SAND2007-7105P

Transducers for Structural Dynamics and Solid Mechanics

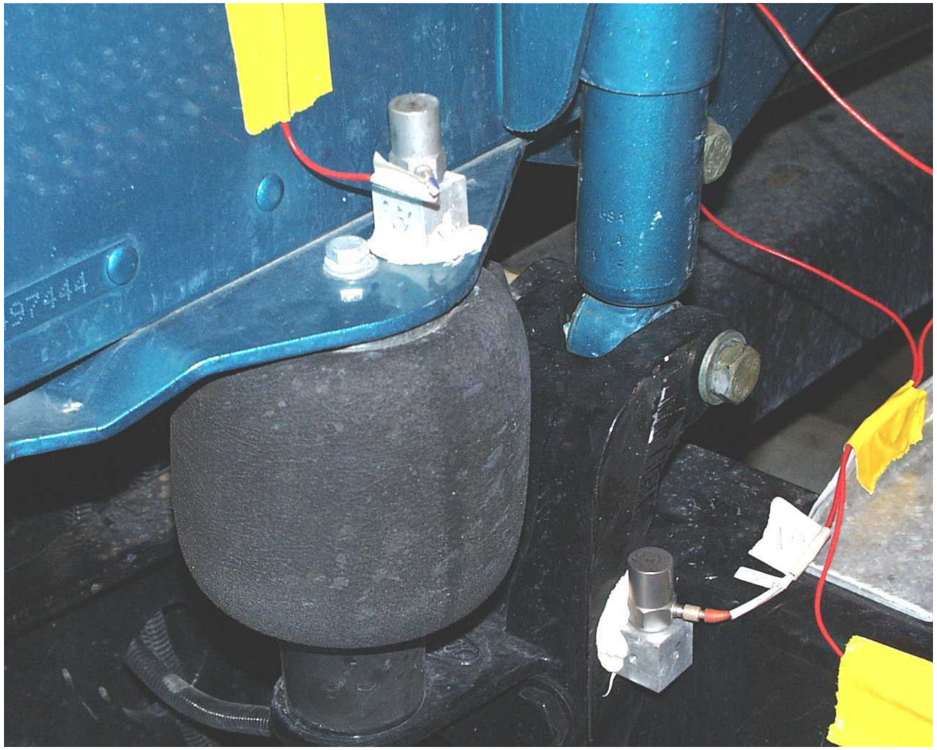
01520

October 30, 2007

Corporate Learning & Professional Development& Training P.O. Box 5800, (MS 0653)Albuquerque, NM 87185-0653 Phone: 845-CLAS (845-2527)

Topics

- Introduction
- Strain Gages
- Accelerometers
- Force Transducers
- Displacement Transducers

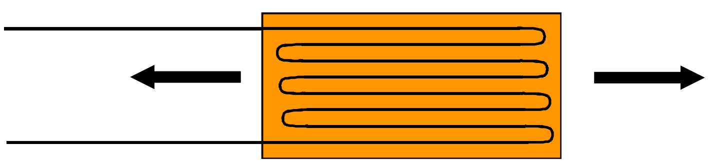


Strain Gages

- Used to measure strain
- Available in
  - Uniaxial: one axis of strain
  - Biaxial: two orthogonal axis of strain (principal strains when orientation is known)
  - Three element Rosettes: complete 2-D state of strain
  - Shear: direct measure of shear strain

How does a Strain Gage work

Δresistivity = Δresistivity due to Δgeometry
+ Δresistivity due to piezoresistive effect



- Gage consists of loops of wire
- Stretching of gage produces a change in resistance in the wire
- Resistance drop is measured by a voltage change in a Bridge
- Measured strain is an average over the length of gage

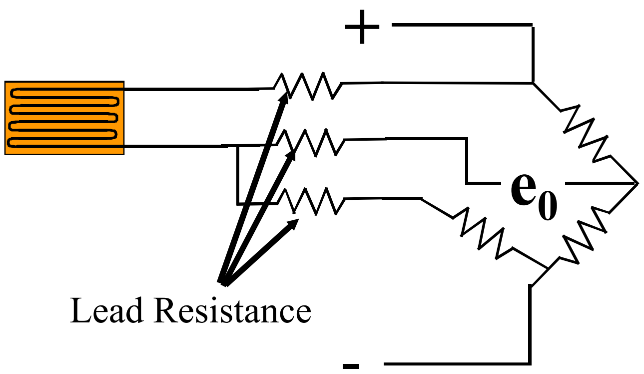
Applications

- Monitoring for yield in materials
- Model validation
- Failure Analysis
- Load Characterization

Implementation Details

- Typically mounted using high strength glue
  - Abnormal environments require advanced bonding
- Requires amplifiers to complete bridge circuit
- Temperature Compensation
- Noise Attenuation
  - Strain gages look and act like antennas

Basic Setup
(3 wire)



Calibration and Sensitivity

- Sensitivity specified in Gage Factor
  - Define Gage Factor
- Gage Factor provided by manufacturer based upon “lot” that gage is a member of
- Sensitivity (strain/voltage) is based upon gage factor
- Sensitivity varies based upon expected range to be measured
  - Resistivity change in wire is slightly non-linear

What to look for in a Strain Gage

- Range of strains expected
- Mounting Surface
- Material being strained
  - Softer material requires softer strain gage
  - Most strain gages designed for steel/aluminum like stiffness
  - Orthotropic
- Operating environment
  - Temperature
  - Electric Fields
  - Flying Debris

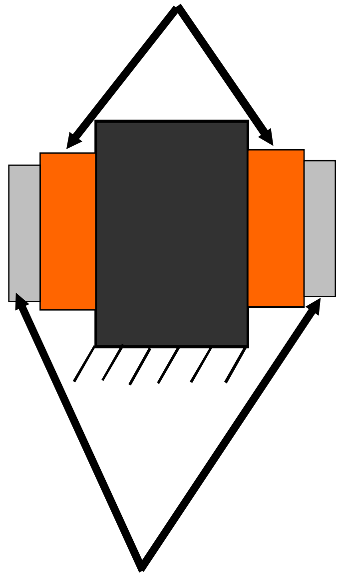
Piezoelectric Strain Gages

- Self contained like an accelerometer
- Conditioned like an accelerometer
- Mounts like an accelerometer
- Only measures dynamic strain
  - PZT is not sensitive to static loads

Accelerometers

- Used to measure acceleration
- Most common measurement in structural dynamics/solid mechanics
- Two major types of accelerometers
  - Piezoelectric
  - Piezoresistive
- Available in
  - Uniaxial: Measures single direction
  - Biaxial: Measures two orthogonal axes
  - Triaxial: Measures three orthogonal axes

Piezoelectric Accelerometers



Shear Mode Accelerometer

- Used to measure low accelerations
  - Modal levels
  - Shaker Environments
  - Non-shock Environments
- Measure the current from a deformed quartz crystal to estimate acceleration
- Not sensitive to DC

Signal Conditioning

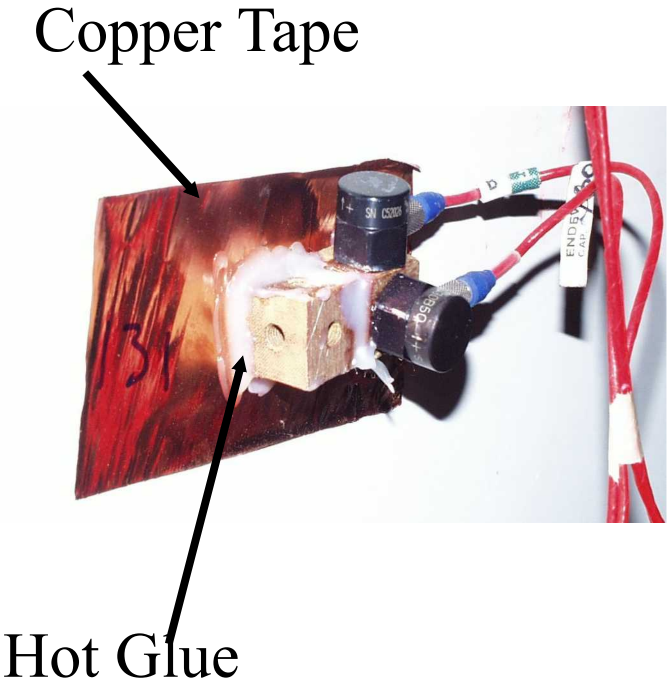
- Three types of Piezoelectric Accelerometers
  - Integrated Circuit (IEPE, ICP, etc)
    - Most common
    - Requires a small current (4-10 milliamps) power
    - Outputs a voltage proportional to acceleration
    - Circuits internal to accelerometer convert charge to voltage
  - Charge Mode
    - Requires external conditioning to convert charge to voltage
  - TEDS (Transducer Electronic Data Sheet)
    - Has internal permanent (ROM) and programmable (EEPROM) memory
    - Has serial number, manufacturer, sensitivity, cal date, etc stored internally
    - Can access serial number, etc through conditioning system
    - Has small amount of internal memory to store other information such as location

