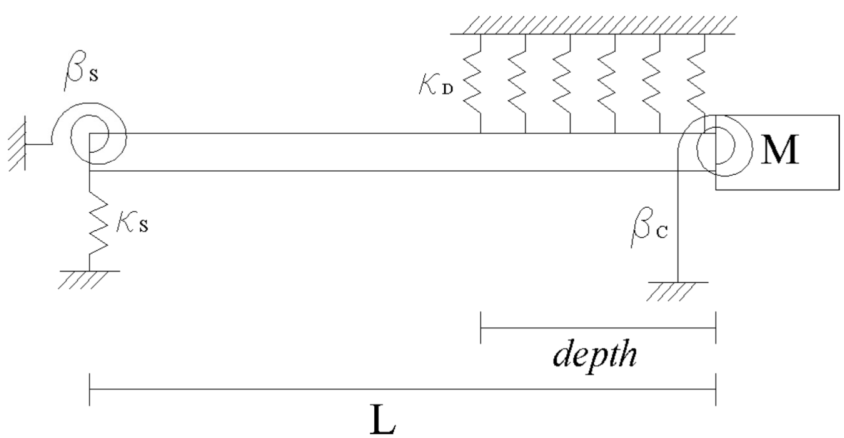
Structural Dynamic Models

- Binding fault model
  - Binding spring: κ_Z
  - Binding location: *L'*



- Choking fault model
  - Choking spring: β_c
  - Choking added mass: *M*



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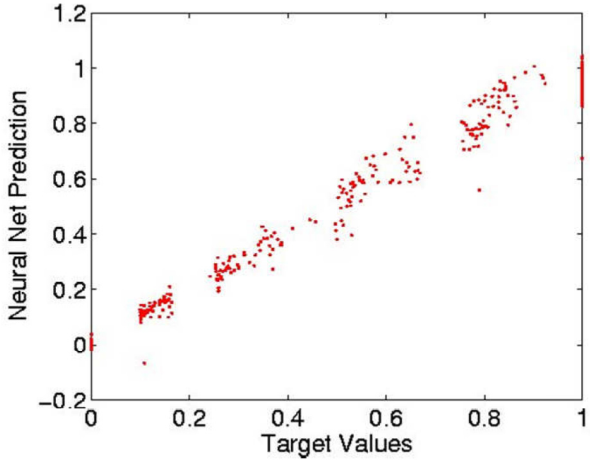
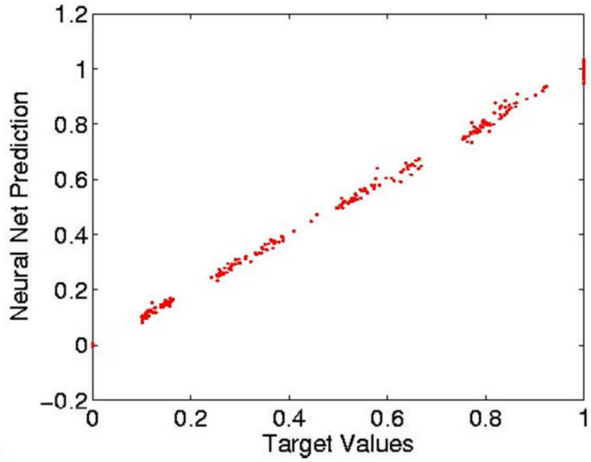
Neural Networks



