Structural Health Monitoring Using
Statistical Pattern Recognition

Data Acquisition for Structural Health Monitoring

Presented by
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The Structural Health Monitoring Process

1. Operational evaluation

2. Data acquisition & networking

- **Data Cleansing**
- **Data Normalization**
- **Data Fusion**
- **Information Condensation**

3. Feature selection & extraction

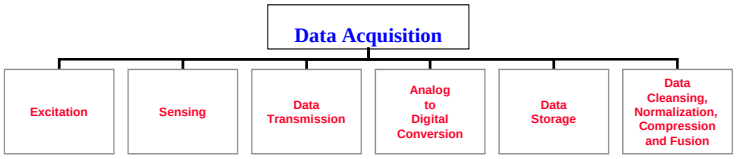
4. Probabilistic decision making

Outline

- Data acquisition components
- System and component level considerations
- Excitation
- Sensing modalities and issues
- Data transmission and networking
- SHM sensing system challenges

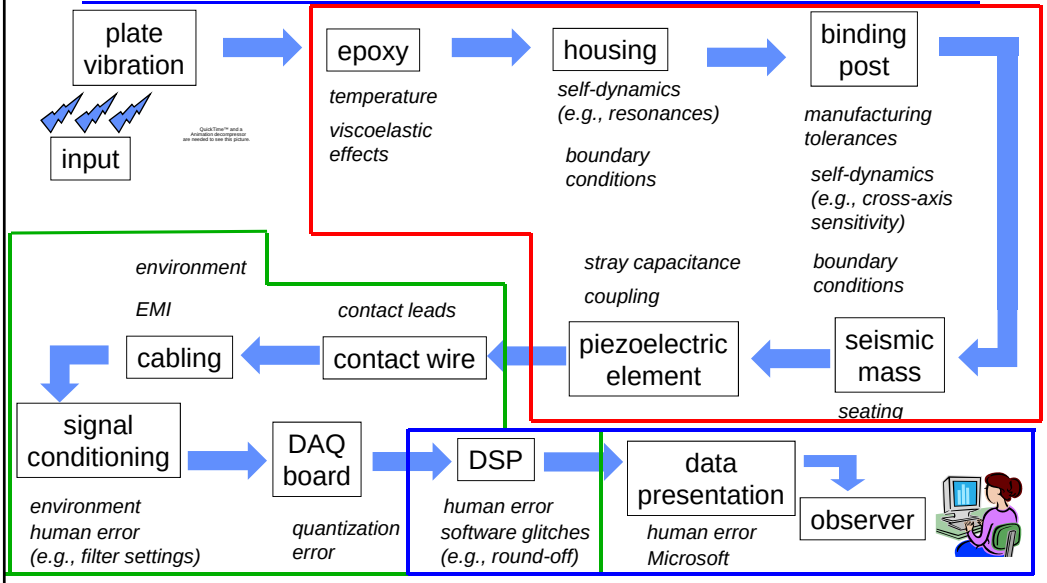
Introduction

- Obtaining accurate measures of the system's dynamic response is essential to structural health monitoring.
- The data acquisition process can be divided into six parts:



- Signal processing is often integrated with data acquisition systems.
- Data cleansing, normalization compression and fusion is integrated in this process as well.
- Increasingly, the development of system-on-a-chip capability has allowed data acquisition components to be directly integrated with feature extraction or other traditional 'software' tasks.

The Process of Getting a Measurement



Method for Obtaining Useful SHM Measurements I

Level 1:

System-level Considerations

What features will be extracted from data for SHM assessment?

- *May determine the type(s) of primary data to be acquired*
- *May determine the periodicity of primary data collection*

Active or passive sensing?

- *Determines need for active actuation (i.e., not ambient)*
- *Strongly influences power, networking, and bandwidth demands*

What other factors may need to be considered for accurate assessment?

- *Operational (e.g., loading conditions during primary data collection)*
- *Environmental (e.g., ambient conditions during primary data collection)*
- *Identification of sources of error*

Overall imposed limitations/constraints?