Environment Sensitivity

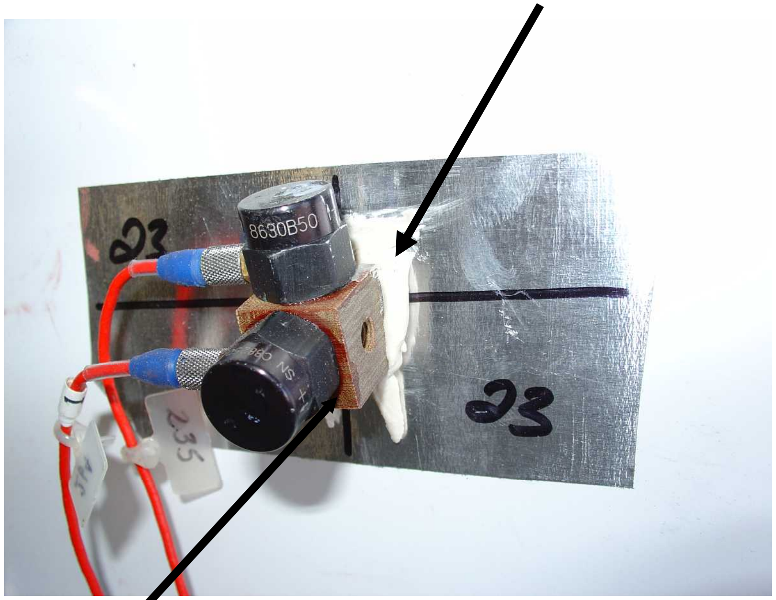
- Base Strain
  - Strain at the base of the accelerometer appears as a measured acceleration
  - Gage needs to be isolated through the use of a mounting block
- Thermal loads
  - Temperature variations cause the sensitivity of the gage to vary
  - May need to insulate gages to protect from thermal variations
- Acoustics
  - Sound waves around test article can induce measured response on accelerometer (non-structural)
  - Test when lab is quite or isolate gage

Mounting Techniques

- Wax
  - Low frequency/Amplitude applications
  - Quick
  - Not permanent or reliable
    - Not for internal gages
- Hot Glue
  - Quick
  - Very common mounting technique
  - Can debond adhesive on mounting surface (copper tape)



Mounting Techniques (con't)



- Super Glue
  - Cyanoacrylate
  - Quick, very common
  - Good for small accelerometers
  - Strong bond
  - No filling capabilities
  - Weak in shear
- Dental Cement
  - Strong, Stiff
  - Can act as filler
  - Good for large accelerometers
- Torr Seal
  - Vacuum bonding agent
  - Very strong bond
  - Not used much with PE

Mounting Techniques (con't)

- Stud Mounting
  - Extremely Strong
  - Used for permanent mounting
  - Sometimes used in combination with a bond
  - Failure requires mounting screw to break

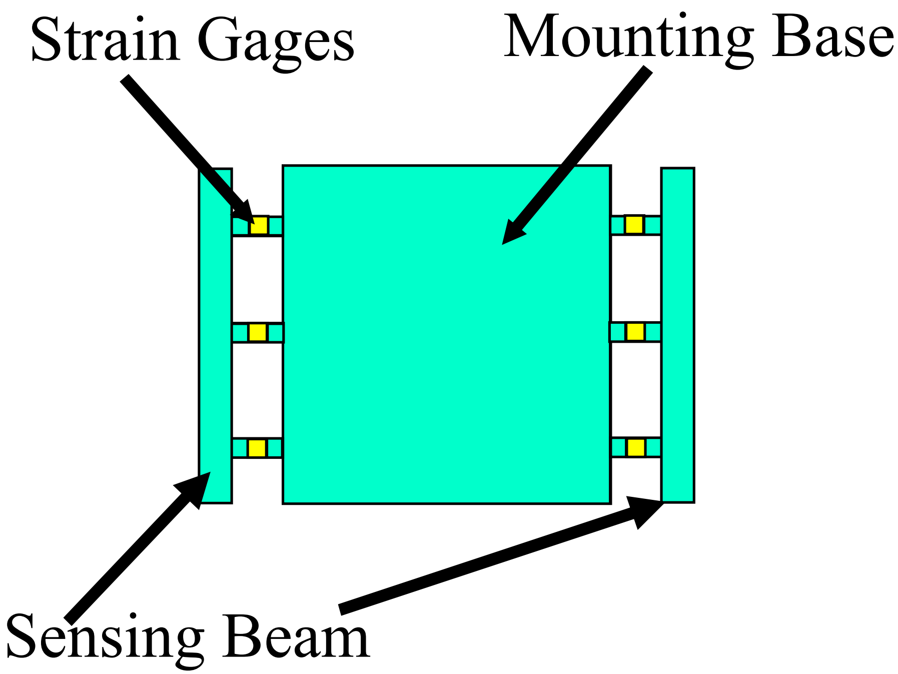
Piezoelectric Accelerometer Summary

- Good for low amplitude, non-shock responses
  - Modal measurements
  - Shaker Environments
- Measures response of crystal to estimate acceleration
- Requires a small current to drive
- Can measure environment as well as acceleration
  - Need to minimize environment sensitivity
  - Acts as an unknown bias (epistemic uncertainty) on the gage
- Mounting dependent on application

Piezoresistive Accelerometers

- Used to measure shock events
  - Hopkinson Bar
  - Drop table
  - Drop/pull-down tests
  - LIHE/Mag-flyer Impulse tests
  - Sled Track
  - Explosive tests

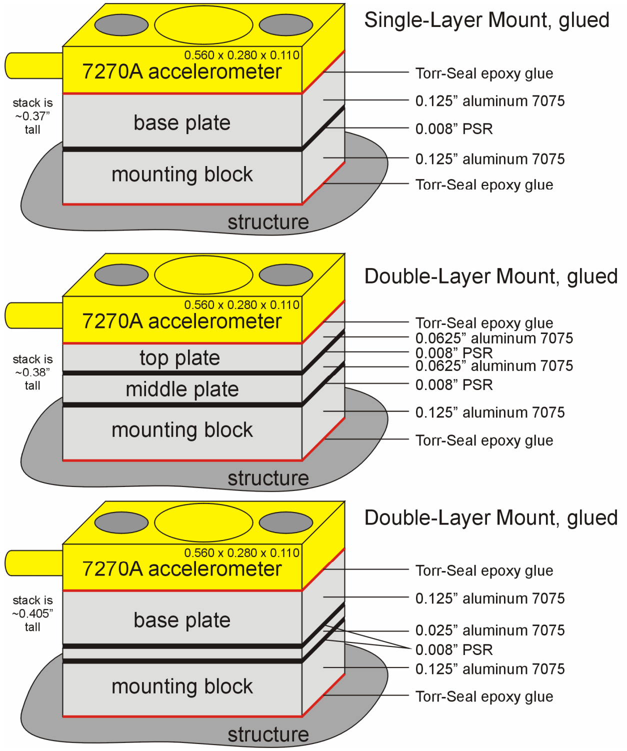
How does a PR Gage work?



- Piezoresistive gages measure the strain developed in a beam during loading
- The strain is linearly related to acceleration (to a point)
- Calibration is used to relate strain to acceleration
- Gage contains three legs of the Bridge
- Conditioning amplifier completes the bridge

Mounting Techniques

- Base Stain Sensitive
  - Mount on a Block
  - Endevco 7270 has mounting requirements called out
- Short duration/High Frequency responses can "ring" the gage
  - Ringing is defined as exciting the natural resonance of the accelerometer
  - Typically for these environments, the gage is mechanically isolated (filtered) to minimize ringing
  - Isolation affects frequency response
    - Can attenuate frequencies of interest
    - Characterize the isolation
- Sensitive to high electric fields
  - Need to isolate/ground properly



Which PR gage do I use?