Layers: 3, Size: 10

Iterations: 500

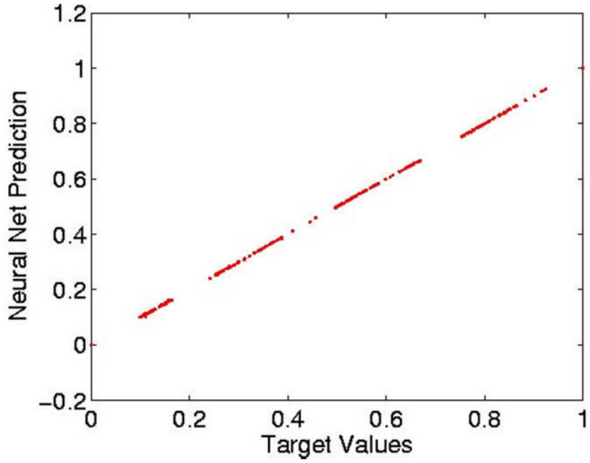
Time: 9.9s, MSE: 9.4e-3



Layers: 4, Size: 20

Iterations: 1000

Time: 8m, MSE 8.4e-5



Layers: 4, Size: 30

Iterations: 1000

Time: 37m, MSE: 4.2e-7

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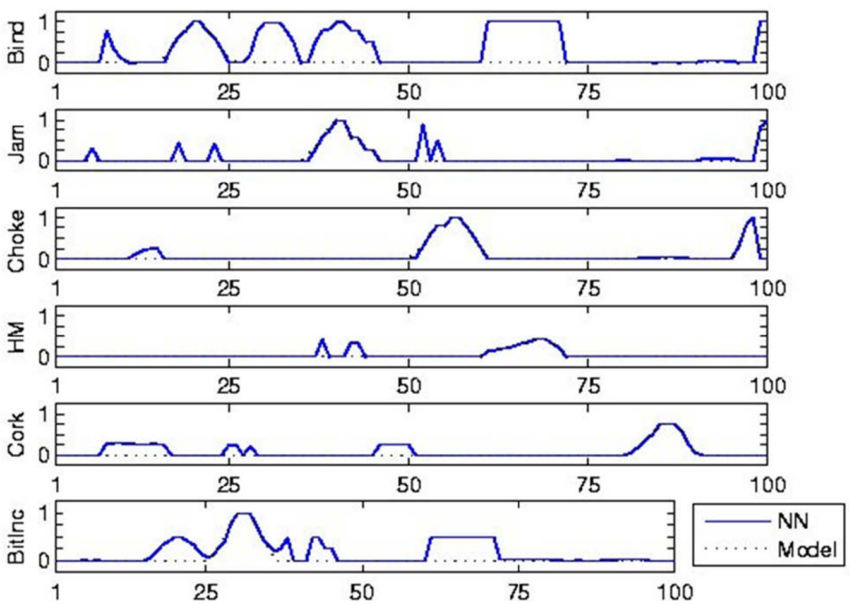
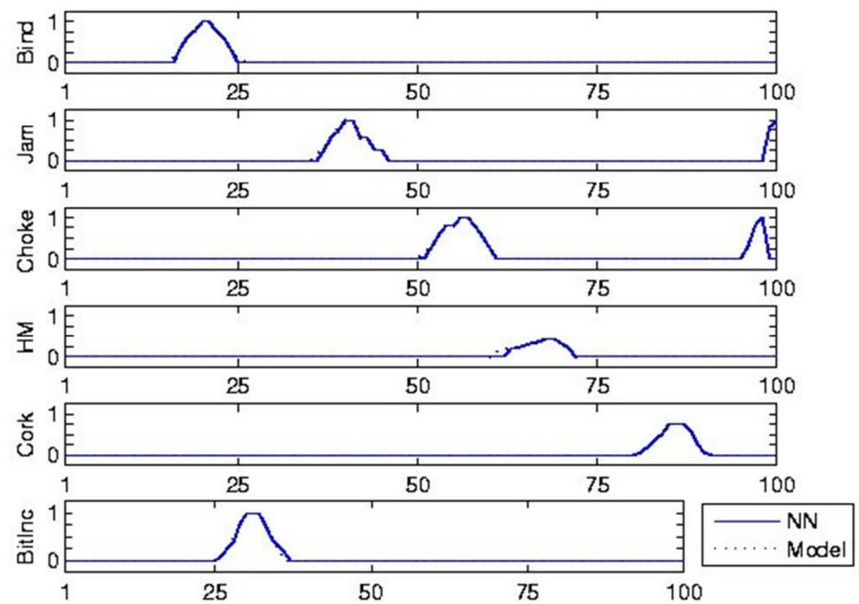
Neural Networks

- Heuristic Filter



Without Heuristic Filter

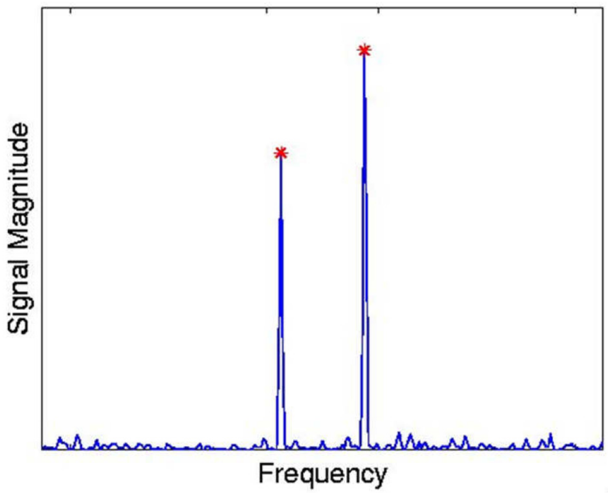


With Heuristic Filter

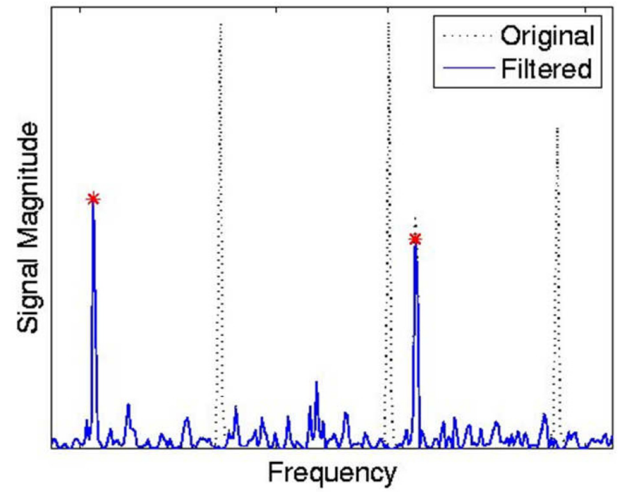
Signal Analysis Algorithm

- Autonomous frequency selection
  - Determine frequency domain from models
  - Select significant peaks
  - Resolve first two auger frequencies
  - Check for filtered auger frequencies

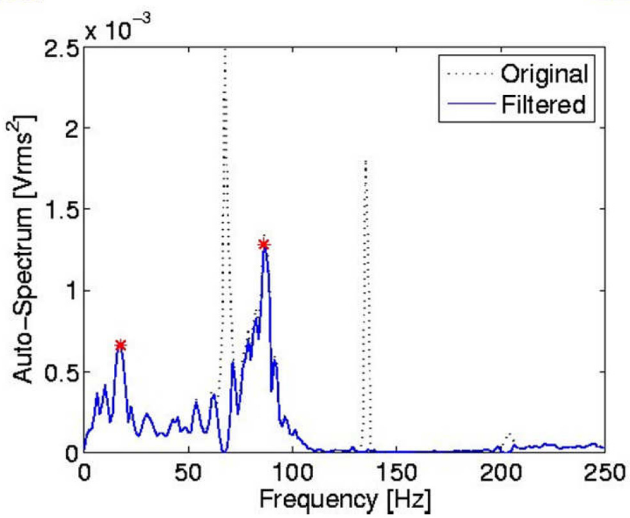
Signal Analysis Algorithm



Simulated without Harmonics



Simulated with Harmonics



Drilling Example

Field Testing & Validation (2006)

- SHM diagnostics system
  - Two LDV sensors for redundancy
  - Equipped for four drilling faults
- Results
  - Drilled to **3.22 m** depth
  - **4.5 hours** of continuous hands-off drilling
  - Detected and recovered from **4 drilling faults**
    - Binding, jamming, choking, hard material

Field Testing & Validation (2007)