- *Economic (e.g.,fixed budgets)*
- *Political (gov't or social influences)*
- *Environmental (e.g., regulations or required procedures)*

Method for Obtaining Useful SHM Measurements II

Level 2: Data Acquisition Component Considerations

• *sensitivity and bandwidth*: What is the response of the sensor to inputs (or the actuator to command signals), usually over a range of time scales? (Usually given in terms of the transfer function)

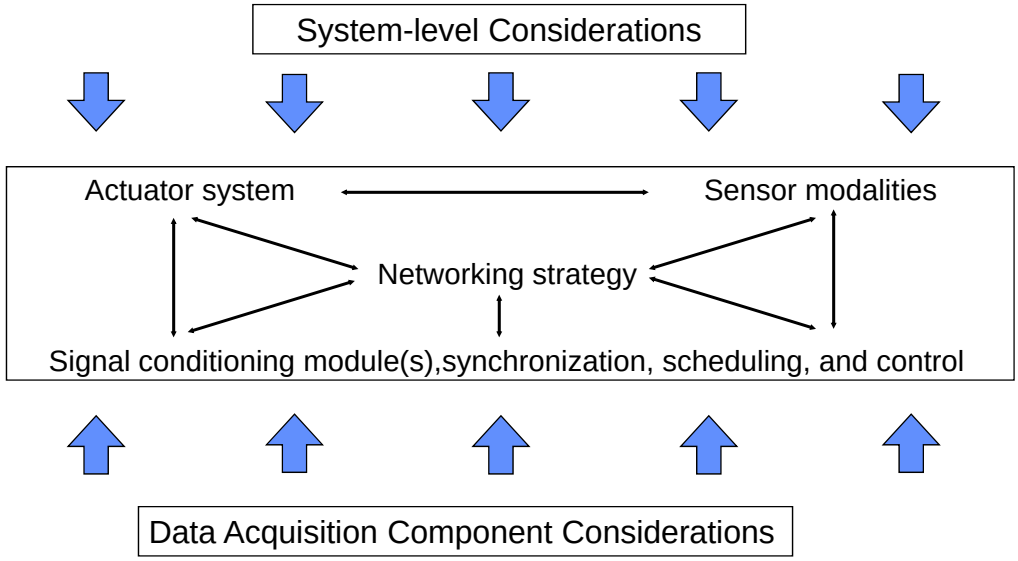
• *resolution*: What is the minimum detectable value of the intended input or the minimum achievable output? (Usually given in terms of power or amplitude spectral density)

• *cross-axis sensitivity*: How much does the sensor respond to inputs (or the actuator excite output) not aligned with the primary sensing (actuation) direction? (Usually expressed as a fraction of the main sensitivity)

• *multiple resonances*: Does the sensor (actuator) have multiple nonlinear (resonant) areas that affect sensitivity and bandwidth? (The answer is typically, "yes").

• *sensitivity to extraneous measurands*: Does the sensor (actuator) respond to unintended inputs (commands)? (Does an accelerometer, for example, also respond to strain or temperature inputs yielding "false" signals?)

Putting it All Together



Time Histories

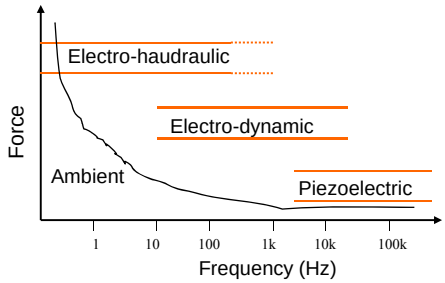
- For dynamic response measurement a time history, sometimes called a signal, is a sequence of numbers representing some parameter that has been sampled at discrete and typically uniform time increments.
- Kinetic/kinematic input- and kinematic response-time histories are the most common measured quantities for damage detection.
  - Force or displacement are typical inputs
  - Displacement (or strain), velocity, and acceleration are typically measured outputs
- Time-histories can be classified as either ***random*** or ***deterministic,*** with some subclassifications.

Classification of Signals

- **Deterministic (data described explicitly by mathematical relationships, and the same initial conditions = same response)**
  - Periodic: steady-state, repetitive with finite period (force resulting from rotating imbalance)
  - Chaotic: steady-state but no repetition, appears 'random-like' (often the result of nonlinearity)
  - Transient: not a steady-state, invariant motion (impulse response, relaxation)
- **Random (characterized by statistical descriptors)**
  - Stationary: described by constant parameter model
    - $x(t)=a_1f_1(t)+ a_2f_2(t)+ a_3f_3(t)$ where $f_i(t)$ are random functions
    - Aerodynamic loading on aircraft wing
  - Non-stationary: described by a time-varying parameter model
    - $x(t)=a_1(t)f_1(t)+ a_2(t)\, f_2(t)+ a_3(t)f_3(t)$
    - Earthquake ground motion
  - Ergodic: a class of stationary data whereby *time* averages and autocorrelations are equal to the corresponding *ensemble* time averages and autocorrelations (this allows us to use, in practice, a single time history to compute properties)

Excitation

- Excitation is the process of applying a time-varying input to the system in order to generate a dynamic response.
- Selection of the proper excitation methods will be influenced by many factors including:
  - The size of the structure.
  - Required frequency range and amplitude of inputs.
  - Operational constraints associated with the system.
  - Power availability.
  - Cost.



