# Application of Smart Material

## Structural Health Monitoring (SHM)

*Several figures have been taken from different internet sources*

# Structural Health Monitoring (SHM)

- A process which provides precise and in-time information related to structural condition and performance on proactive basis
- SHM aims at real-time characterization of structural performance
- Detection of damage occurrence and gathering of information regarding location, nature and severity of this damage
- Uncertainty regarding reliability of routine maintenance methods necessitates condition based maintenance methods
- Many conventional ways of damage detection are expensive(conventional non-destructive testing, NDT), require heavy instruments and unsuitable for online detection.

# Relevance

We might need to monitor:

- an earth filled masonry arch bridge carrying a road or railway
- cracking at joints in an offshore oil exploitation rig jacket
- corrosion of a liquid storage tank while full of hazardous chemicals
- barely visible impact damage (dropped tools on CFRP aircraft wings)

# The options include

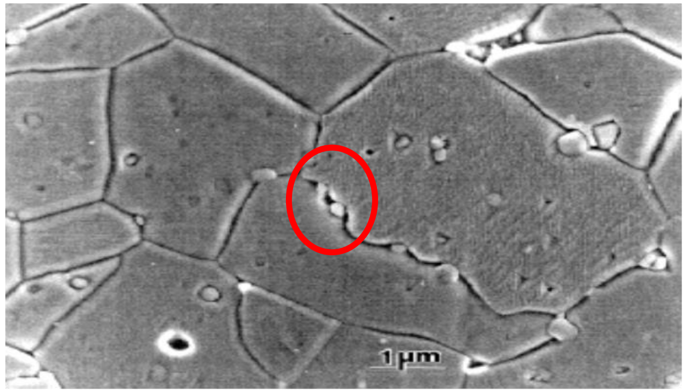
- mechanical/dead-weight loading with measurement of deflections
- modes and frequencies of vibration
- embedded sensors
- *non-destructive testing NDT* technologies

# Definition of "Damage"

- Damage will be defined as changes to the material and/or geometric properties of a structural or mechanical system, including changes to the boundary conditions and system connectivity, that adversely affect current or future performance of that system.
- Implicit in this definition of damage is a comparison between two different states of the system.

- Examples:
  - crack in mechanical part (stiffness change)
  - scour of bridge pier (boundary condition change)
  - Mass imbalance in rotating machines (mass change)
  - loosening of bolted joint (connectivity change)

- All materials used in engineering systems have some inherent initial flaws.
- Under appropriate loading flaws will grow and coalesce to the point where they produce component level failure.




- Further loading may cause additional component failures that can lead to system-level failure.
  - In some cases this evolution can occur over relatively long time scales (e.g. corrosion, fatigue crack growth)
  - Other cases cause this damage evolution to occur over relatively short time scales (e.g. earthquake loading, impact-related damage)
- Must consider the length and time scales associated with damage initiation and evolution when developing a SHM system.

# Current Safety Assurance Practices

- Design with large safety factors-overdesign
- Design for damage tolerance
  - Life prediction (material damage, fracture mechanics)
  - Quality control (material processing, manufacturing, assembly)
  - Accurate specification of operational conditions
- Periodic Inspection
  - Manual
  - Nondestructive Testing (visual, ultrasound, eddy current)

# Motivation of SHM

NDT methods have difficulty when large surface areas need to be inspected and when the damage lies below the surface.

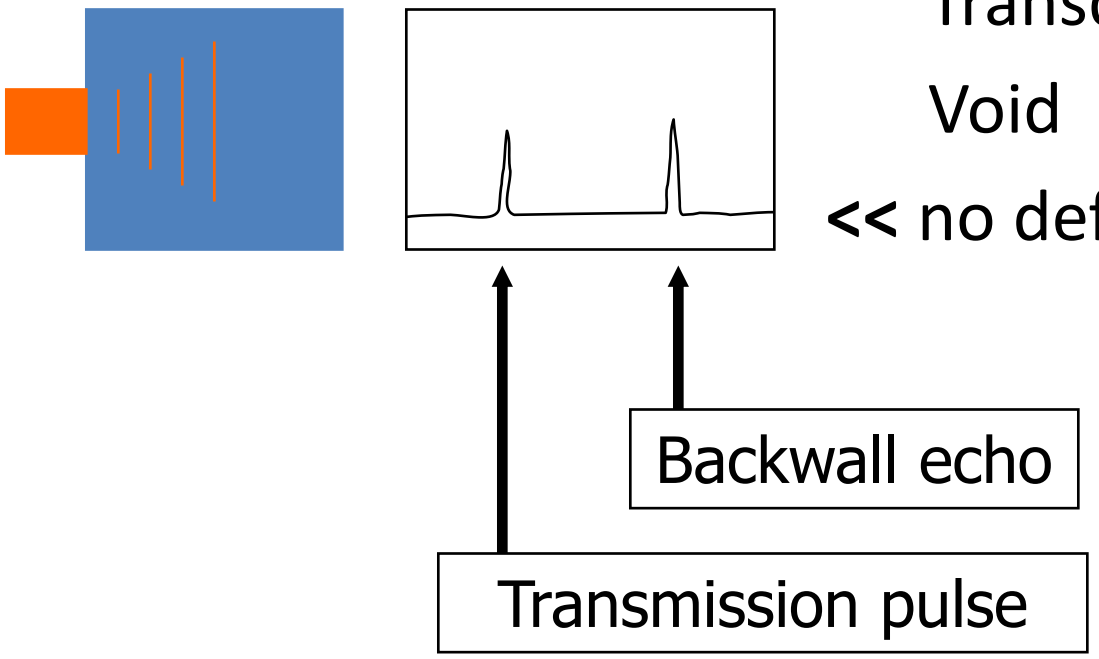
**Recent (2001) failure of offshore oil platform near Brazil**

Minneapolis Bridge 2007

# Conventional NDT Methods

- Ultrasonic Scanning
- Eddy Current Methods
- Radiography
- Thermography
- Acoustic Emission
- Others