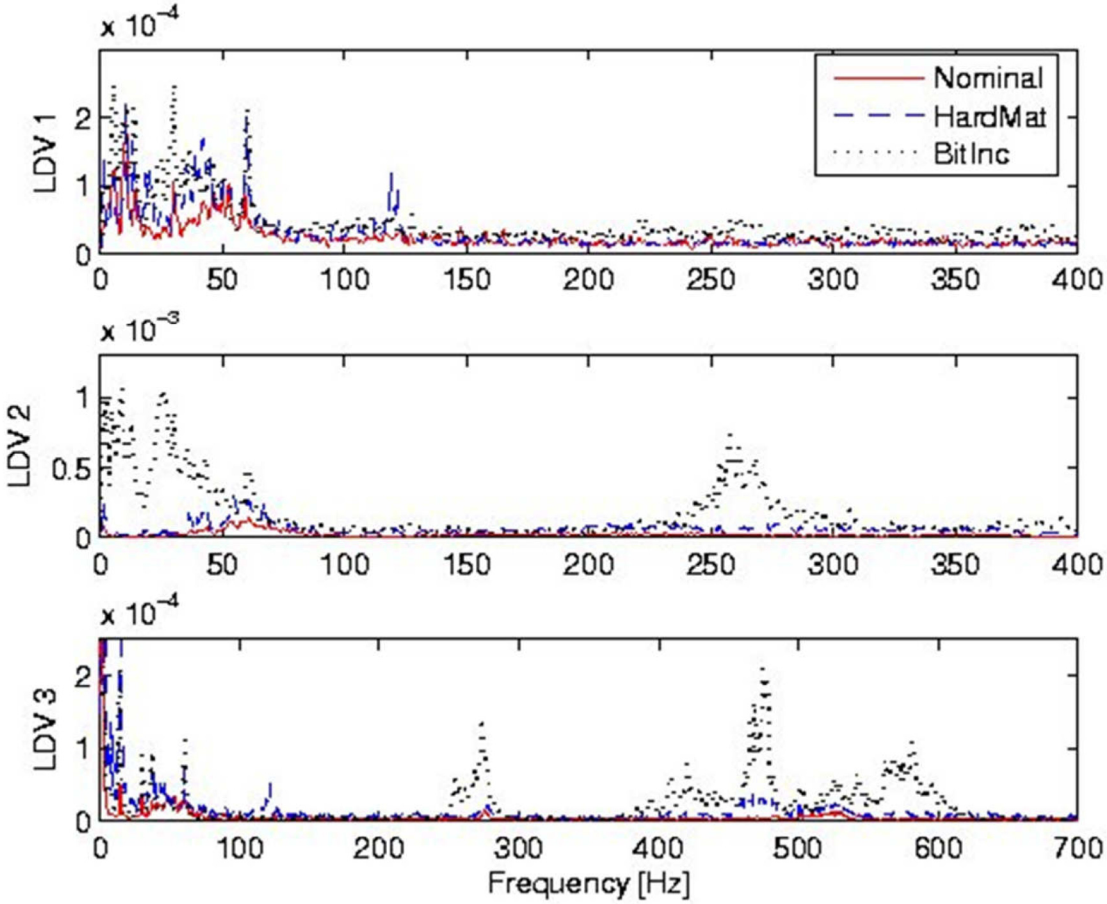
- JPL, California
  - Blind drilling tests
- Test objectives
  - Demonstrate drilling automation technologies
  - Demonstrate repeatability

DAME Drill at JPL Bay

Field Testing & Validation (2007)

- SHM diagnostics system
  - Three LDV sensors for signal in three directions
  - Equipped for all six drilling faults
  - Heuristic NN filter
- Results
  - Drilled through **3.3 m** of material test columns
  - **35 hours** of hands-off, automated drilling
  - Detected and recovered from **5 drilling faults**
    - Binding, jamming, hard material, bit inclusion, corkscrewing

Field Testing & Validation (2007)



Field Testing & Validation (2008)

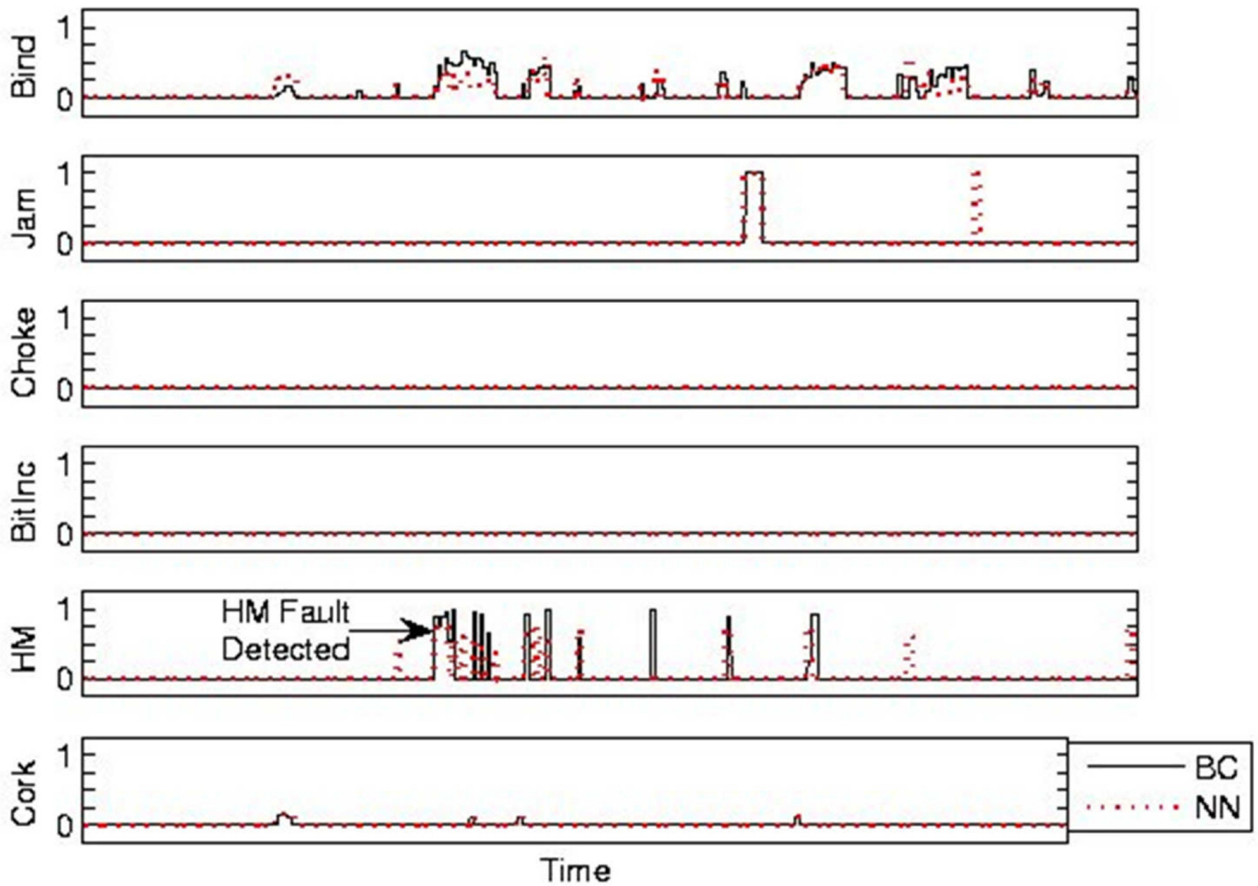
- Haughton Crater
- Field objectives
  - Integrate new Executive
  - Modify diagnostic systems
  - Collect samples
  - Reach 2m drill depth