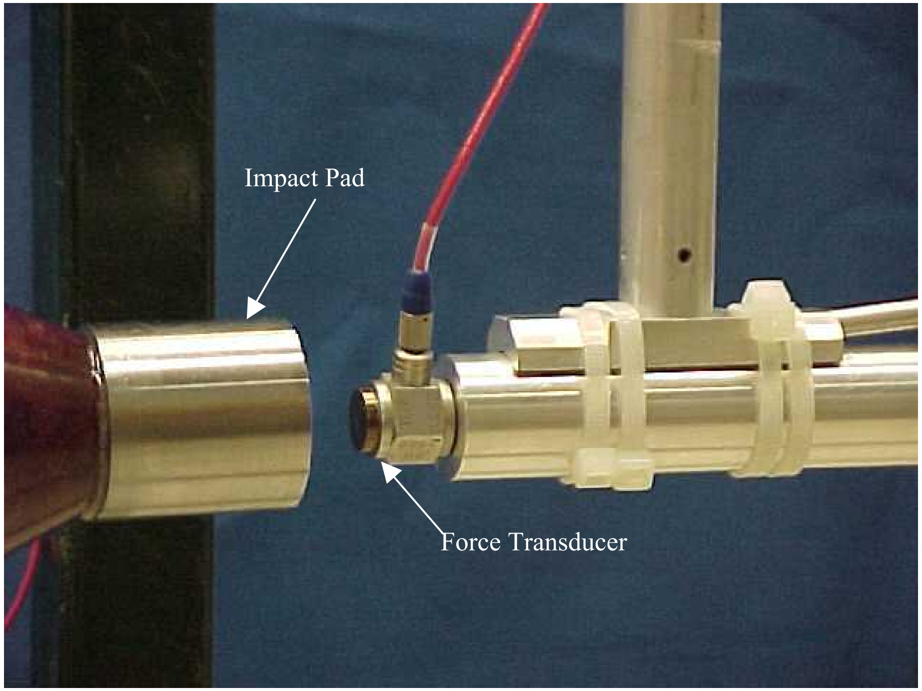
- Expected range of Accelerations
  - 2 kG, 6 kG, 20 kG, 60 kG, 200 kG
  - Size high for application to insure gage doesn't over-range
  - Gage is linear (good) to about 2 (3) times the rated range of gage – except for 200 kG gage
- Mounting Technique
  - If low frequency, hard mount accelerometer to structure
  - If high frequency
    - Choose appropriate isolation
    - Choose gage resonance to be out of bandwidth of interest, if possible

Summary of Accelerometers

- Piezoelectric
  - Low acceleration, low frequency environments
  - Very common in modal applications
- Piezoresistive
  - Shock environments
  - High accelerations, high frequency events
  - May need mechanical isolation (mechanical filtering)

Force Transducers

- Used to measure force
- Available for static and dynamic applications
  - Static works like a strain gage
  - Dynamic operates similar to a piezoelectric accelerometer
    - Down to 0.0003 Hertz for some
    - Based upon charge leakage from crystal
- Available with a built in accelerometer (Impedance head)
- Instrumented bolts are also available to measure preload/fixture loads
- Pressure transducers are similar



Signal Conditioning

- Static Force Gages require bridge completion like strain gages
- Dynamic Force Gages are conditioned with amplifiers used for piezoelectric accelerometers
  - Require a small (4-20 milliamp) current source
  - Output a voltage

Mounting Techniques

- Typically stud mounted or bolted to structure
- Can be part of testing machine (MTS)
- Calibration performed using reference load cell
- Alignment critical to insure accurate measurement (no moments)

Which Force Gage do I use?

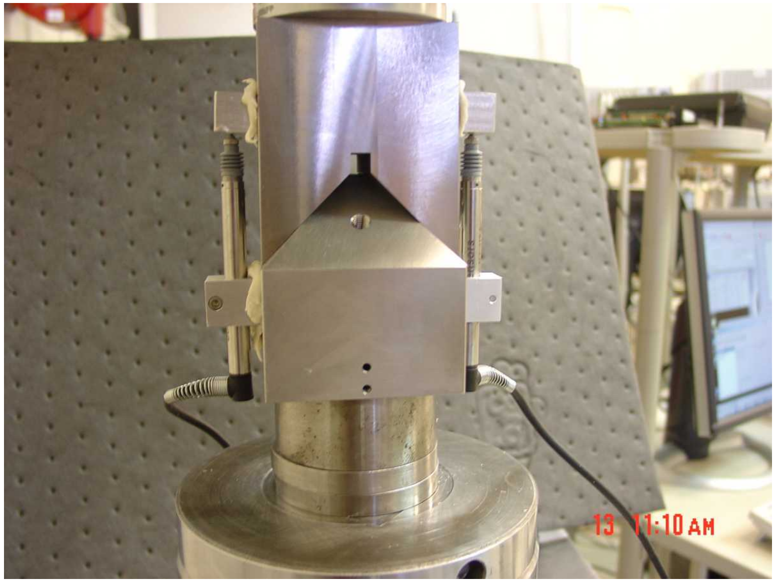
- Static vs Dynamic
- Load range expected
  - Appropriately sized gage will be more accurate in range of interest
- Operating environment
  - Explosive
  - Corrosive
  - High Temperature
- Gage size for application
- Impact of inserting gage into system
  - Typically gage will soften the original system

Displacement Transducers

- Used to measure displacement
- Many different types
  - Linear variable differential transformer (LVDT)
  - String potentiometers
  - LASER based
  - Extensometers (Strain based)
- Frequency response of displacement gages vary greatly

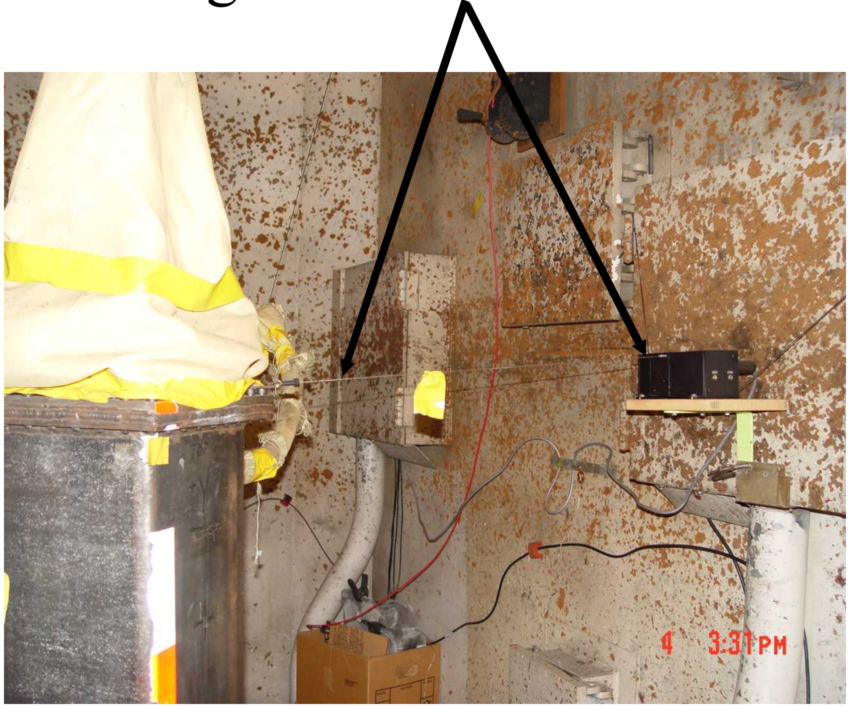
LVDT

- Linear variable differential transformer
- The gage generates a voltage dependent on the location of the center rod
- Has an internal transformer
- Very little applied force
- Very common gage