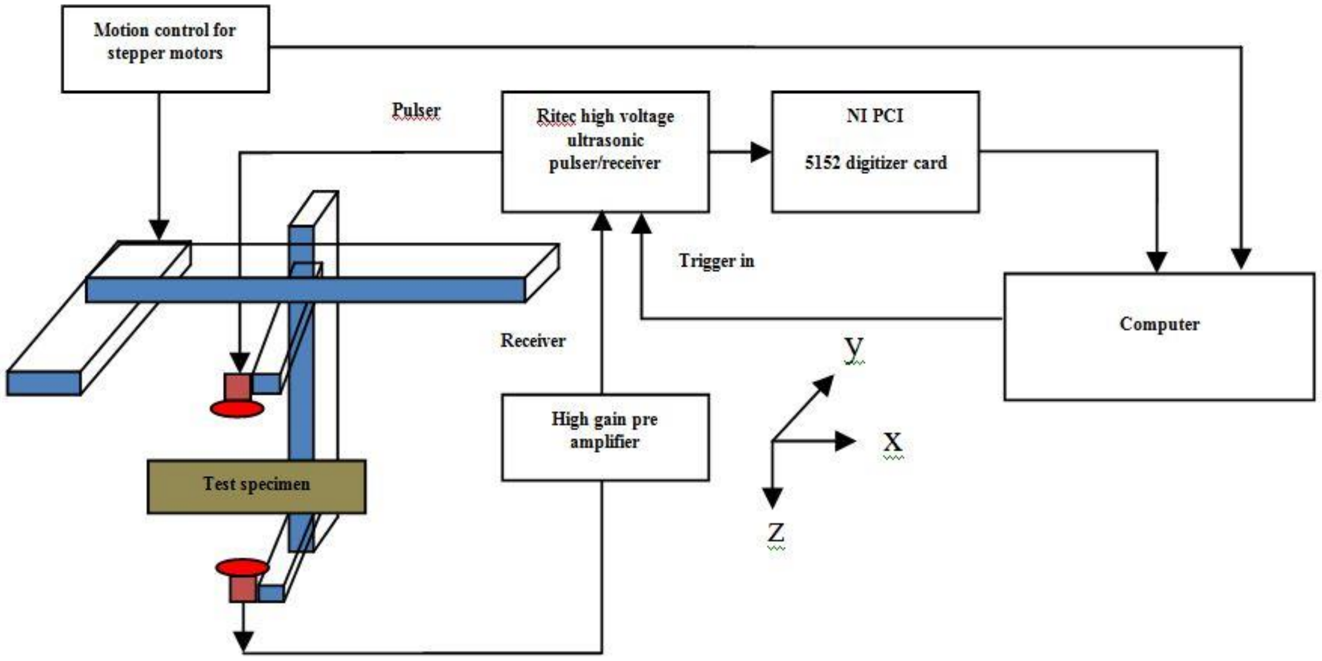
# US scan without/with defect (voltage *vs* time trace)