Excitation sources are classified two ways:

- **Measured/controllable**: usually imposed deterministic waveforms
- **Unmeasured/uncontrollable**: usually stochastic ambient input sources (wind, waves, traffic, etc.)

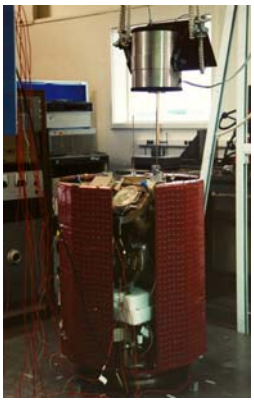
Excitation Signals

- **Steady-state Deterministic** (stationary periodic; chaotic)
- **Nonstationary Deterministic** (impulse; step-relaxation; swept sine/chirp; quasi-periodic)
- **Random** (full random, band limited to actuation bandwidth window; pseudo-random, constant amplitude, random phase; burst random, short in time but fully random)
- **Ambient**
  - Often the only method that can be used for large structures, or if the structure is not to be taken out of service, or if regulations prohibit introducing energy into the structure.
  - Parameter identification is more challenging without a measured input.

Mirage F1-AZ under controlled ground vibration testing.

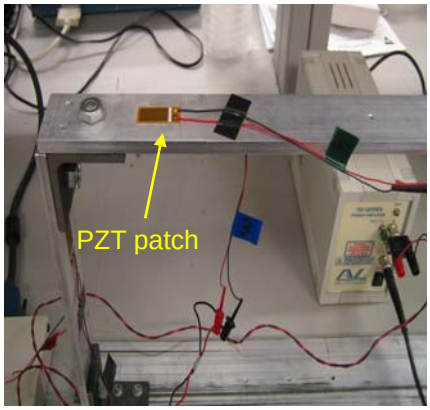
Ship on the high seas.

Measured Input Excitation Examples



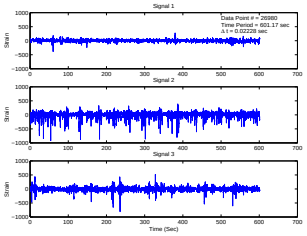
Electro-dynamic shaker applying random excitation to satellite (low-frequency, fully random)

Tensioning device putting an impulse force load on the rotor (wide-band, transient deterministic)



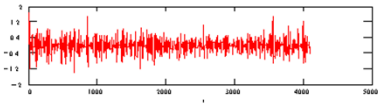
Piezoelectric patches being used to impart high-frequency Lamb waves on a frame structure (periodic deterministic)

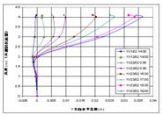
Unmeasured Input Excitation Examples



Norwegian Navy composite fast-patrol boat hull vibration strain response to wave impacts.

Di-Wan Towers (Shenzen, China) sway and vibration acceleration response to wind.

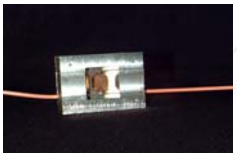




Primary SHM Sensing Modalities

- Most modern sensors used for SHM convert measured quantity (force, acceleration, displacement, etc.) to an analog electrical signal.
- Sensors can be classified as contacting and non-contacting.
- Discrete sensors (surface point, contacting measurements)
  - Piezoelectric and piezoresistive force transducers
  - Accelerometers
    - Piezoelectric
    - Piezoresistive
    - Capacitive
    - Servo
    - Fiber optic
  - Strain gages
    - Foil
    - Fiber optic
  - Impedance (piezo)

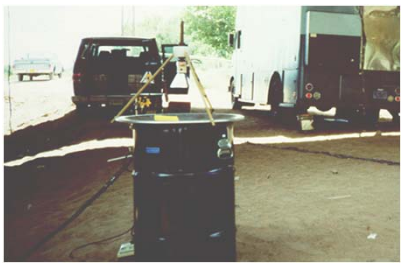


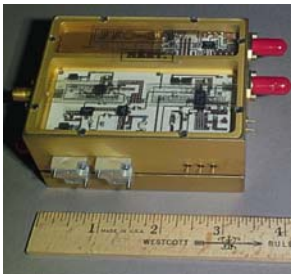



Non-contacting Sensors

- Scanning laser Doppler velocimetry
- Laser holography
- Laser/microwave displacement measurement systems
- GPS