String Potentiometer

String Potentiometer

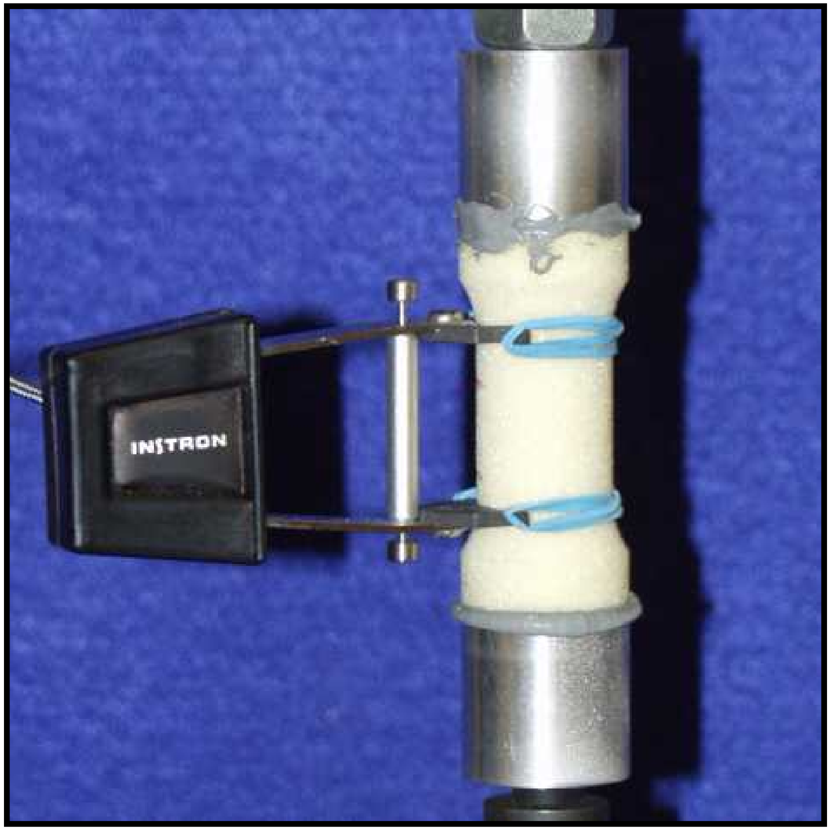


- Very simple in principle
- A string is wrapped around a potentiometer.
- As string is pulled out, the resistance across the pot changes
- Very low frequency response
- Low displacement resolution
- Exhibits drag on string
- Good for measuring very large displacements (inches to feet)

LASER Displacement Gages

- Good for measuring very small displacements (< 0.001 inches)
- Requires accurate alignment
- Non-contacting (no applied force)
- Large mass

Extensometers



- Operates like a strain gage
- Measures very small displacements
- Produces a force in parallel with test region
- Very robust

Which Displacement Gage to Use?

- Estimate displacement range expected
- Is the force over the test region important?
  - If so than non-contacting or low force gages are important
  - If not than more common options are available
- Operating environment (any special concerns)
- Is the mass of the gage important
  - A displacement gage in a drop test with many accelerometers would need to be smaller than a test to yield of a material

Summary

- Many different quantities to be measured
  - Strain
  - Acceleration
  - Force
  - Displacement
  - Velocity (to be covered in a later lecture)
- Different gages for different response levels/environments
  - Important to choose proper gage for application
- Mounting of gage important
  - Ease of mounting vs integrity of mount
  - Mounts can affect response

Thanks for the Help!

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Measurement Techniques for Structural Dynamics and Solid Mechanics

01520

November 6, 2007

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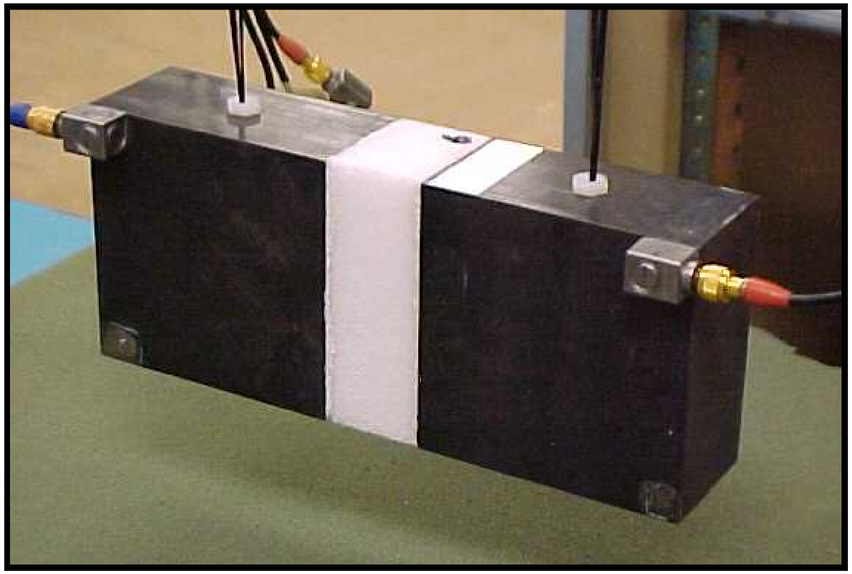
Topics

- Test Preparation
- Test Setup
- Data Quality Evaluation
- Signal Processing

Test Article Example



- Two large masses connected with a sample of foam
- Model validation experiment for the foam
- Example will be used throughout lecture/lab

PreTest Planning

- Identify Purpose of Test
  - Model Validation
  - Production Qualification
  - Control Design
  - Identification (Experimental)
  - Damage Assessment
  - Trouble Shooting (instead of Problem Analysis)
- Level of Rigor
  - Low (Quick, few accelerometers, only relative amplitudes)
  - Medium (many accelerometers, model assessment helpful)
  - High (many accelerometers, care in input/response placement, absolute amplitude matters, reviews and assessments to insure quality of test)

Safety Issues

- Generate Test Plan of work
  - Hazards mitigated by ISMS
  - Classification
  - Desired data, analysis and format
  - Input/Response locations
  - Reporting requirements
- Perform Safety Assessment
  - Preliminary Hazard Assessment
  - Experiment Development Plan
  - Management Operational Review

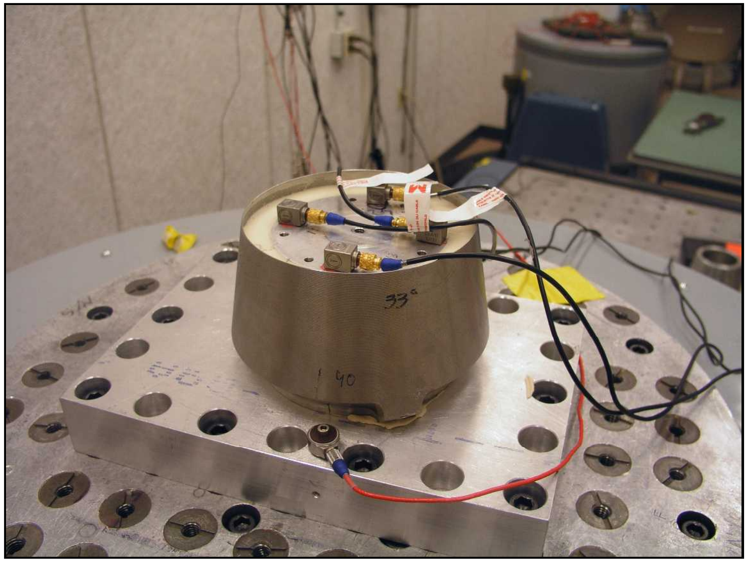
Boundary Conditions

- Boundary Condition characterization crucial to understanding results
  - Perfect boundary conditions do not exist
  - Fixed boundaries are not fixed and have some flexibility
  - Suspension rigging will have stiffness and damping
  - Any fixturing will influence the measurements in some way
    - The key is to minimize/*understand* the effects of the fixture

Free Boundary Condition

- Can only really be achieved on-orbit
- Can be simulated on the ground with soft suspensions
  - Suspension by bungee cords
  - Placing test article on soft, resilient foam
  - Structure will be preloaded by suspension
- First frequency (flexible response) of the structure will not be affected by the suspension if it is approximately 10 times higher than highest rigid body frequency
- Suspension system will change the damping
- Suspension system should have safety controls to minimize damage in the event of failure

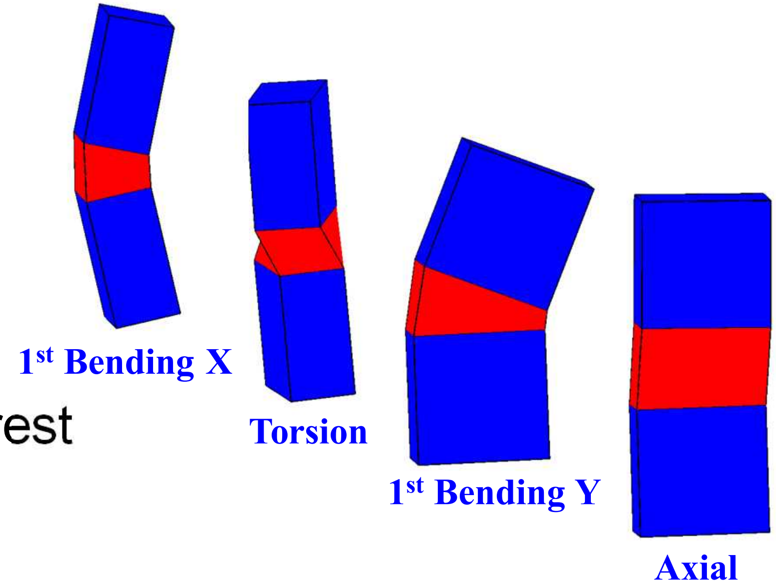
"Fixed" Boundary Condition



- True, zero displacement/rotation boundary cannot be realized
  - "Everything is Jello above 500 Hz" – Smallwood
  - Bolts have flexibility
  - Seismic masses are flexible
  - Shaker heads are flexible
  - Fixturing is flexible
- Understand fixture flexibility through instrumentation
  - Triaxial Accelerometers in the corners of your fixture
  - Base accelerometers