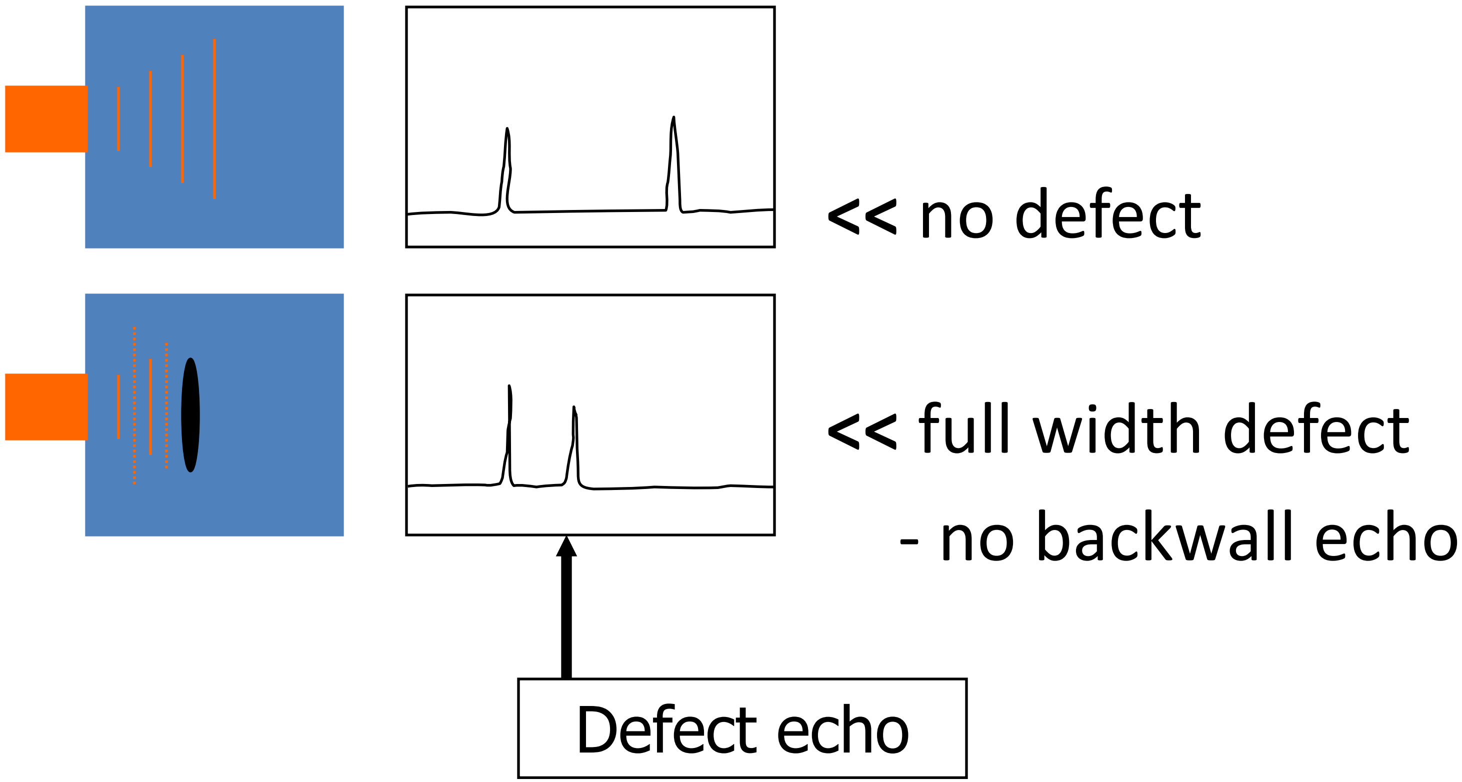

Transducer

Void

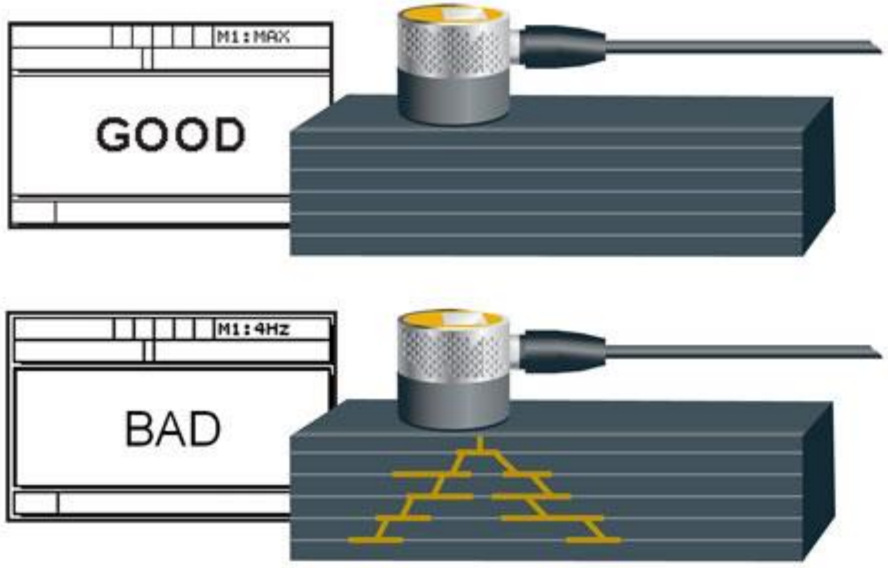
<< no defect

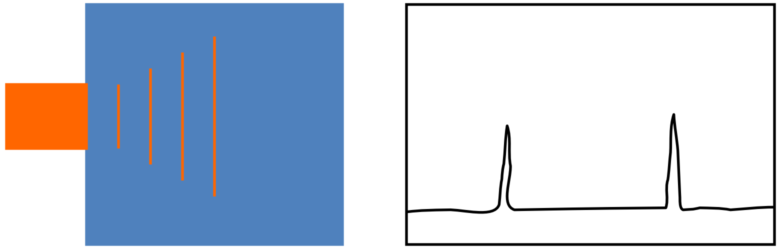


# US-scan without/with defect (voltage *vs* time trace)

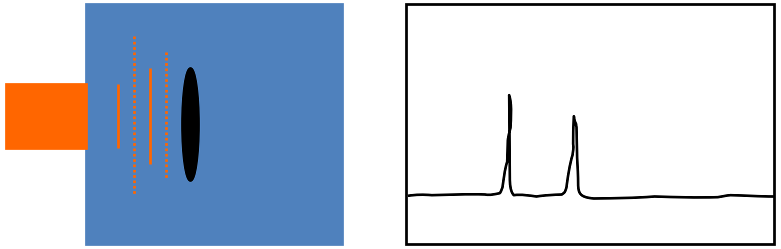


# US scan without/with defect (voltage *vs* time trace)

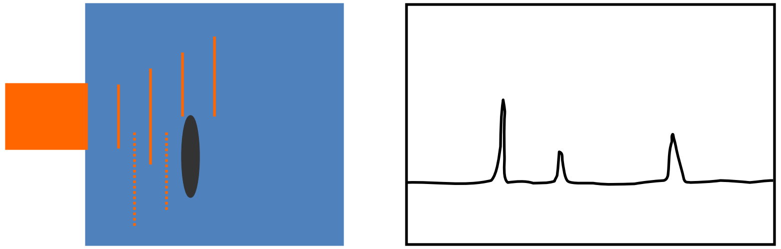


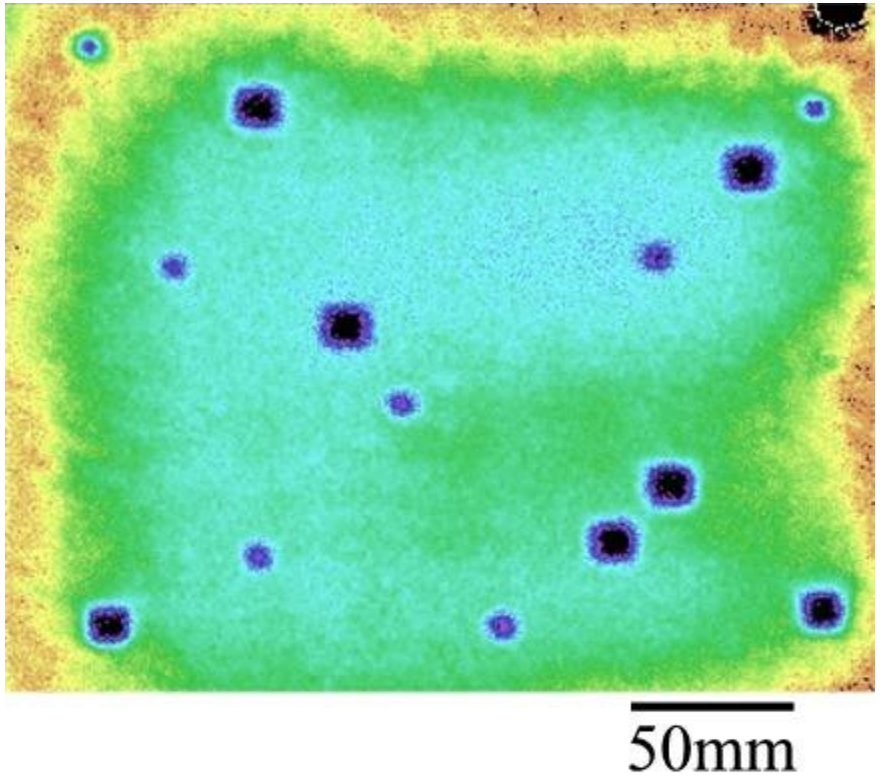
<< no defect



<< full width defect



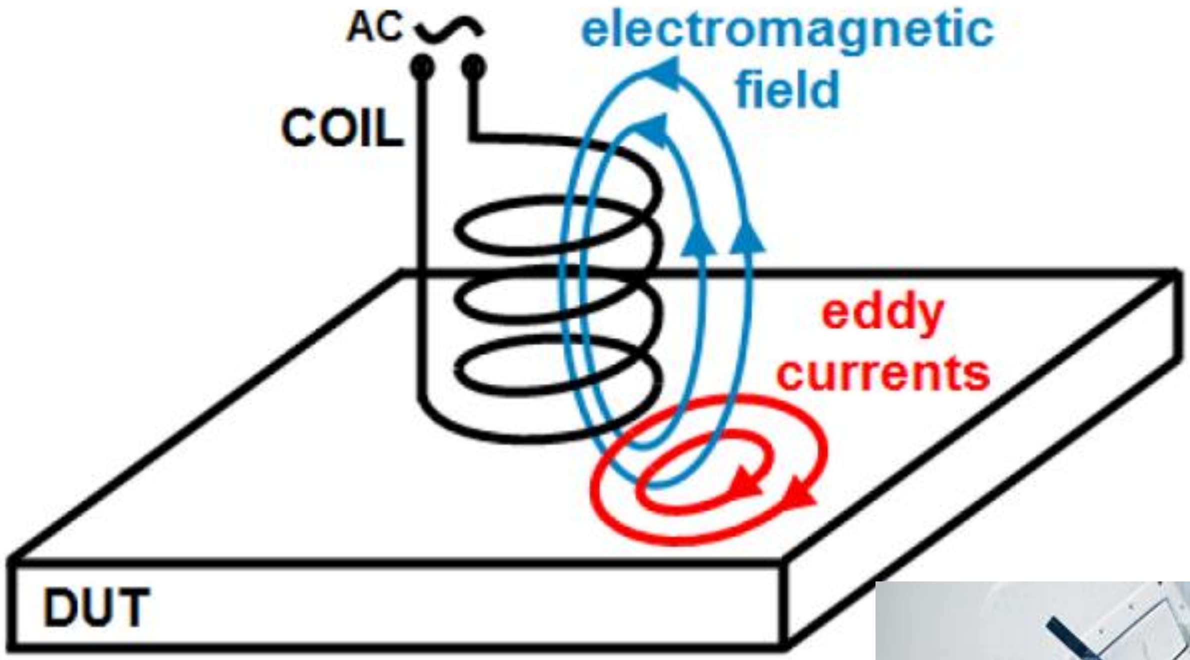
<< part width defect



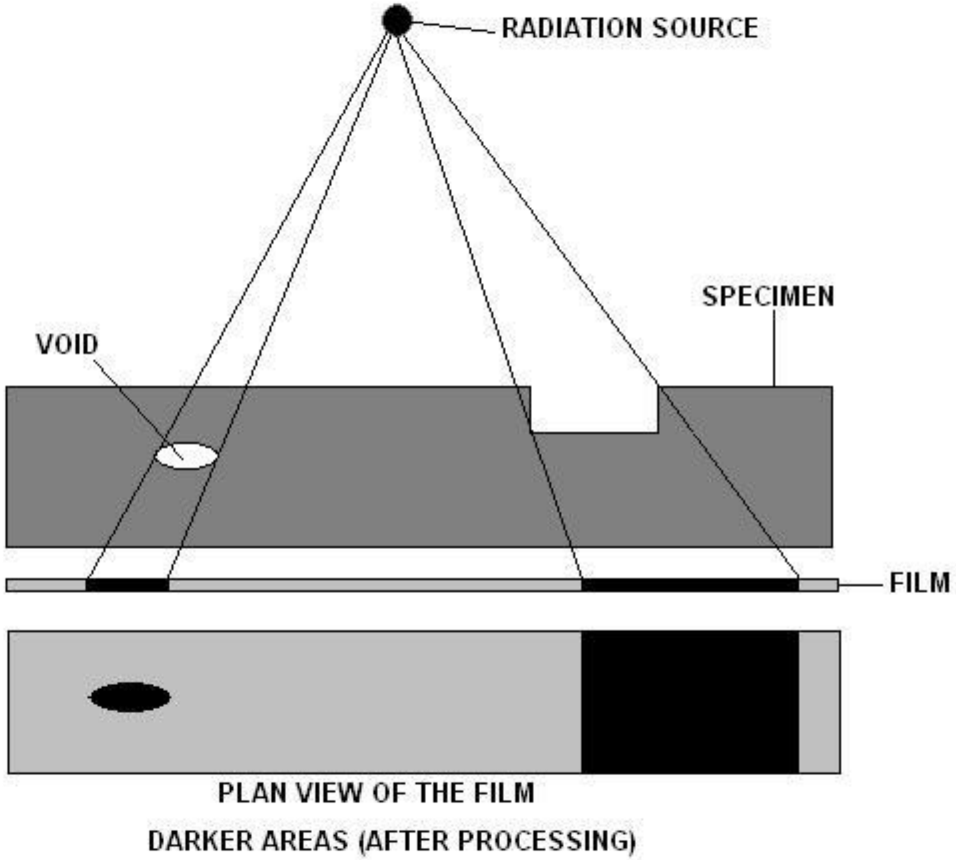

The sample was a thin panel of Kevlar-fibre reinforced polymer having transverse dimensions of approximately 300mm by 300mm. Within the sample were 14 simulated delaminations. These delaminations were created by carefully embedding thin pieces of Teflon tape of different sizes and were introduced in such a way as to replace some of the central fibers of the panel. The existence of the defects was not evident by visual inspection of the finished sample.

The dark squares that appear reveal the positions of the simulated delaminations within the plate whereas the more gradual colour variations of the background (from blue-green in the middle to orange-yellow at the edges) are due to thickness variations not evident from visual inspection of the panel.