2008 Devon Island Drill Site

Field Testing & Validation (2008)

- SHM diagnostics system
  - Three LDV sensors for signal in three directions
  - Dual diagnostic system
    - Sensor-based diagnostics (NN probabilities)
    - BC-based diagnostics (telemetry thresholds)
- Results
  - Collected core samples every 25-50 cm
  - Final drill depth at **2.03 m**
  - Detected and recovered from **5 drilling faults**
    - Binding, jamming, hard material, bit inclusion, corkscrewing

Field Testing & Validation (2008)



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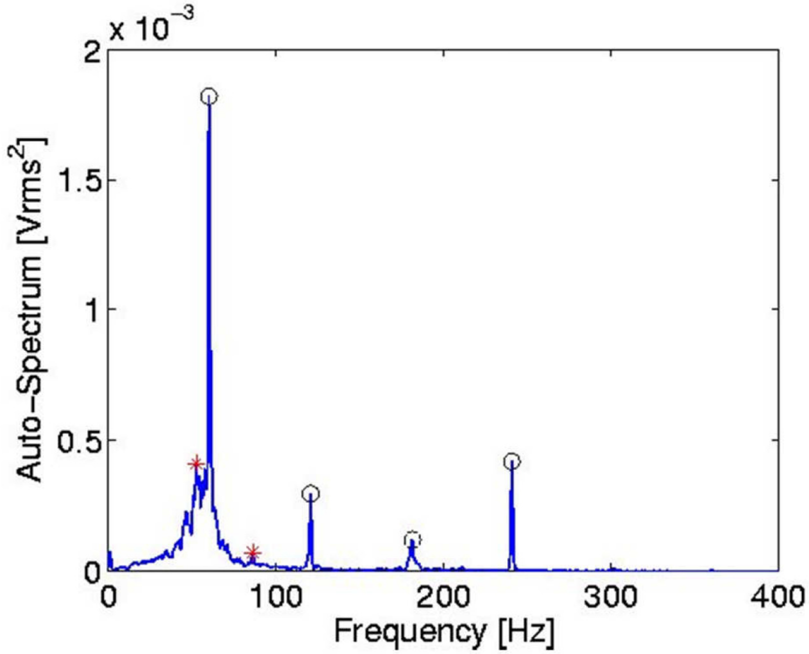
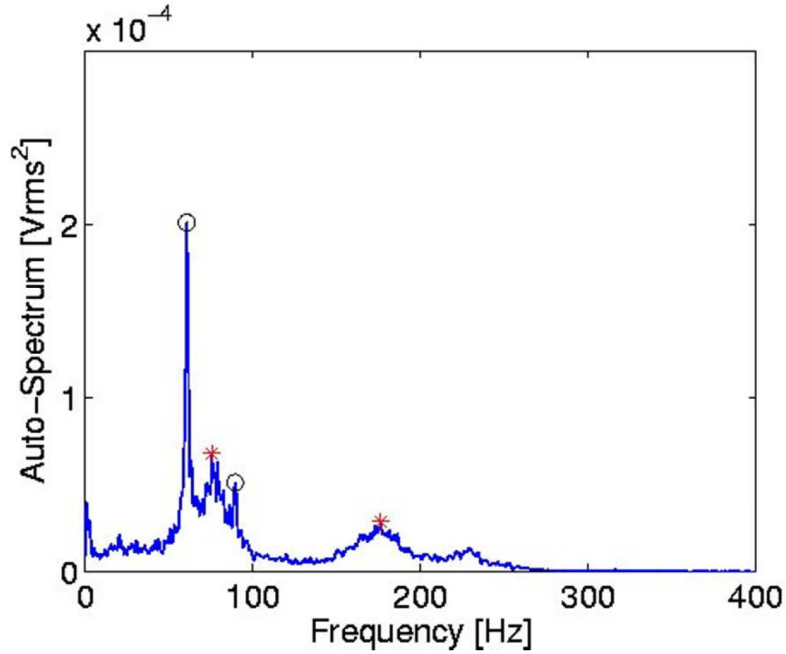
Field Testing & Validation (2008)



Nominal Drilling



Hard Material Fault

*Natural Frequencies, ºHarmonic Frequencies

Contributions & Significance

- List of publications

1. S. Hanagud, S. Statham, M. Ruzzene, B. Glass, and H. Cannon, "Health and Usage Monitoring for Space Applications: DAME," *HUMS 2007 Conference*, March 2007.
2. S. Statham, S. Hanagud, M. Ruzzene, V. Sharma, B. Glass, and H. Cannon, "Design and Validation of an LDV-Based Structural Health Monitoring in 'DAME'," *48th AIAA SSDM Conference*, April 2007.
3. S. Statham, S. Hanagud, V. Sharma, and B. Glass, "Three Dimensional Structural Health Monitoring in Space Applications using LDVs," *49th AIAA SSDM Conference*, April 2008.
4. S. Statham, S. Hanagud, and B. Glass, "Autonomous Structural Health Monitoring for Space Drilling Application," *7th IWSHM*, September 2009 (invited paper).
5. S. Statham, S. Hanagud, B. Glass, "Structural Health Monitoring for Space Exploration Systems," *AIAA Journal* (Under Review).
6. S. Statham, S. Hanagud, "Effects of Drilling Operations on Drill Dynamic Characteristics," In Progress.