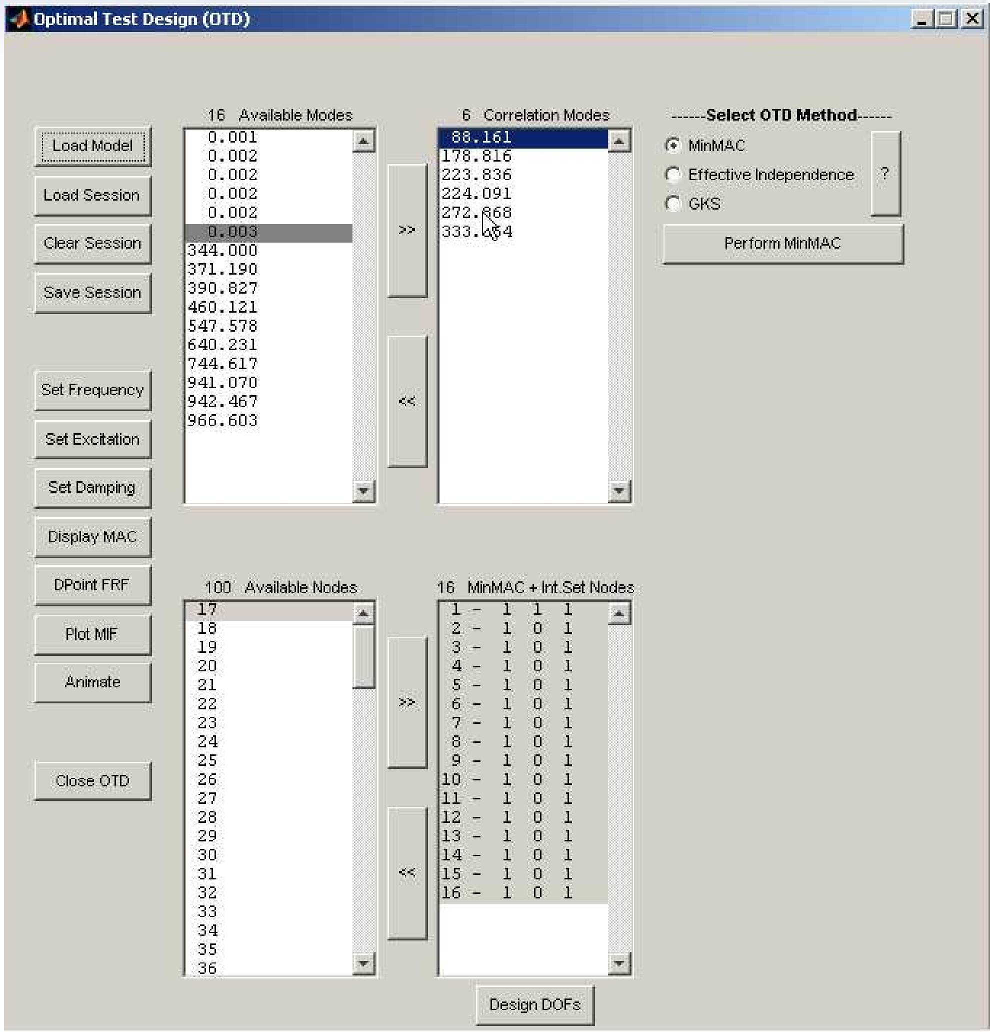
Identification of Input/Output Locations

- Intuitive
  - Instrument to identify key modes
    - Bending
    - Axial
    - Torsion
  - Instrument all appendages of interest
    - Antennas
    - IMUs (Inertial Mass Units)
    - Fins
    - Cantilevered Components
  - Models can provide valuable insight for test planning



Identification of Input/Output Locations

- Model based identification of Input/Output locations
  - Important for model validation
  - Typically based upon Observability/Controllability of Modes
  - OTD is the in-house code used
    - Utilizes the Modal Assurance Criteria
    - Requires a FE model modal solution
    - Only as good as the model
  - Other techniques/packages available



Data Acquisition Parameters

- Are multiple data acquisition systems required?
  - High cost, one-off tests should have a backup system
    - Backup *may* not have to be as “complete” as primary system
      - Lower sample rate
      - Less resolution
- Sample Rate
  - Need to know maximum frequency of interest and maximum frequency excited
  - Piezoresistive (and other) gages
    - Set Sample rate high enough to capture resonance of gage
    - Necessary to fully assess over ranging
  - Understand anti-aliasing filters (to be discussed later)
  - Data can always be decimated (resampled at lower rate), if necessary

Sampling Parameters

- Bandedge Predictions
  - Necessary to optimize dynamic range of A/D process
  - For modals, range is set based upon input (Autoranging)
  - For one-off testing, range is more critical
    - Use model to predict expected ranges
    - Add large safety factor to prevent overloads
    - Be conservative with gage choices
    - Overloads, clipping, and under-sized gages exceeding capabilities suck

Duration Specification

- Duration
  - Fully capture event of interest
  - Based upon duration/type of input
    - Long duration input requires longer recording times
    - Random inputs require very long durations
    - Shock events are typically short
  - Frequency range of interest
    - Would like several cycles of lowest modes
  - Dependent on Damping
    - Low damped structures require longer durations
    - High damped structures can use shorter duration
  - Can always truncate time history if too much data is recorded

End-to-End Calibration

- Uncertainty Quantification of Data Acquisition
  - Some labs quantify each component of the Data Acquisition system is individually
  - Some labs perform end-to-end
  - Combination
- Interactions between the cabling and components could produce variations
- Need to send a known signal through as much of the system as possible to insure data quality
  - Pure sine tone at single frequency
  - Random Inputs
  - Chirps

Data Setup Check-outs

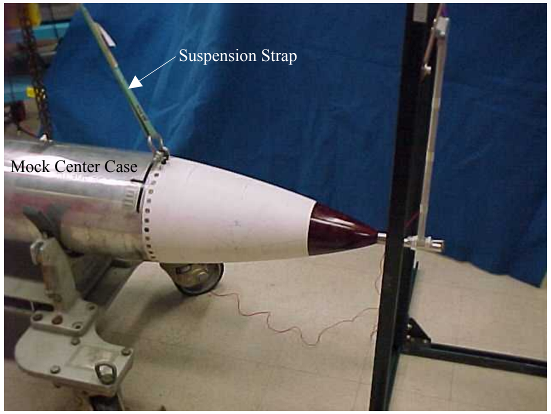
- Many accelerometers, many cables provide greater chance for errors
- Careful bookkeeping will help
- More rigorous to verify location of gages
  - Squeeze test
    - Some accelerometers are base strain sensitive
    - “squeezing” these mounted accels should induce a response at the data acquisition system
    - If the accel produces a response on the expected channel then all is well
  - Thermal test
    - Similar to squeeze test, many accels are sensitive to heat (Kistler – B50)
    - Place a heat source (soldering gun) near (don’t touch) accelerometer
    - An expected response at the data acquisition system will verify the location

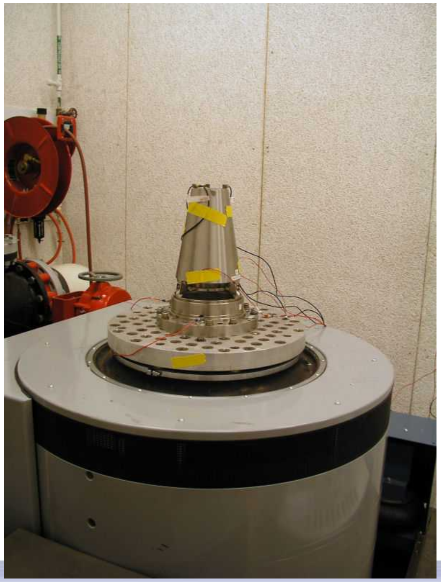
Data Setup Check-outs

- Quick Modal Test to verify channel setup
  - Quick Modal consists of impact test
  - Frequency Response Function/Time history
    - Verify that the accelerometers are functional
  - Low Frequency Mode Shape
    - Orientation of accelerometers
    - Location of the accelerometers
    - Approximately the correct sensitivity
    - Confirm accelerometers are functional

What input do I use?