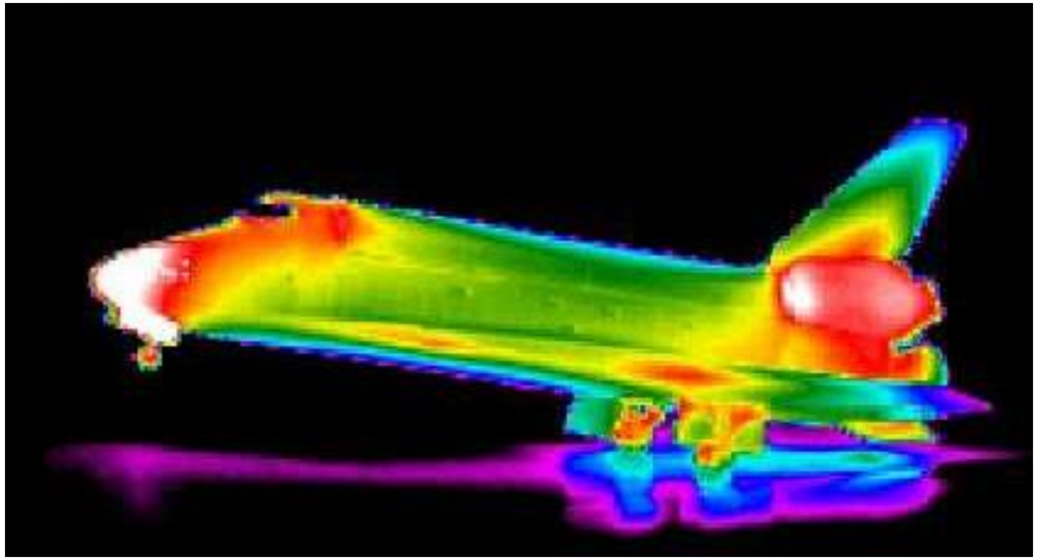
# Eddy Current Technique




# Radiography



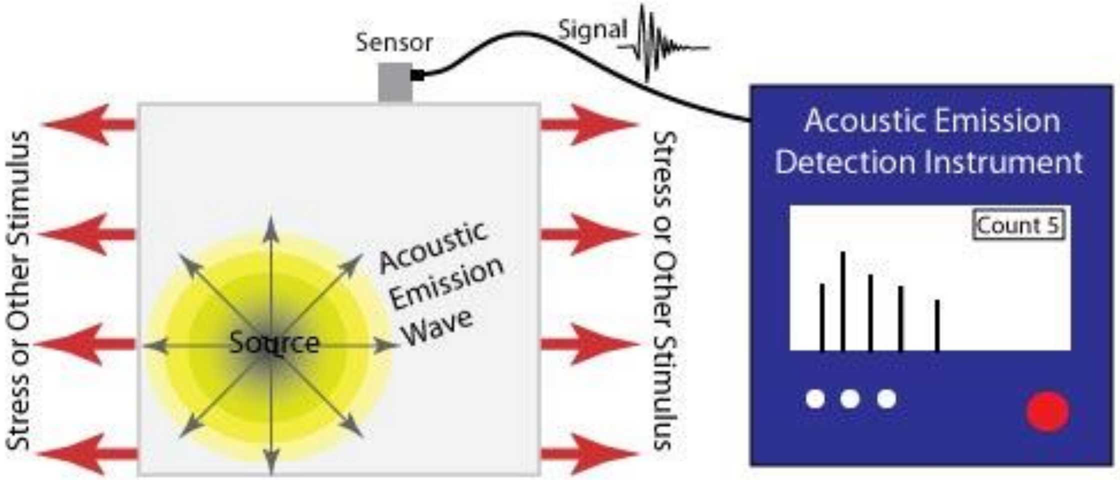

# Thermography



Thermal NDT methods involve the measurement or mapping of surface temperatures as heat flows to, from and/or through an object. The simplest thermal measurements involve making point measurements with a thermocouple. This type of measurement might be useful in locating hot spots, such as a bearing that is wearing out and starting to heat up due to an increase in friction.

# Acoustic Emission Testing

AE is commonly defined as transient elastic waves within a material, caused by the release of localized stress energy. Hence, an *event* source is the phenomenon which releases energy into the material, which then propagates as an elastic wave. Acoustic emissions can be detected in frequency ranges under 1 kHz, and have been reported at frequencies up to 100 MHz, but most of the released energy is within the 1 kHz to 1 MHz range.



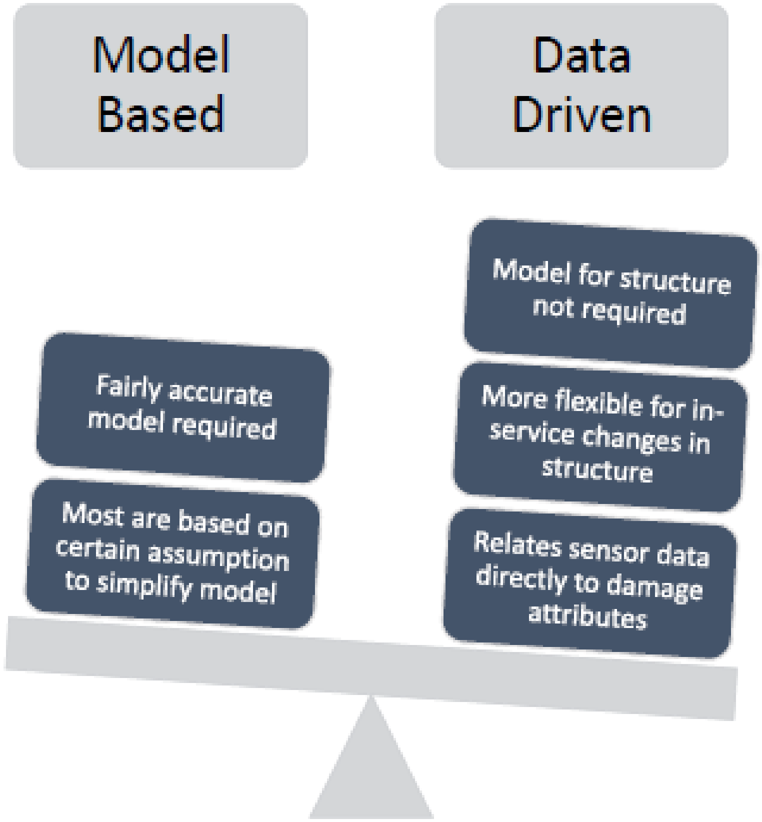
# Advantages of SHM over NDT

- SHM allows larger area scanning as compared to NDT
- Less manual intervention
- Lighter and cheaper transducer and thus possess potential for in-service monitoring
- Time and cost effective

## Challenges

- Complexities in analysis, modeling and interpretation

# Approaches for SHM




Data used
- Strain, displacement
- Vibration response
- Wave response

Sensors

MEMS sensors

PZT sensors

Fiber Optics Sensors

Excitations
- Ambient vibration
- Ambient strain due to traffic movement
- Diagnostic waves

# Basics of vibration-based SHM methods

The basic premise of vibration-based damage detection is that the damage will alter the stiffness, mass or energy dissipation properties of a system, which, in turn, will alter the measured dynamic response of the system.

# Basis of vibration-based SHM methods

- Modal parameters (notably *frequencies*, *mode shapes, and modal damping*) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause changes in the modal properties.
- Use an initial measurement of an undamaged structure as the baseline for future comparison of measured response.
- An important feature of any viable damage ID methods is their ability to discriminate between damages, analysis uncertainties and environmental influences (temperature, humidity)

# Vibration-based SHM Methods

Critical issues in applying vibration-based SHM methods:

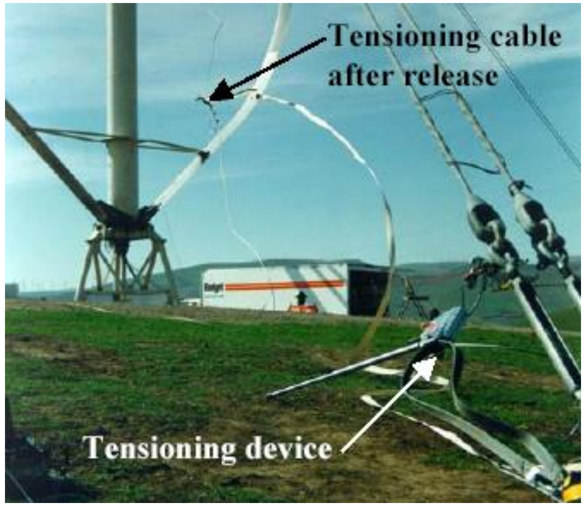
- Type and location of sensors
- Type and location of excitations
- Types of damage detection algorithms employed

# Vibration Excitation Technique

- Ambient excitation
  - E.g., loading on a highway bridge from passing traffic
- Forced excitation
  - Impact hammer
  - Bumper
  - Eccentric mass shaker
  - Electromagnetic shaker
  - Servohydraulic linear inertia shaker

# Vibration Excitation Equipment

- Quick release device to excite free vibration by pulling the structure and releasing