LDV


Microwave Interferometer


LANL HERTS

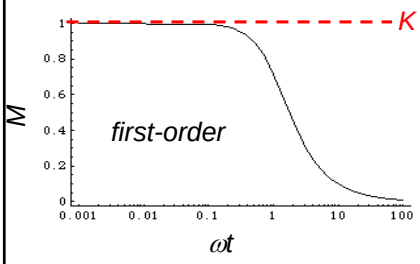
Sensing Issues: Sensitivity

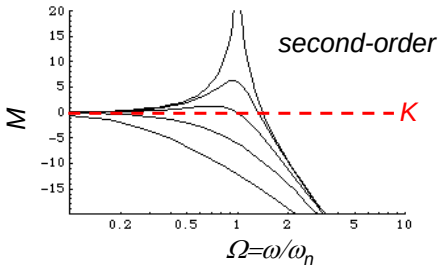
static sensitivity, *K*: sensor's static response to a static input; the steady-state response to a unit amount of step input yields a sensor output of *K*:

$$y(t) = K \qquad y(t) = K + (K - y_0)e^{-t/\tau} \qquad y(t) = K - Ke^{-\zeta\omega_n t}\left(f(\zeta)\sin(\omega_d t + \phi)\right)$$

zero-order *first-order* *second-order*

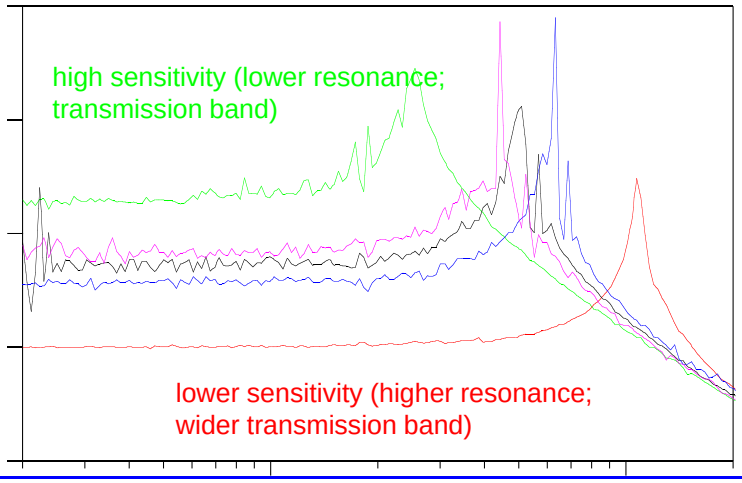
dynamic sensitivity: the modification of the static sensitivity by dynamical properties of the sensor system; the steady-state response to a unit input at a certain frequency





Tradeoff: Sensitivity vs Bandwidth

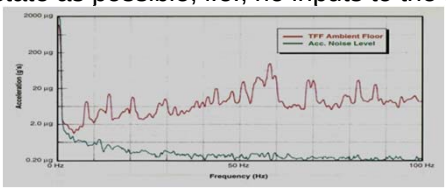
The mechanical designs of seismic mechanical motion sensors often involve design trade-offs between performance properties: higher sensitivity often means a lower transmission band:



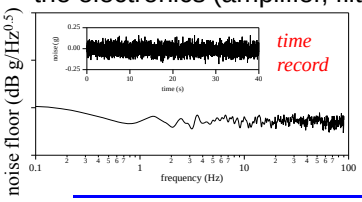
Resolution

Resolution refers to the sensor's minimum detection capability for the intended input; this property is usually expressed as a power or amplitude spectral density

• One way of determining resolution capability is to take data with the sensor in an as quiet an environmental state as possible, i.e., no inputs to the sensor

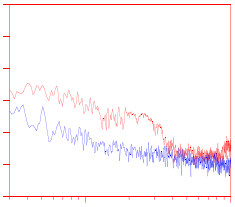


• The practical resolution capability not only includes the sensor dynamics but all aspects of the electronics (amplifier, filter, D/A)



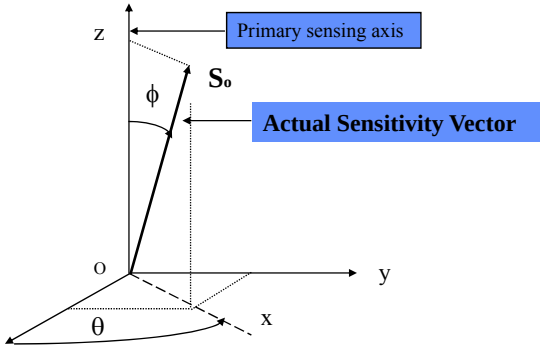
FBG optical accelerometer
• flat response over wide bandwidth
• 3 mg/Hz$^{0.5}$ resolution over all freq.