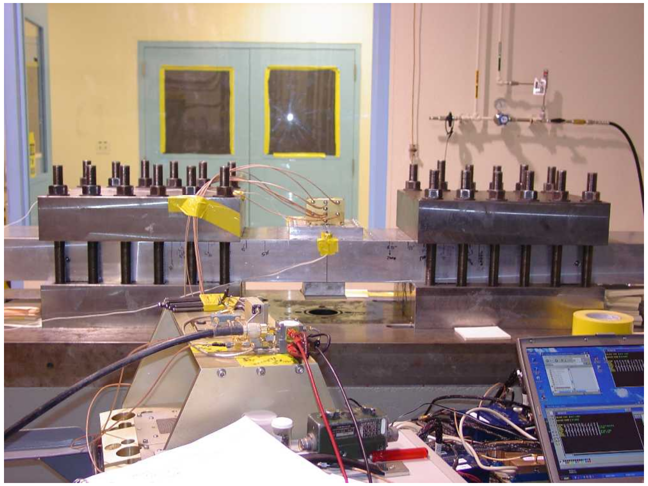
- Hammer Impact (Modal)
  - Quickest first time setup
  - Can exercise nonlinearity
  - Minimal boundary condition effects
- Shaker (Modal, higher levels)
  - Better signal/noise ratio than a hammer impact for modal
  - Input can be tailored to frequency band
  - Minimizes nonlinearity for modal
  - Requires fixturing to interface with structure
  - Longer first time setup
  - Faster for multiple inputs or retaking data
- Explosive (High level)
  - Plenty of energy
  - Typically expensive (few number of tests)
  - Requires large effort to characterize input





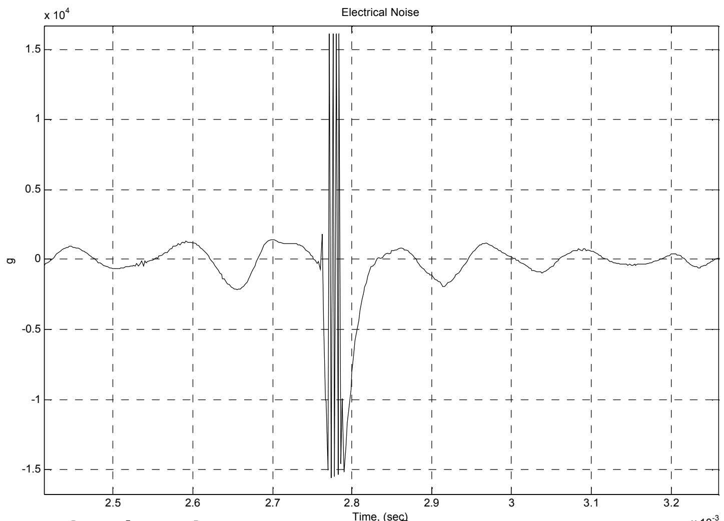
Shock Inputs

- Hopkinson Bar
  - Smaller test articles
  - Repeatable, easily characterized
- Drop table
  - Large velocity changes
  - Single sided inputs
- Resonant plate/beam
  - Double sided inputs
- Others – pneumatic actuators, air guns, etc.

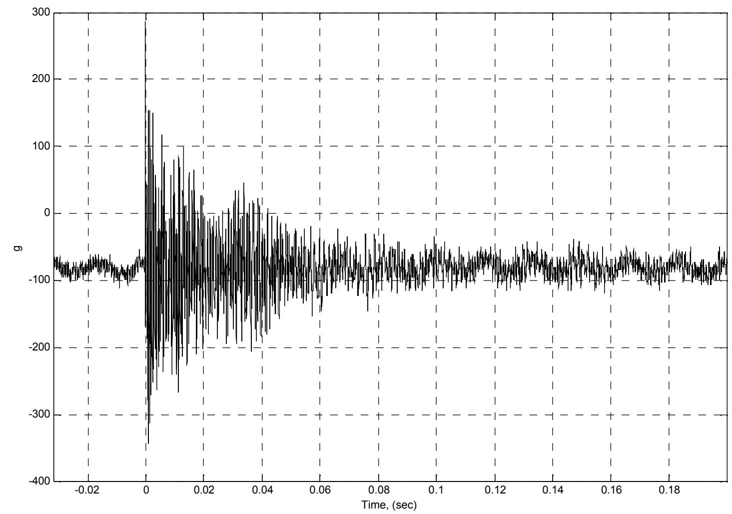


Data Quality Evaluation

Electrical Noise



Noise/60 cycle

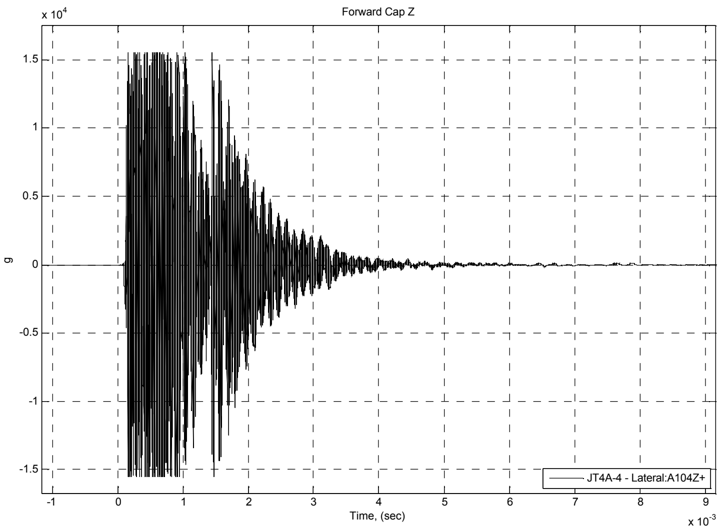


- Electrical noise comes from many sources
  - Line (60 cycle)
  - Broken cables, loose connections
  - EMF
  - Ground loops
- Sometimes can be removed (minimized) with signal processing

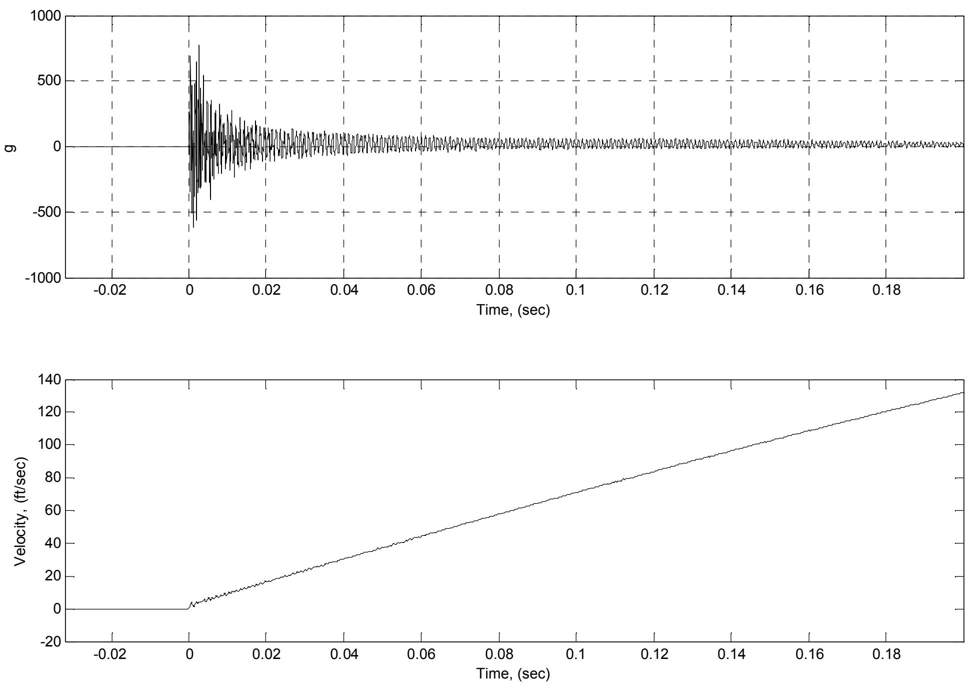
Data Quality Evaluation

- Clipping occurs due to bandedge set too tight
- Sometimes data is salvageable
- Need good predictions and lots of safety factors on expensive tests
- Modal is usually set through trial and error (low cost of repeating test)
- Gage range can also be exceeded producing bad data which looks "good"