Multi-Dimensional Experiments

- Motivations
  - Dependency of sensor locations
  - Signal response in multiple dimensions
    - More information regarding dynamic characteristics
  - Sensor limits (cost, space limitations)
  - Single LDV for 2-D and 3-D monitoring

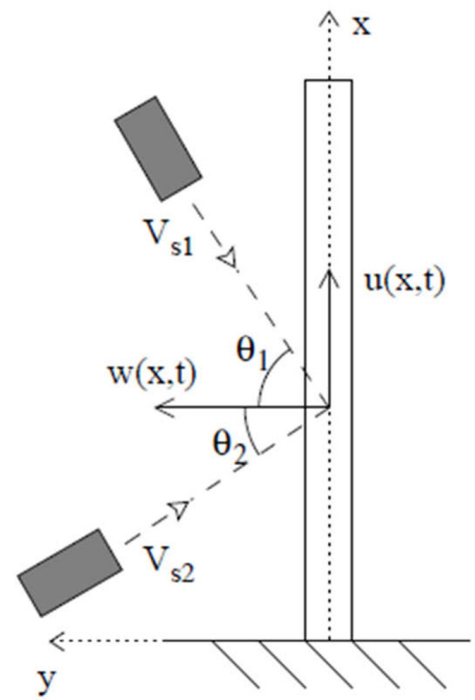
Multi-Dimensional Experiments

- Theory

$$V_{L1} = U_2 \cos(\theta_1) + U_3 \sin(\theta_1)$$

$$V_{L2} = U_2 \cos(\theta_2) + U_3 \sin(\theta_2)$$

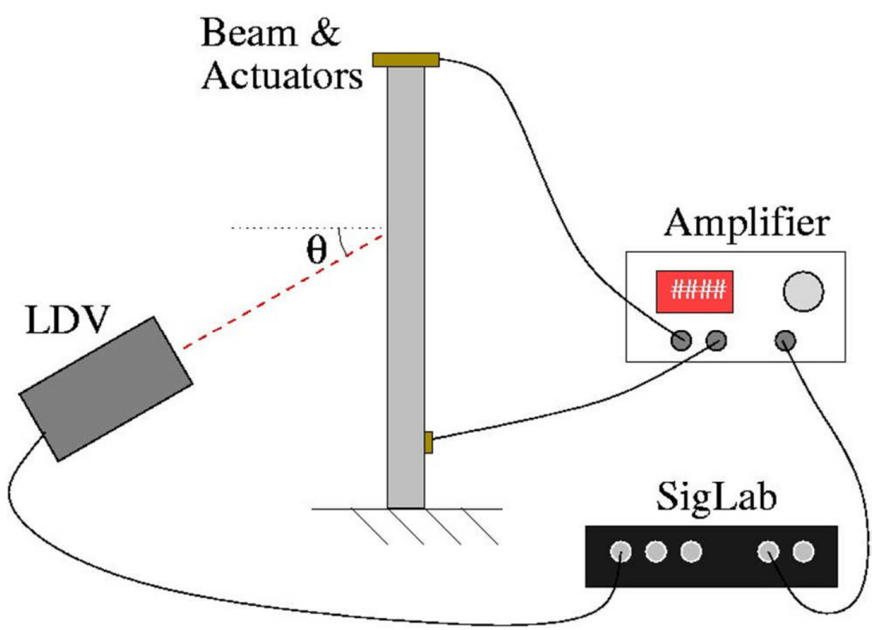
$$\begin{Bmatrix} U_2 \\ U_3 \end{Bmatrix} = \begin{bmatrix} \cos(\theta_1) & \sin(\theta_1) \\ \cos(\theta_2) & \sin(\theta_2) \end{bmatrix}^{-1} \begin{Bmatrix} V_{L1} \\ V_{L2} \end{Bmatrix}$$