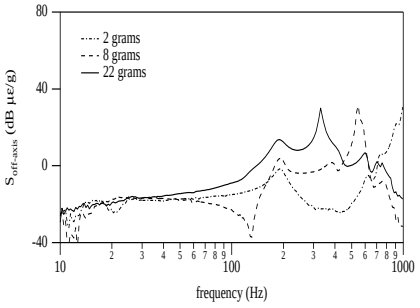
interferometric optical accelerometer
• 2 μg/Hz$^{0.5}$ resolution at low-mid freq.
• electronic noise rise at low freq.



Cross-Axis Sensitivity

Design imperfections often cause the intended sensing axis to be misaligned with the actual sensitivity vector, leading to cross-axis sensitivity:





The sensitivity vector for a single intended axis may be characterized by its orientation in θ and ϕ:

$$\mathbf{S} = \{K\sin(\phi)\cos(\theta)\}\mathbf{i} + \{K\sin(\phi)\sin(\theta)\}\,\mathbf{j} + \{K\cos(\phi)\}\mathbf{k}$$

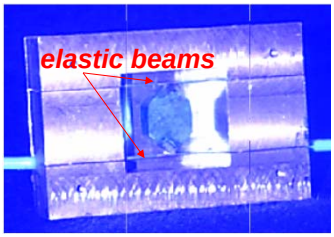
$$\mathbf{S}_{ideal} = K\mathbf{k}$$

Usually characterized in same units as sensitivity

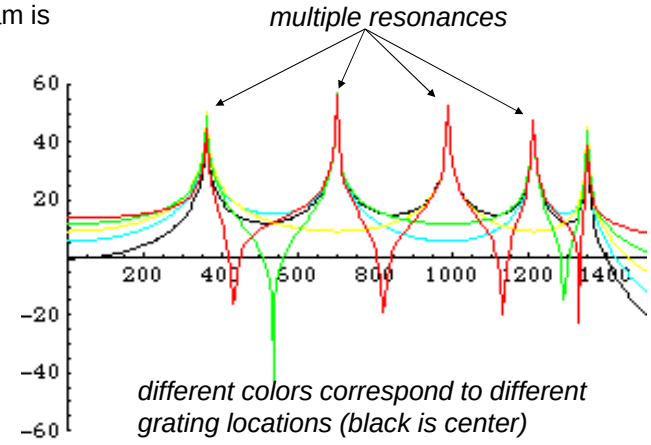
Transmission/Linearity Bands

- In reality, most sensor transducer elements comprising the “mass” and “spring” elements are *themselves* continuum structures and thus have multiple resonances

- Case of FBG accelerometer: elastic beams used as springs, and the full-spectrum frequency response diagram is



the beam/mass system has multiple resonances and multiple transmission bands



Sensitivity to Extraneous Measurands

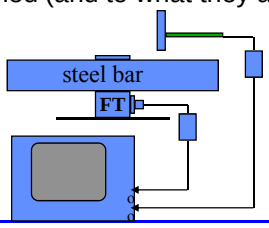
- The elements of many sensors are often sensitive to unintended inputs (due to their construction, operation, or connection to other elements), making the sensor produce a signal even when an actual intended signal is not present

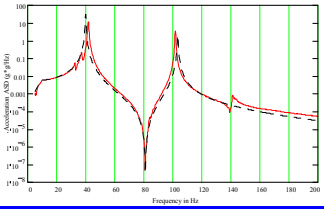
- Some examples include temperature, pressure, or strain dependences; for example, with the FBG accelerometer, what if the ambient temperature changed? FBGs are just strain gages, so they will measure temperature.

- Some force transducers (which are just like accelerometers in design!) have bending moment sensitivity and base strain sensitivity...local bends or strains applied at the attachment points can cause a signal because the housing is coupled into the sensor dynamics

- How sensors are attached (and to what they are attached!) are CRITICAL!

The force transducer is supporting a structure with large inertia, and its modes (translational, bending) are being detected.*





*K. G. McConnell and P. S. Varato, “A Model for Force Transducer Bending Sensitivity and Response During Calibration,” Proc. 11th IMAC, pp. 516-521, 1993.