Overload/Clipping



Data Quality Evaluation

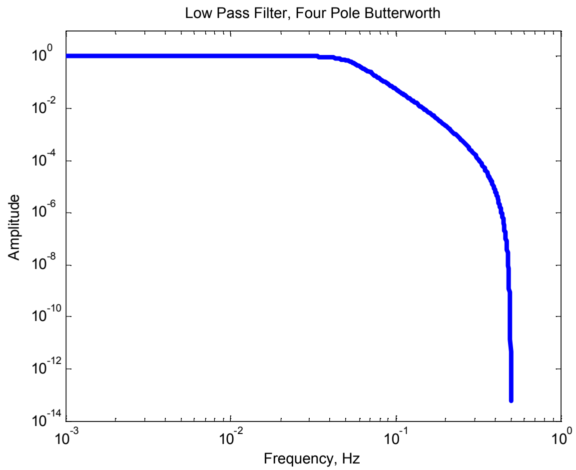


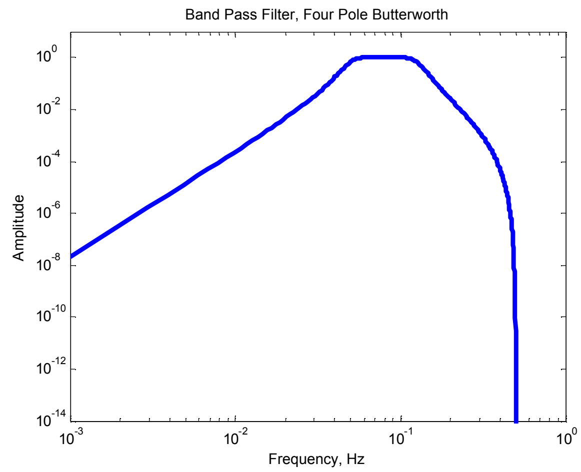
- Zero shift can occur in shock events
- Not visible in measured acceleration
- Very clear in integrated acceleration (velocity)
- Causes problems in calculated quantities
  - SRS (flat at low frequencies)
  - FFT (can corrupt all of frequency range)
- If it is mild, it can sometimes be reduced with signal processing
  - Produces "plausible" trace
- Double hits
- Coherence (output~input)

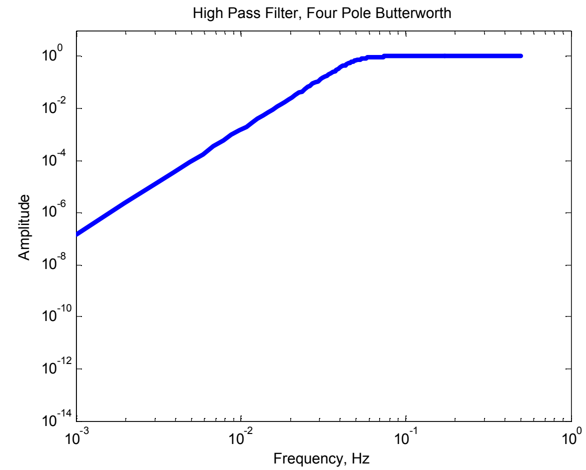
Signal Processing

- Some form of processing/analysis necessary for most/all measurements
- Anti-aliasing filters critical to good measurements
  - Analog only, low pass filters
  - Removes frequency content above Nyquist frequency
  - Without some form of anti-aliasing filters, data is questionable
- Digital filtering most basic form of post processing
  - Minimizes out of band response
    - Isolates response of interest
  - Minimizes high frequency noise

Filtering

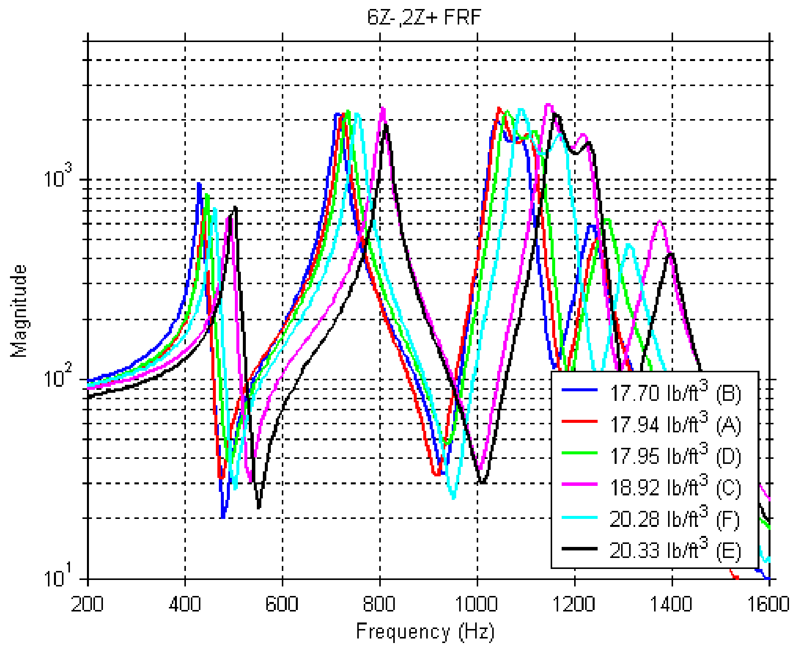






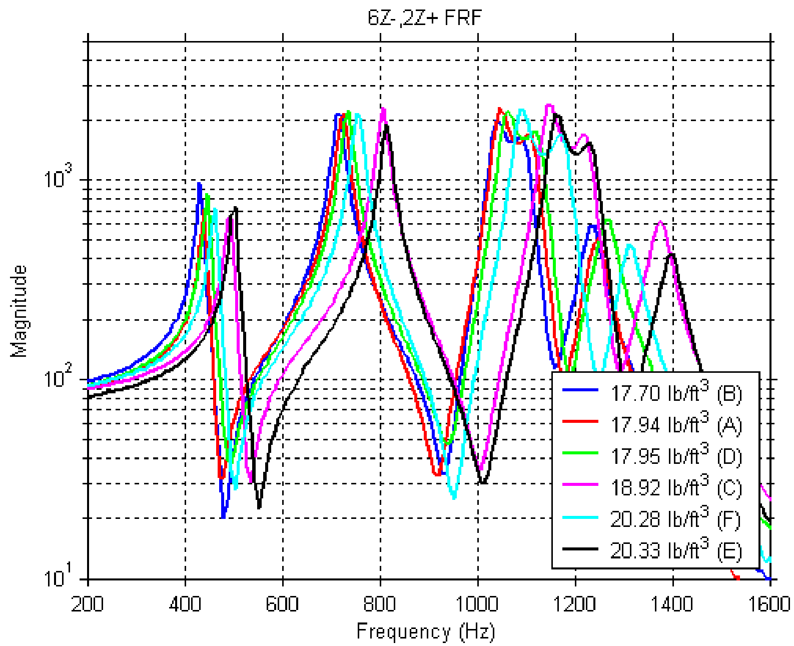
- Low pass (Left) removes high frequency content
- Band pass (center) removes high and low frequency content
- High pass (Right) removes low frequency content

