Structural Health Monitoring

Overview & Aerospace Applications

An invited lecture series for ME/MSE 568: Active and sensing materials and their devices

Presented by
Dr. JB Ihn

Affiliate Assistant Professor, ME, Univ. of Washington Technology Lead Engineer, Boeing Research & Technology
A Brief Biography….

• 1970: Born in Seoul, Korea
• 1993: BSE, Univ. of Michigan, Aerospace Eng.
• 2003: Ph.D, Stanford University, Aero/Astro
• 2003 ~ 2005: Research Associate, Stanford University
• 2005 ~ Current: Boeing Phantom Works/BR&T
• 2006 ~ Current: Affiliate Assistant Professor, Univ. of Washington

→ R&D in Structural Health Monitoring and Smart Structures for the last 15 years
→ Recently focused on technology readiness and implementations for Boeing products
Outline

Lecture 1
• Introduction to SHM (need and benefit)
• Elements of a SHM system
• Damage Detection Principles

Lecture 2
• SHM Technology Integration
• Examples in Aerospace Applications
Smart sensors + intelligent algorithms +..

- Basic idea is to build a system similar to human nervous system
- More nerves (sensors) around critical organs (parts)
Some Definitions

• **Structural Health Monitoring (SHm)** - the scientific process of nondestructively identifying four characteristics real-time or near real-time related to the fitness of an engineered component (or system) as it operates using a built-in sensory and reasoner system:

  (1) the operational and environmental loads that act on the component
  (2) the mechanical damage that is caused by that loading
  (3) the growth of damage as the component operates
  (4) the future performance of the component as damage accumulates

  assess symptoms, find location, type and severity of disease

• **Structural Health Management (SHM)** – the process of determining the ability of the structure to continue to perform its desired function and making appropriate decisions/recommendations about mission and maintenance actions based on structural health assessment data in light of the inevitable ageing and degradation resulting from the operational environments
determine if person can function in normal life, need surgery, post treatments, how long can he live?

• A key to enabling management as opposed to simple monitoring is **prognosis**.

• **Information technology** is the key to prognosis for structures.
What is 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)
  – loosening of bolted joint (boundary condition/connectivity change)
  – corrosion in mechanical part (mass change)
What is damage?

- 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 timescales (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.
How Engineers and Scientist “Study” Damage

• What causes damage?
  - Material Science (material aging and degradation processes)
  - Engineering analyses

• What can be done to prevent damage?
  - Material Science (new materials)

• Is damage present?
  - SHm

• How fast will damage grow and reach a critical level?
  - SHm and SHM (Prognosis)

• How do we mitigate the effects of damage
  - Change in operational environment
  - Maintenance and repair (SHM)
  - Self-healing structures (SHM)
Need for SHM

1908 First airplane fatality
Damage in the propeller

2003 Columbia Shuttle Disaster
Accidental damage in leading edge

• Could they have been avoided if knew the true condition of structure?
Need for SHM – Aging Aircraft

- Increasing number of aircraft remain in service beyond their design life
- Aging aircraft are subject to cracks due to fatigue and corrosive environment

→ Aging trend requires stringent and efficient maintenance (with much higher cost)
Need for SHM

- F-16 requires 25 h of maintenance per flight hour (Malley, 2001)

- Alaska Airlines Flt Number 536 in Dec 2005 was struck by baggage carrier, not reported, lost pressure at 26K ft, had to emergency land - Safety issue, as well as major delay in regional air traffic
Current State: Schedule-Based Maintenance

Structural Design

Problem Areas Identified
- Main Spar
- Rear Spar
- Closure Spar

F-15 Wing

Inspection Schedule Constructed
(adding conservatism to compensate for uncertainty)

Conduit Hole (hot spot)

Full-Scale Fatigue Testing
Schedule vs Condition

• Schedule-based maintenance
  – Initially works well
  – However, over time req’ts change
    • Use vehicle systems longer than planned
    • Use for different missions than designed
    • New problem areas identified
  – Results in decreased availability, increased inspection times, and increased O&S costs

• Condition-based maintenance via SHM
  – Increases availability, increases reliability, and decreases O&S costs while maintaining vehicle safety
Benefits of SHM

• Significantly reduce Life Cycle Costs
  – Eliminate unnecessary inspections (schedule driven)
  – Minimize inspection cost (Time, and Effort)
  – Provide Accurate Information for Vehicle Life Extension

• Enable Condition Based maintenance
  – Increases availability, increases, reliability, and decreases O&S costs while maintaining vehicle safety

• Enable New Innovative Composite Structure Designs
  - SHM ingenerated structure design removes design conservatism
  - *Reduce Weight and Cost* Associated with Over-Designed Structure
SHM Elements

Data Collection
- Sensors
- Data Acquisition Hardware
- Visual Inspection
- NDI/NDE
- Other Data (reports of damage events, fleet history …)
- Loads & Environments

Data Processing
- A1
- A2
- An
- A1, A2, An = Multiple algorithms for SHM information processing

Information Processing to Define Current State
- Data Fusion & Integration
- Material State Awareness
- Structural State Awareness

Decision Making & Dissemination
- Capability analysis
- Margins
- Prognosis
- Maintenance & Operations Recommendations

SHm
SHM Elements To be Covered

(1) Data Collection
   - Sensors (passive and active)
   - Data acquisition and Integration

(2) Information Processing
   - Understanding wave propagations
   - Signal Processing

(3) Diagnostics – Defining current state
• MEMS, accelerometers, fiber optic, etc
- Monitoring global restructure response; load, temperature, etc.
- Difficulty in relating global response to local damage
- Sensors need to be very close to damage: high sensor density required
Active Sensors (Active SHM)

- Piezoelectric (PZT) ceramic

- both transmitters and receivers

- interrogate local defects within a large structure
Passive Sensor: Fiber Optic Sensor

• Derived initially from fiber optic communication technology, fiber optic sensing has matured into a well developed technology in the past decade.