2D Measurements

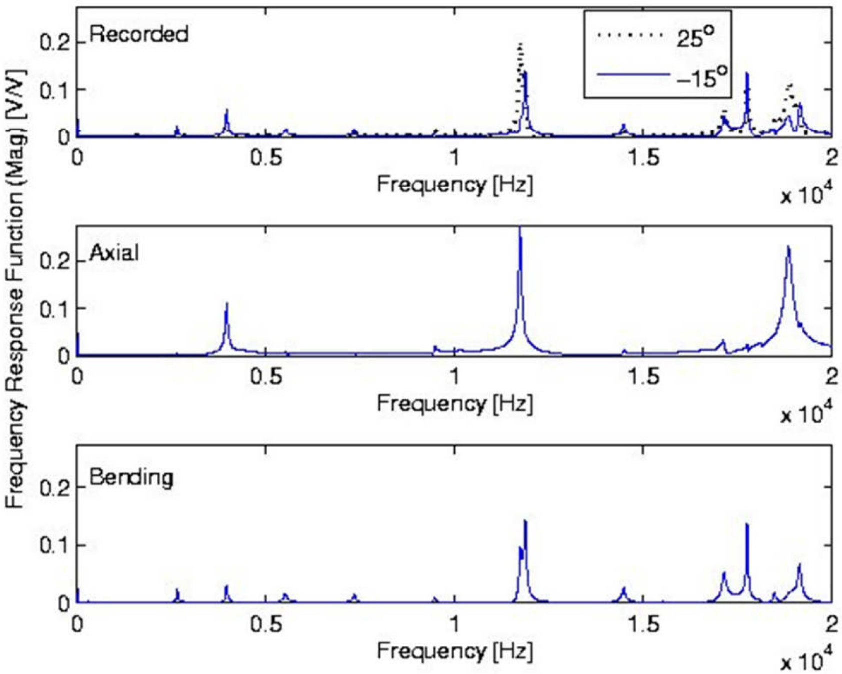
Multi-Dimensional Experiments

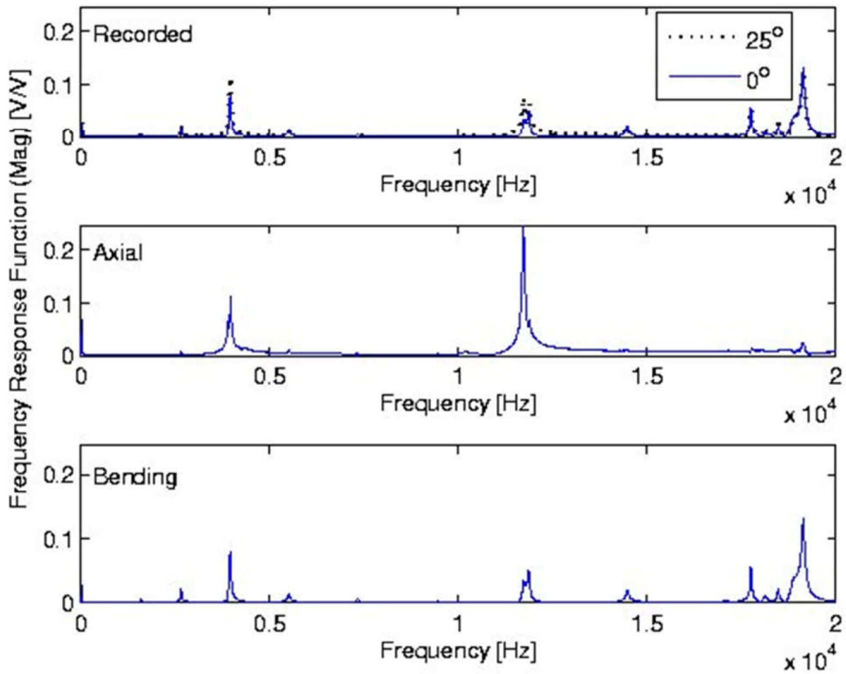
- Cantilevered beam experiments



Multi-Dimensional Experiments

- Cantilevered beam experiments





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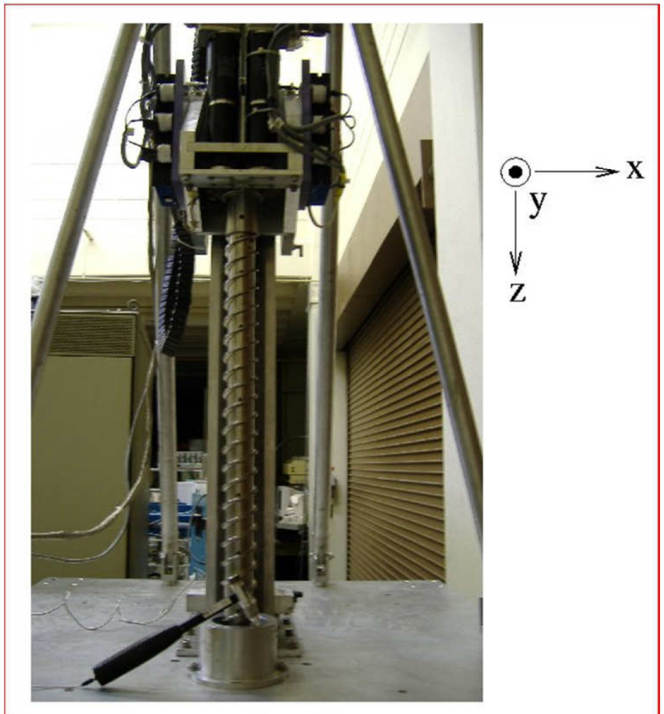
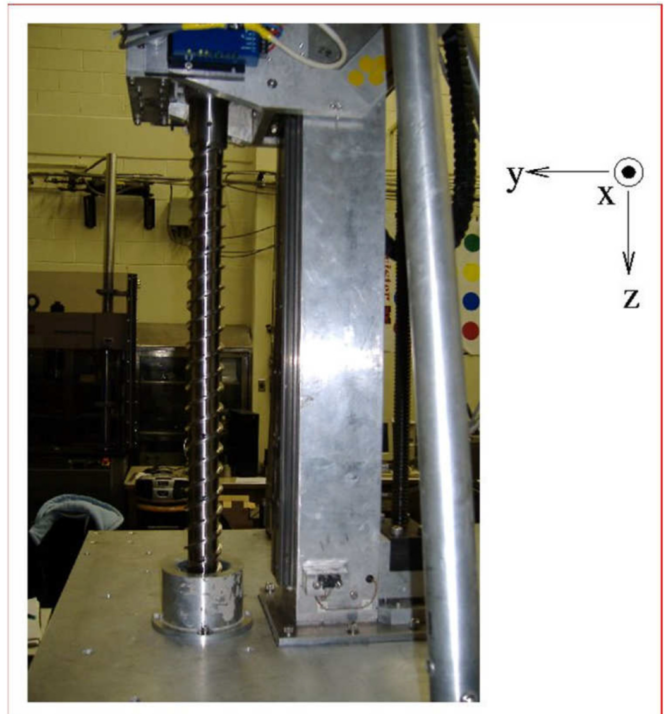
Multi-Dimensional Experiments