Frequency Response Function



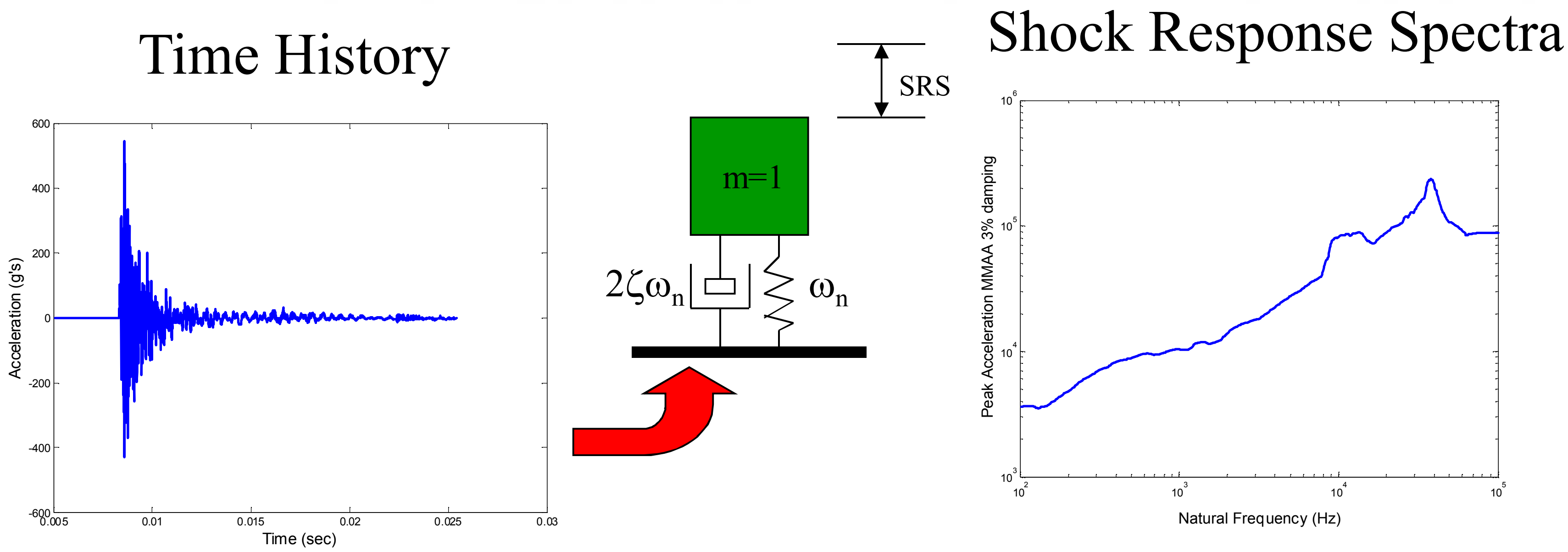
- Frequency Domain, used in structural dynamics
- Transfer function between single point input and single point response
- Requires measurement of input and response

Frequency Response Function



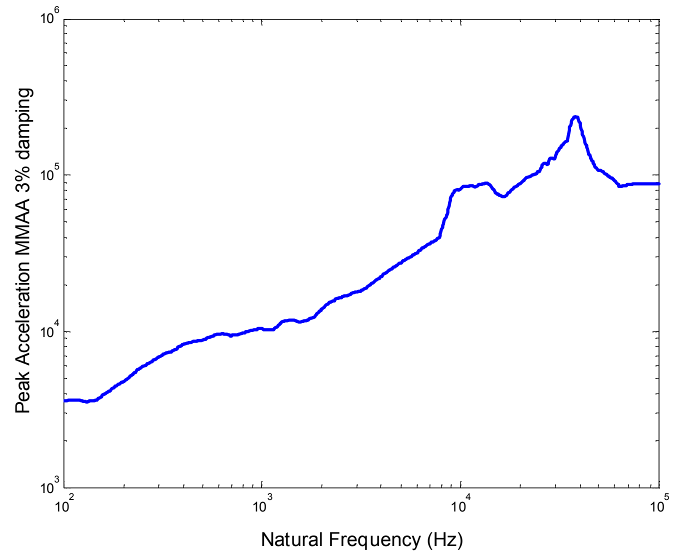
- Peaks indicate natural frequency (pole, mode, resonance)
- Width of peak indicates damping levels
- Low frequency shows static (rigid) response, boundary response
- Dips indicate frequencies where location does not respond (zeros, anti-resonances)

Shock Response Spectra



- Used to assess short duration, transient events
- Calculated using response of a single degree of freedom oscillator to a base input of the signal

Shock Response Spectra

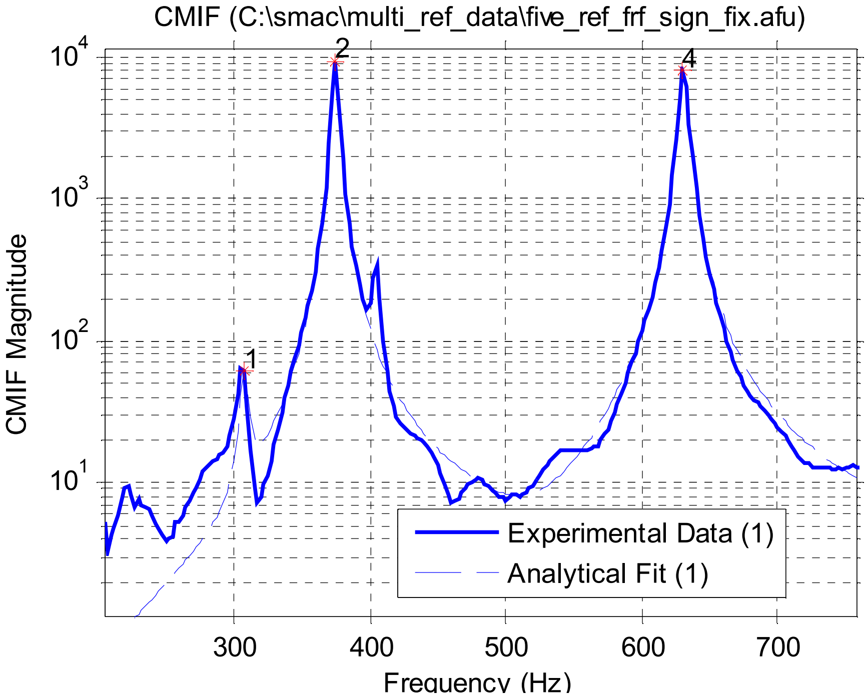


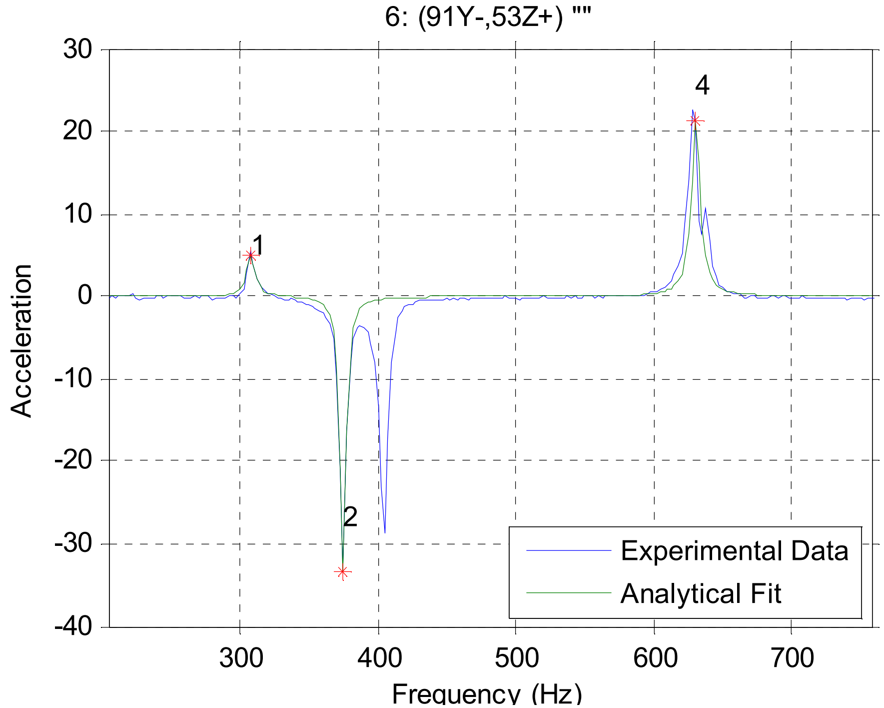
- Abscissa is "natural frequency" not "frequency"
- Low frequency asymptote indicates velocity change
- High frequency asymptote indicates peak acceleration
- Typically plotted in "g's"

Structural Dynamics Curve Fitting

- Curve fits typically performed on Frequency Response Functions
- Fitting parameters
  - Frequency
  - Damping
  - Mode shapes
- Many different methods available, we use SMAC
- Fit quality assessed using Mode Indicator Functions
  - CMIF (Complex mode indicator function)
  - NMIF (Normal mode indicator function)

Fit Quality Comparisons





Complex Mode Indicator Function

Frequency Response Function

- Fits performed using SMAC

Data Management and Archival

- Large quantities of data can be produced
- Keeping track of data for documentation and archival important
- Ability to track processing and pedigree of data difficult
- Many test parameters need to be recorded/documented
- Need some form of database
  - IMAT – Matlab based, written by ATA Engineering
  - sdChannels – Matlab based, currently under development at SNL

Summary

- Test Planning important
  - Safety/hazard concerns
  - Location of sensors
  - Type of excitation
  - Boundary Conditions
- Data Quality is critical
  - End-to-End Calibration
  - Preliminary data checks
  - Signal Processing
- Documentation and Data Archival Important