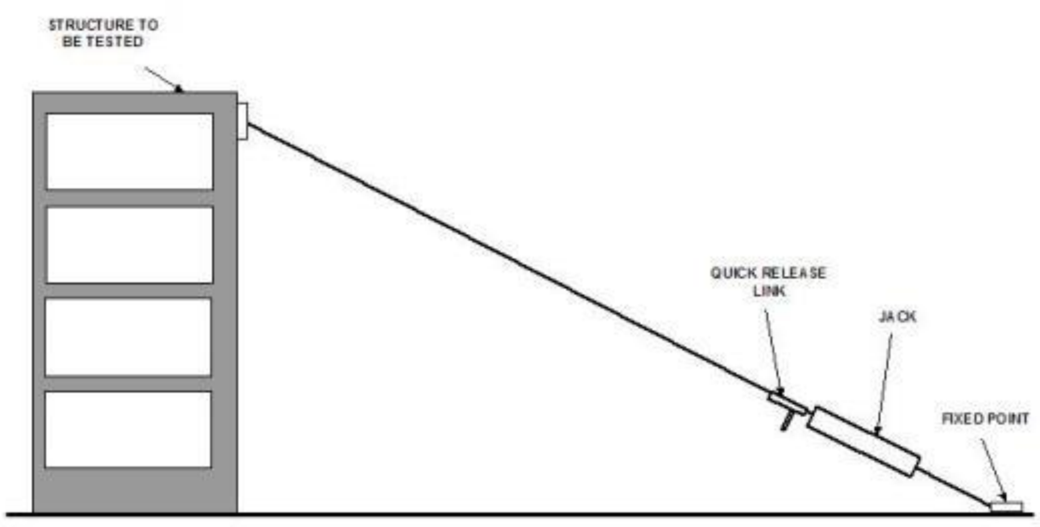




Image courtesy of LANL & Anco Engineers

# Vibration Excitation Equipment

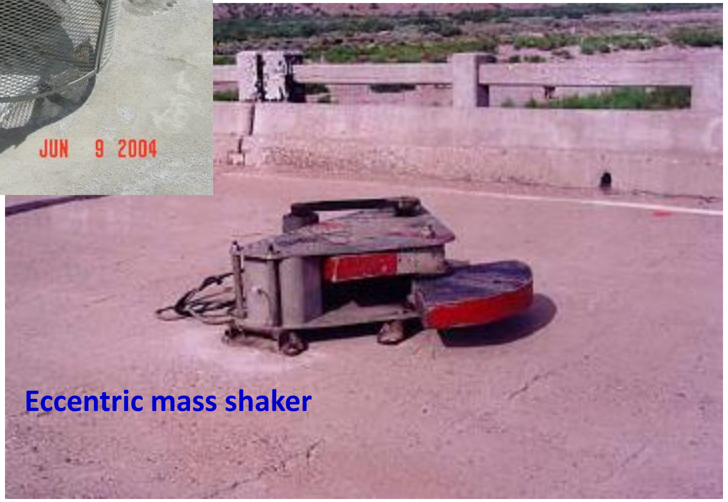
- Pulse load generated by running a car (with pre-determined mass) over a bumper: pulse duration depends on the speed of the car
- Instrumented impact hammer



Image courtesy of LANL

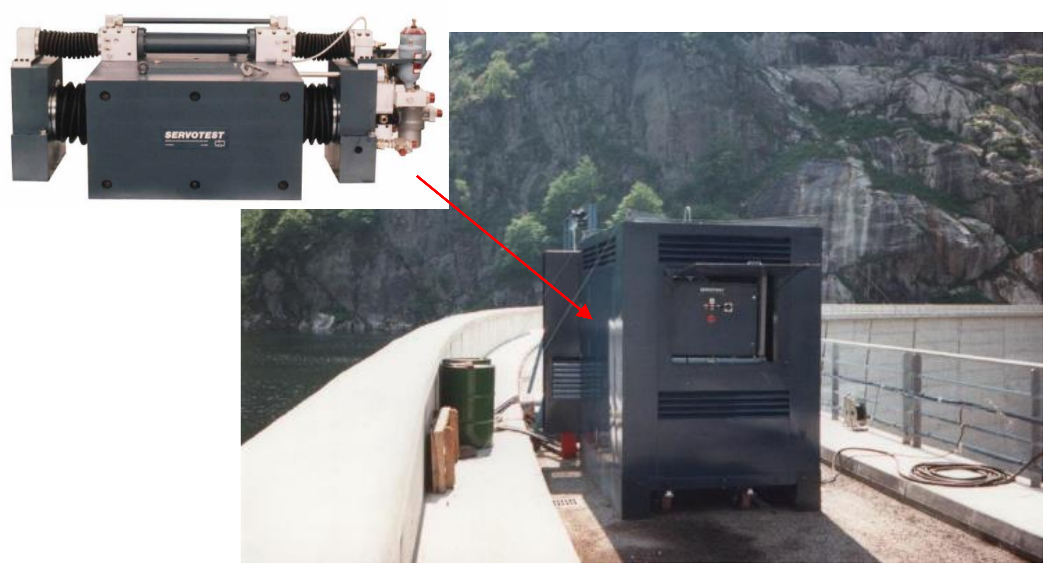
# Vibration Excitation Equipment

- Eccentric mass shaker (electrically powered)
- Electromagnetic shaker



Eccentric mass shaker

# Vibration Excitation Equipment

- Servohydraulic linear inertia shaker

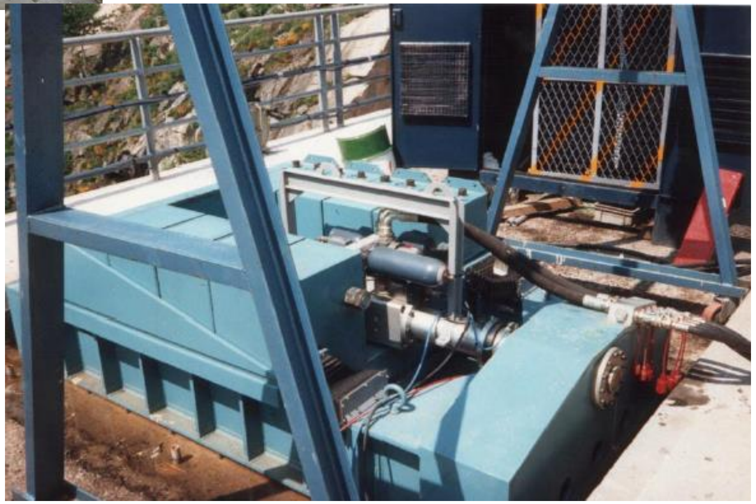



Image courtesy of J. Wallace, UCLA & Servotest

# Data Acquisition for SHM

- The data-acquisition portion of the structural health monitoring process involves:
  - selecting the types of sensors to be used,
  - the location where the sensors should be placed,
  - the number of sensors to be used,
  - the data-acquisition/storage/transmission hardware.