Signal Conditioning Issues: A/D Conversion

- Analog to digital conversion is the process of converting the analog signal from a sensor to a digital signal that accurately represents the measured time-varying physical parameter.
- Issues

  1. Sampling rate (maximum frequency to be resolved; Nyquist criterion: $f_{sample}>2f_{max}$)

  2. Sampling duration (frequency resolution, Rayleigh criterion: Δf=1/time record length)

  3. Averaging (reduction of zero-mean, non-coherent noise)

  4. Quantization (converting analog signal to closest discrete value available in A/D converter hardware; error depends on word size, usually 8-24 bits and voltage dynamic range of reader)

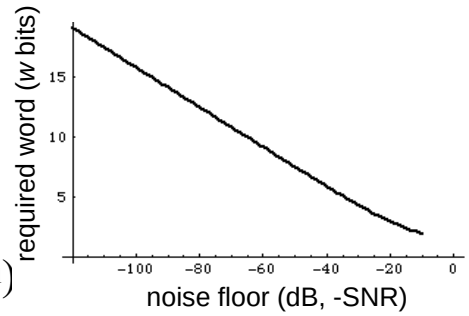
Aliasing and Quantization Noise

As f_s decreases below the Nyquist frequency $f_N = 1/2/\Delta t$, each frequency f below f_N is potentially aliased by frequencies $2nf_N$ +/- f, where n is any integer.

voltage resolution: $\Delta V = \frac{V_{\text{range}}}{2^{w-1}-1}$

noise floor: under ideal A/D conversion, the round-off error is uniformly distributed between V+ΔV and V-ΔV, so

$$\text{SNR} = 20\log\frac{V_{\text{range}}}{\sigma_V} = 20\log\frac{\left(2^{w-1}-1\right)\Delta V}{\Delta V/12} = 20\log 12\left(2^{w-1}-1\right)$$



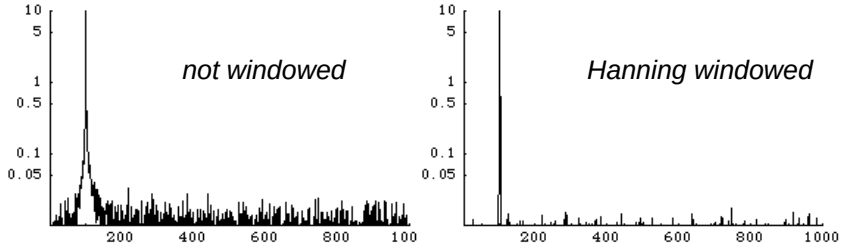
Signal Conditioning: Data Cleansing

- Data cleansing is the process of selecting, modifying or rejecting acquired data before it is passed on to the feature selection process.
- Many times data cleansing will be performed in a qualitative manner based on the observations of individuals doing the data acquisition.
- Data cleansing includes post-acquisition initial signal conditioning such a filtering, decimation, trend removal, averaging, and windowing.

Data Cleansing: Windowing and Filtering

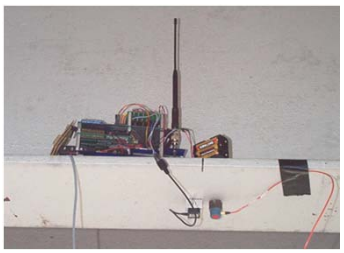
- One of the most common methods used to reduce leakage effects in the frequency domain (such as when computing an FFT) after the data has been acquired is to window the data.
- Windows compensate for frequency domain characteristics associated with truncation of the data in the time domain.
- Common window functions: *Hanning, Hamming, Kaiser-Bessel, Rectangular, Triangular, and Flat top; General form:*

$$w(t) = a_0 - a_1 \cos\left(\frac{2\pi t}{T}\right) + a_2 \cos\left(2\frac{2\pi t}{T}\right) - a_3 \cos\left(3\frac{2\pi t}{T}\right) + a_4 \cos\left(4\frac{2\pi t}{T}\right), \quad 0 \le t \le T$$