- Drilling experiments



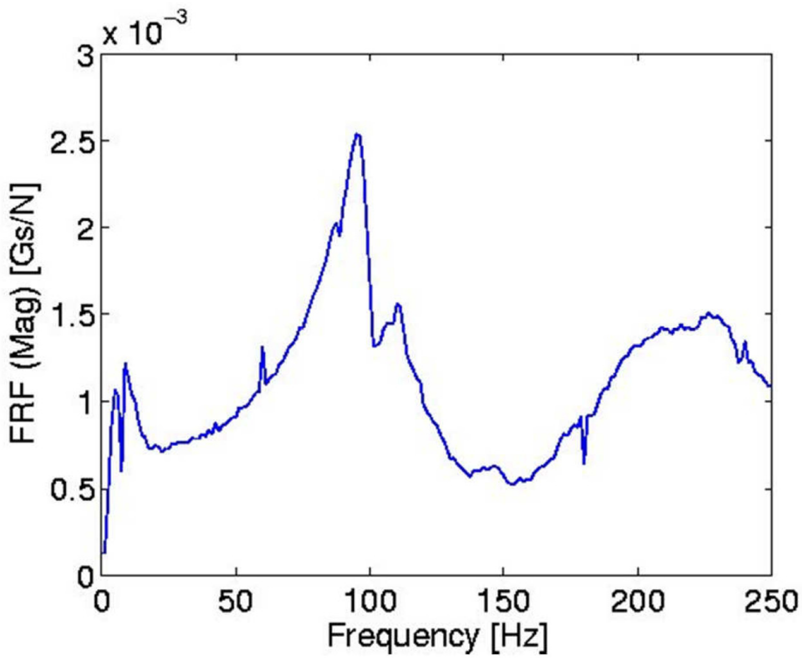
Front View



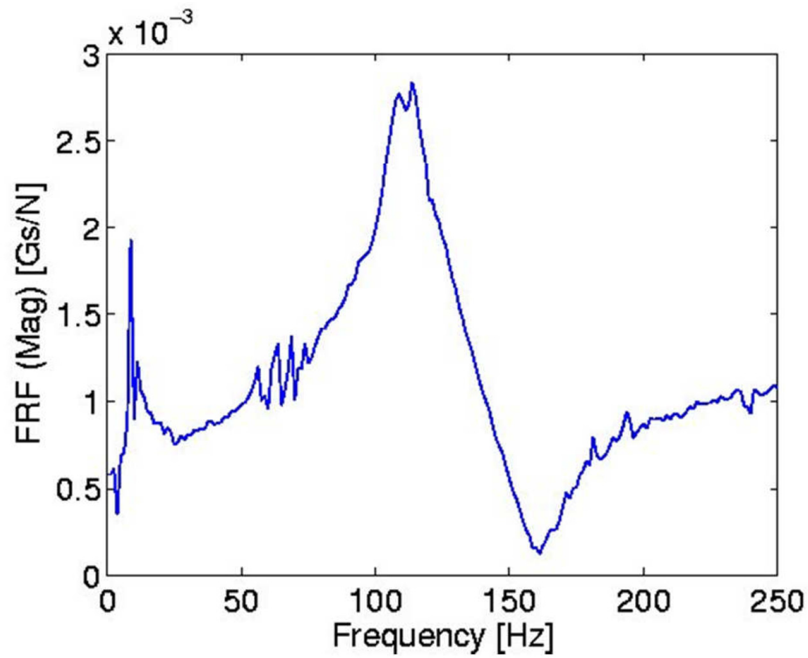
Side View

Multi-Dimensional Experiments

- Drilling experiments



Impact Response: Front



Impact Response: Side

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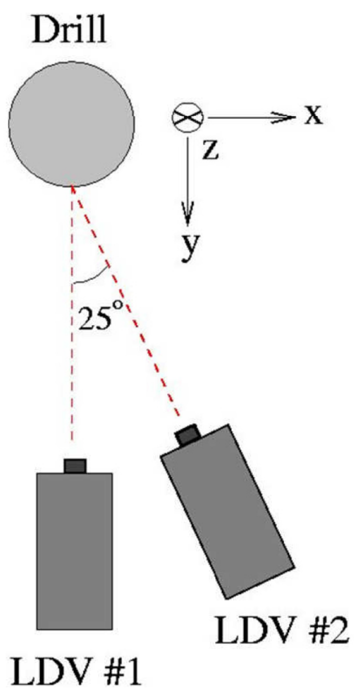
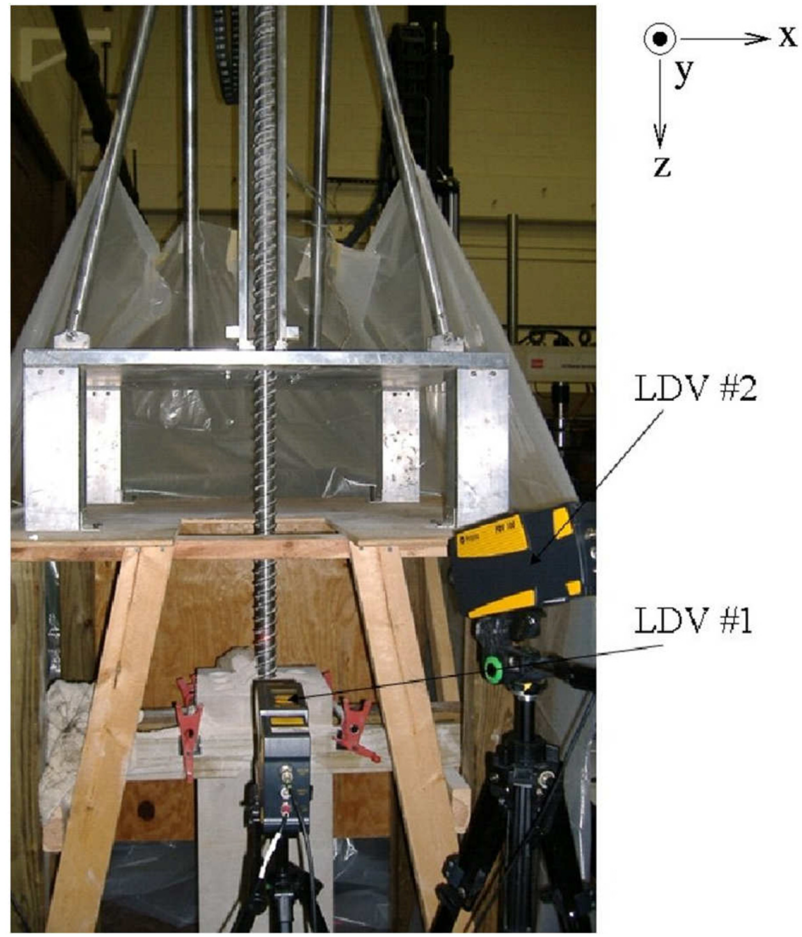
Multi-Dimensional Experiments