# Modal Parameter

- Modal Frequency
  - Changes in modal frequencies do not disclose spatial information about structural damage.
  - Frequency change generally not very sensitive to structural damage

- Mode shape vectors
  - Spatially distributed quantities and therefore, they provide information that can be used to locate damage. However, a large number of sensors are required for sufficient spatial resolution.
  - Mode shape derivatives, such as curvature, may be more sensitive to damage

# Damage ID using Modal Parameters

- Laboratory testing of a ¼-scale steel frame structure

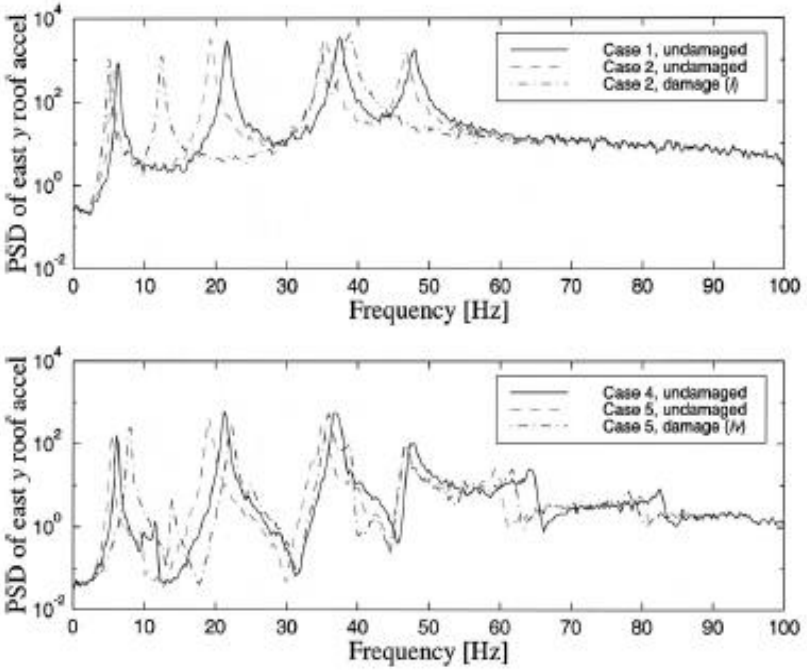




Image courtesy of EA Johnson et al, USC

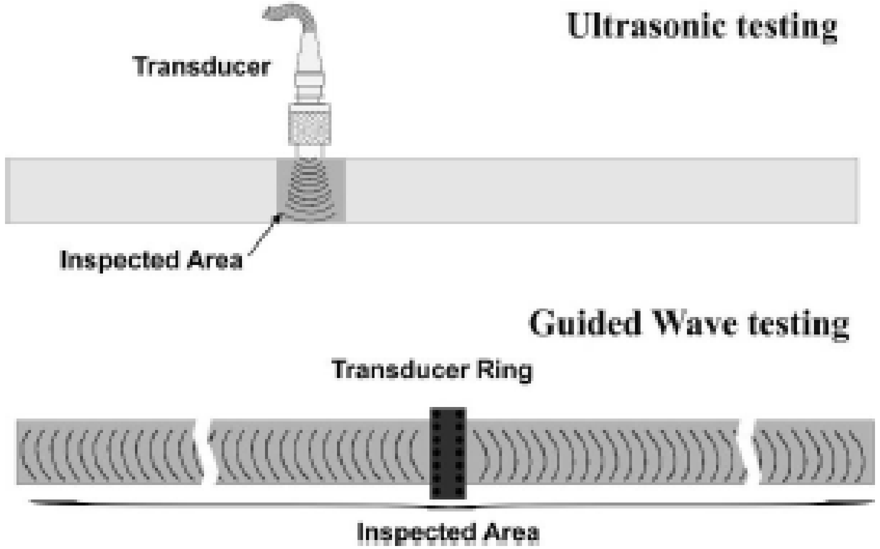
# Challenges in Vibration-based SHM

- Many technical challenges are identified in vibration-based structural health monitoring techniques, including
  - Better use of the nonlinear response characteristics of the damaged system
  - Development of methods to optimally define the number and location of the sensors
  - Identification of the features sensitive to small damage levels,
  - The ability to discriminate changes in features cause by damage from those caused by changing environmental and/or test conditions
  - The development of statistical methods to discriminate features from undamaged and damaged structures,
  - Performance of comparative studies of different damage-detection methods applied to common datasets (or benchmark problems).
  - and many others

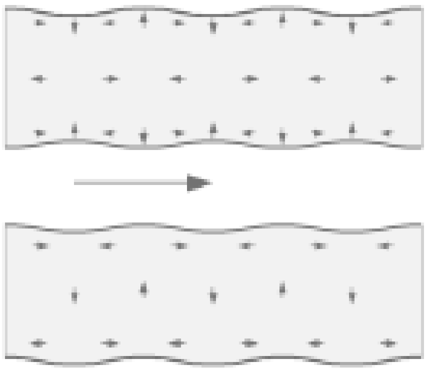
# Guided Wave based SHM

## Lamb Waves

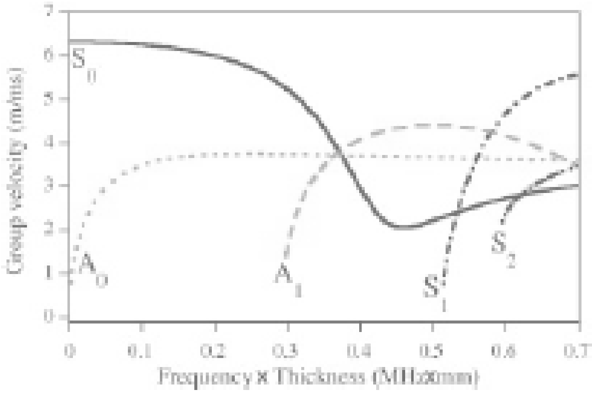
- Exist in plate-like thin bodies or thin walled structures
- Bounded by the plate surface causing a wave-guide effect
- Ability to inspect large lengths, good sensitivity to multiple defects
- Propagation is complicated
  - Dispersion
  - Multiple modes
  - Reflections