Data Transmission

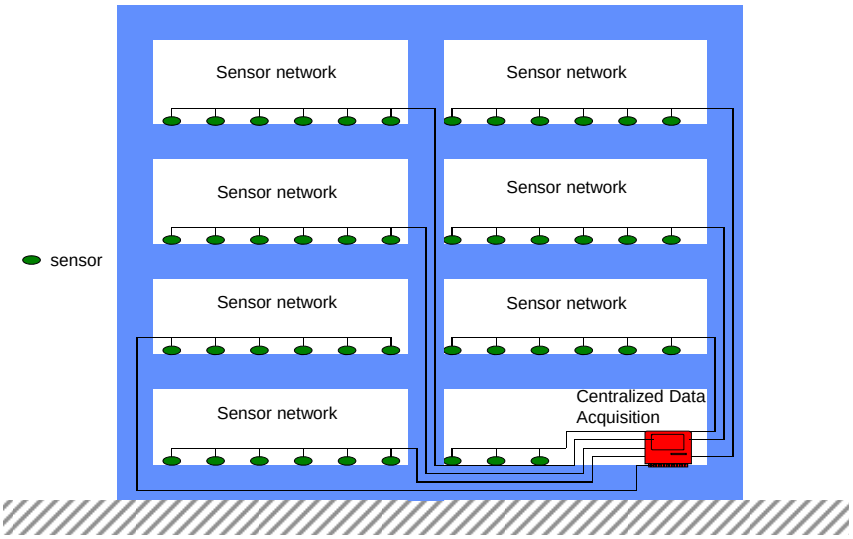
- Most modern data acquisition systems transmit the analog signal from the sensor to the A to D convert through hard-wire connections.
- Alternative is to record analog signal on magnetic tape, or to record with a digital tape recorder, record directly to hard disk
- Current research is focusing on wireless data transmission of digital signals.



"Shoe box" size wireless sensing system, mid 1990's

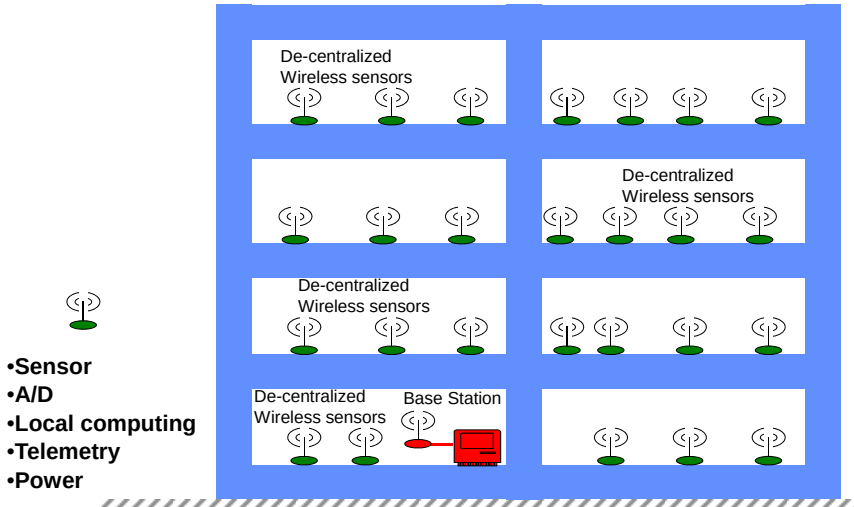
"Credit card" size wireless sensing system, mid 2000's

Networking: Conventional Wired Network



Networking: Passive Wireless Network

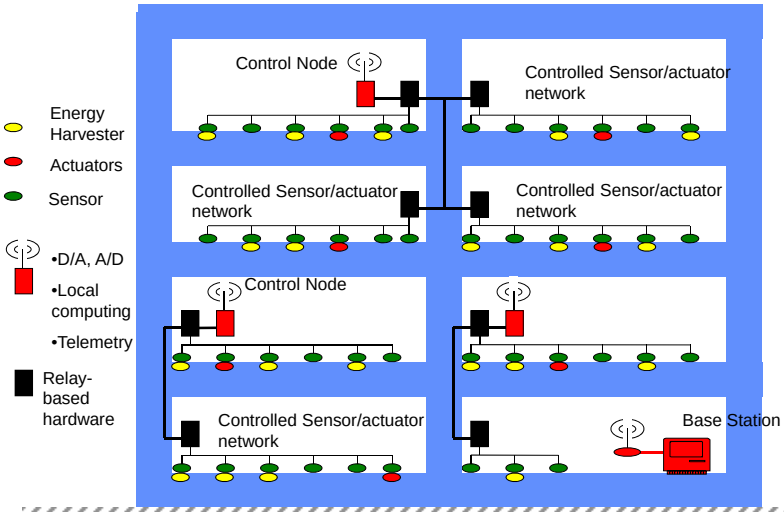
Variations proposed scheme by Lynch (2007), Spencer (2004), and others