- Drilling experiments





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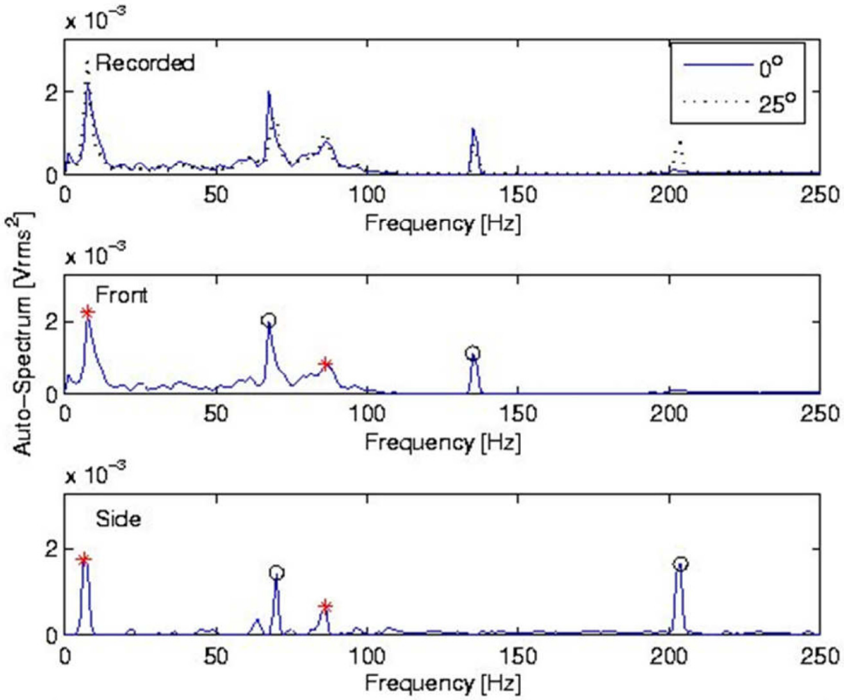
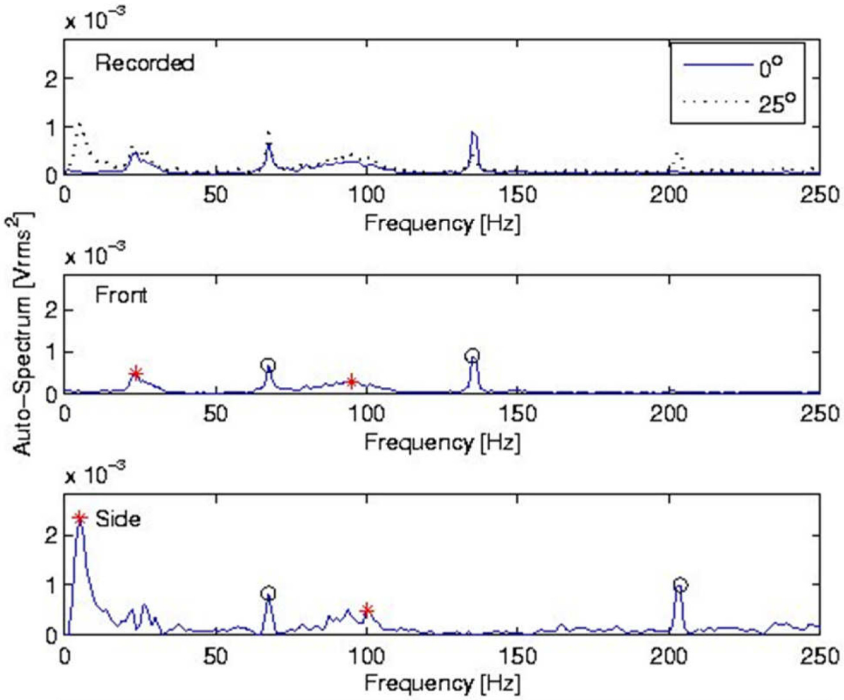
Multi-Dimensional Experiments

- Drilling experiments



1m Auger, 10cm Depth

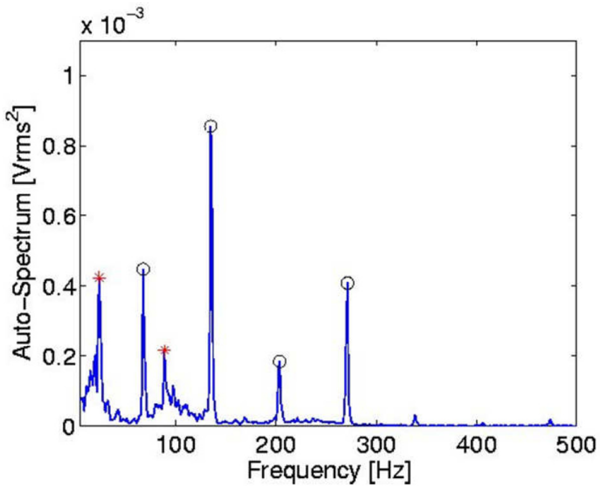


2m Auger, 40cm Depth

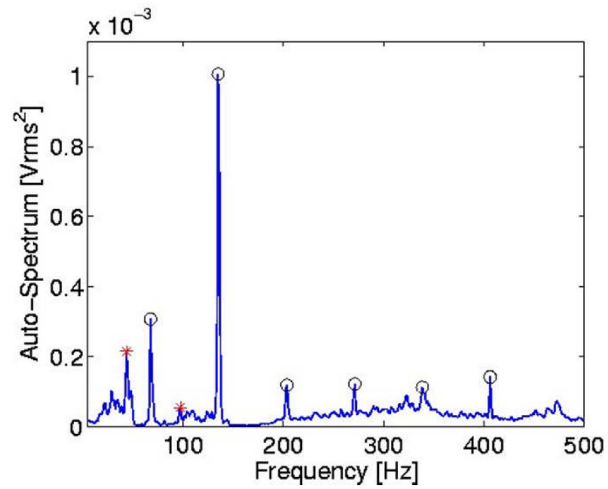
Surface Measurement Limitations

- Use of LDV sensors:
  - Surface measurements only (optical sensors)
  - Limited measurement capabilities at surface with increasing depths
  - Limited information about subsurface conditions and drill bit

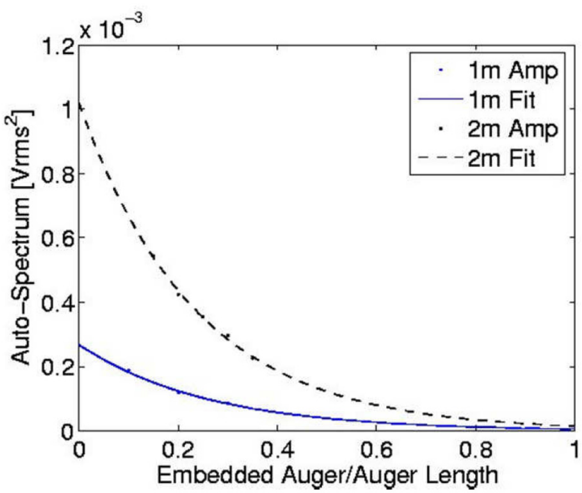
Surface Measurement Limitations



2m Auger, 45 RPM, 50cm Depth



2m Auger, 45 RPM, 70cm Depth



Magnitude of First Frequency