Guided Wave Testing



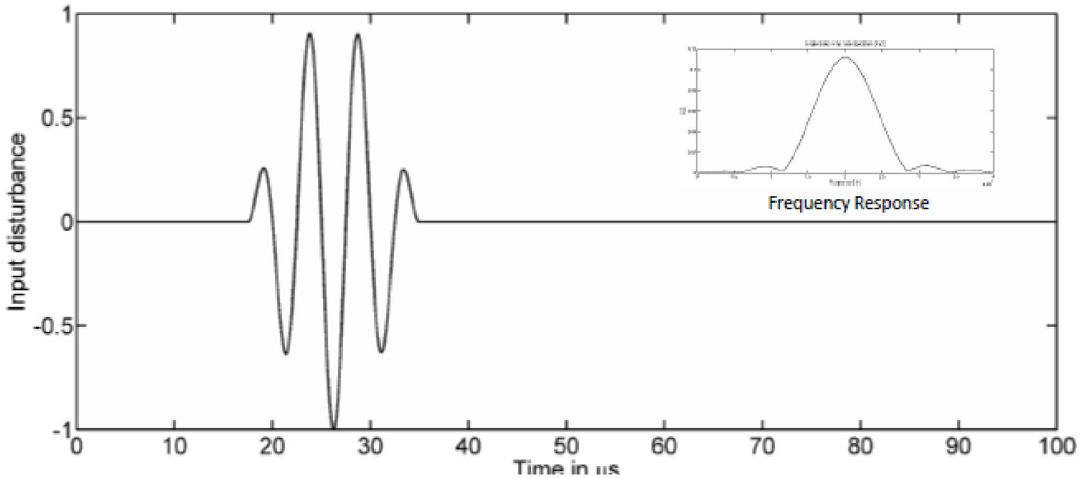
Schematic of Lamb Wave



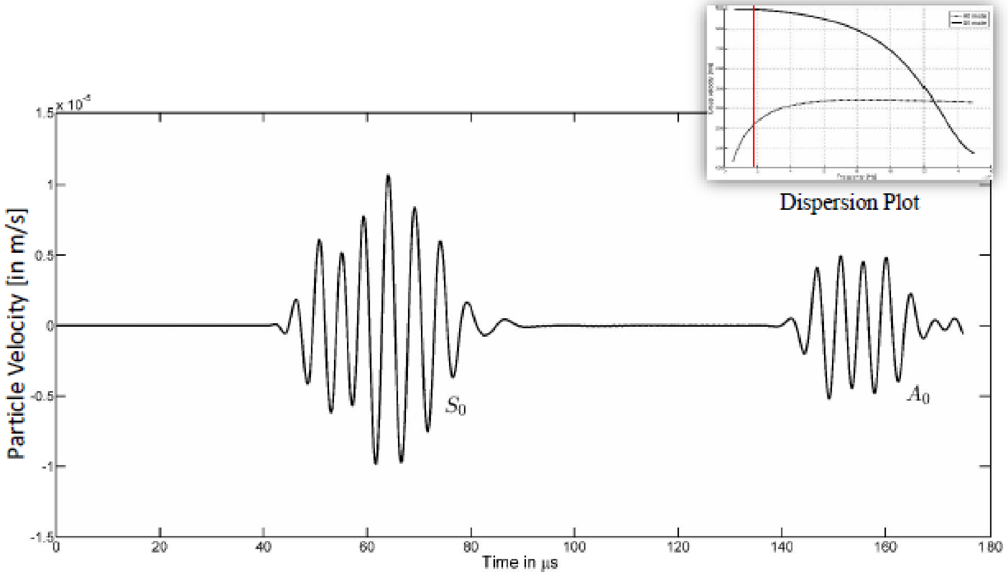

Dispersion plot

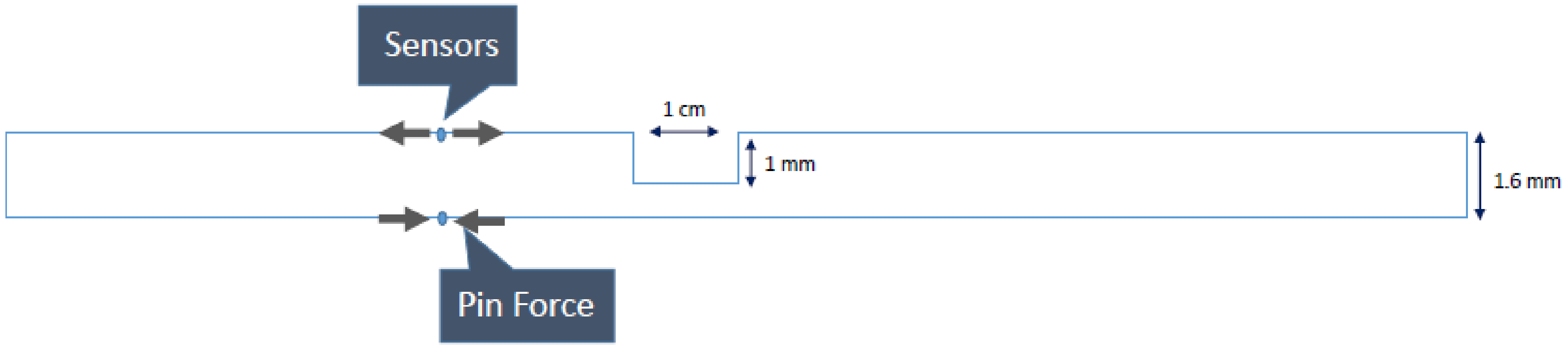
Graphics Reference: Wikipedia

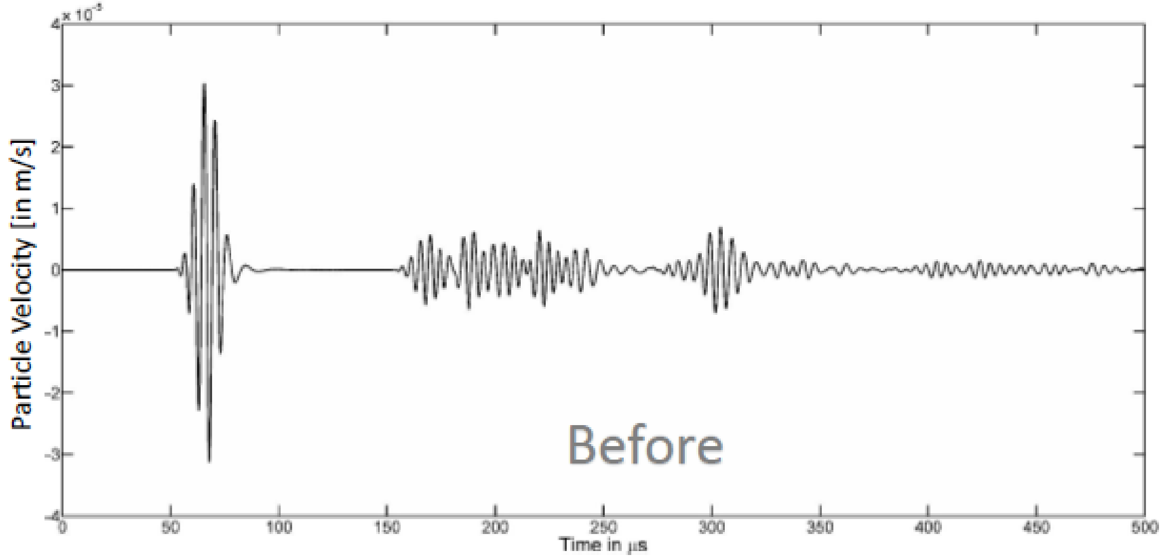
# Initial Disturbance




# Velocity Response $A_0$ and $S_0$ wave






Response of top sensor