- **Sensor**
- **A/D**
- **Local computing**
- **Telemetry**
- **Power**

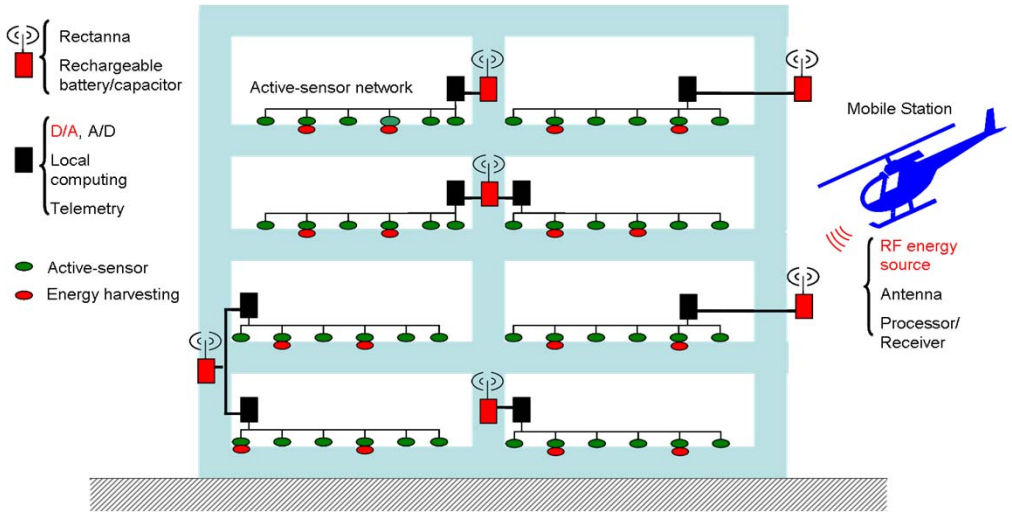
Networking: Active, Hierarchical Wireless Sensing

Proposed scheme by LANL (Dove, et al) & Motorola 2006



Networking: Active Wireless Sensing and Energy Delivery

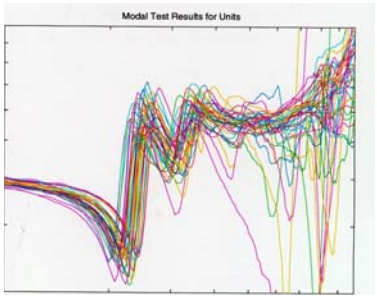
Demonstrated by Mascarenas, 2008, Taylor et al., 2009



Repeatability in Procedures and Hardware

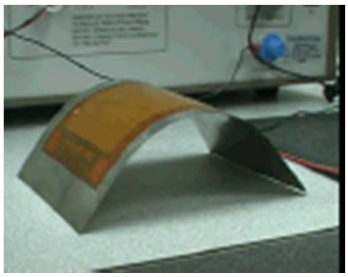
- Definitions: If two separate experiments are run on the same object by different experimentalists using different equipment, will the same results be obtained?
- Repeatability in Test Procedure
  - Excitation device
    - Spectrum
    - Location
    - Orientation
  - Roving sensors (placement)
- Repeatability in Test Hardware
  - Electronics
  - Cables / sensor connections
  - Sensor sensitivity / calibration
  - Unit-to-unit variability

Variability in FRFs measured on units manufactured in an identical manner with strict quality control



Final Comments on SHM Data Acquisition

- **THERE IS NO SENSOR THAT MEASURES DAMAGE! (and there never will be!!)**
- **However, can't do SHM without sensing**
- Define data to be acquired and the data to be used in the feature extraction process.
  - Types of data to be acquired
  - Sensor types, number and locations
  - Bandwidth, sensitivity (dynamic range)
  - Data acquisition/transmittal/storage system
  - Power requirements (energy delivery)
  - Sampling intervals
  - Processor/memory requirements
  - Excitation source (active sensing)
  - Sensor diagnostic capability



Challenges for SHM Sensing Systems

- **Number of sensors**
  - Instrumenting large structures with thousands of sensors still represents a sparsely instrumented system!
  - Large sensor systems pose many challenges for reliability and data management
- **Ruggedness of sensors**
  - Sensing systems must last for many years with minimal maintenance
  - Harsh environments (thermal, mechanical, moisture, radiation, corrosion)
  - Need sensor diagnostic capability
- **The sensing system must be developed integrally with the feature selection/extraction and classification.**
- **There is no accepted sensor design methodology**
  - **Optimal Sensor placement (need models)**
  - **Optimal waveform design for active sensing (need models)**

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