• Technical advantages of fiber optical sensors
  – High sensitivity and bandwidth
  – Lightweight
  – Passive, low power consumption
  – Immune to electromagnetic interference
  – Wide dynamic range (submicron to >4% strain)
  – Distributed sensing capability (only one fiber is required for sensing and transmission)
  – Low signal attenuation
  – Environmental ruggedness
Some Fundamental Optics Ideas

• Optical radiation is an electromagnetic phenomenon and may be described by electromagnetic field equations (electromagnetic waves).

• A waveguide is a dielectric (electrically non-conducting) material that is used to “guide” or propagate these waves.

• Optical propagation features:

  ![Optical Propagation Diagram]

  • The refraction angle depends on the relative light wave speeds in the two materials; the refractive index ($n$) of a material is the ratio of light speed in a vacuum to light speed in the material (so always greater than 1).
Fiber: Cylindrical Optical Waveguide

- If medium 1 index is larger than medium 2 index, and the incident angle is large enough, then **total internal reflection** occurs: wave will not transmit into medium 2, and this is the basis for how an optical waveguide works.
- Optical fibers are cylindrical dielectric waveguides:

  **core**
  - glass-based (silica, fluoride, chalcogenide)
  - $n \sim 1.44$ (1.31-1.55 μm)
  - 8-980 μm in diameter

  **cladding**
  - glass-based or plastic-based
  - $n < 1.44$
  - 125-1000 μm in diameter

  **coating/jacketing**
  - plastic (acrylate, polyimide)
  - for protection, mechanical strength
Categorization of FOS

• The concept of fiber optic sensing is based on the modulation in the sensing element, by a particular measurand (strain, temperature, moisture, chemical, etc.), of one or more of the parameters (e.g., intensity, polarization, phase and wavelength) of the light which is guided by an optical fiber. For example, it can be categorized as:
  – Intensity vs. Interferometry-based Sensing
    • Sensors are generally based either on measuring an intensity change in one or more light beams or on looking at phase changes in the light beams by causing them to interact or interfere with one another.
  – Point vs. Distributed Sensing
    • In the case of a point sensor, the transducer may be at the end of a fiber the sole purpose of which is signal transmission; while in a distributed sensor, sensing is performed all along the fiber length.

Component Integration: General Sensing System

- Optical source
- Sensing mechanism
- Photodetection
- Intensity modulation
- Interferometry
- Bragg gratings
  Most popular!
- Electronic processing (non-optical)

~30 cm
Fiber Brag Gratings (FBG)

- Apply a modulation of refraction index, speed bump to a fiber core
- This photosensitivity occurs because electronic absorptions in silica materials are in this UV regime; this effect is enhanced with Germanium-doping through Ge sub-oxide defect production

\[ \lambda_B = 2nT = \frac{n \lambda_{UV}}{\sin \theta/2} \]
Fiber Bragg Gratings (FBG)

- if the fiber is locally stretched or compressed, $T$ changes, meaning $\lambda$ changes
- Broad spectrum input light is reflected only at a specific wavelength determined by the grating spacing which varies with strain
Schematic representation of a FBG array
Some Issues in FBG

- Cost per sensor is high for FBGs (~$100 per sensor), BUT cost per channel is competitive
- Fiber size (128 micron or even 80 micron) may lead possible delamination sites for embedded applications - 56 micron single mode fiber now available!
- For FBGs, severe strain gradients over gage length cause chirping leading to loss of signal
- Serialization causes risk: loss of one FBG sensor array leads to loss of all “downstream” sensors
Active Sensor: Piezoelectric Sensors

• Piezoelectricity means “pressure electricity”, which is used to describe the coupling between a material’s mechanical and electrical behaviors.
  – Piezoelectric Effect
    • when a piezoelectric material is squeezed or stretched, electric charge is generated on its surface.
  – Inverse Piezoelectric Effect
    • Conversely, when subjected to a electric voltage input, a piezoelectric material mechanically deforms.
Piezoelectric effect

Electrometrical Equations

\begin{align*}
    S_{ij} &= S_{ijkl} T_{kl} + d_{kij} E_k \\
    D_i &= d_{ikl} T_{kl} + \varepsilon_{ik}^T E_k
\end{align*}

- \( S_{ij} \): strain tensor
- \( S_{ijkl} \): compliance tensor (constant electric field)
- \( E_k \): applied electric field
- \( \varepsilon_{ik}^T \): dielectric constant (at constant stress)
- \( T_{kl} \): stress tensor
- \( d_{kij} \): piezoelectric constant
- \( D_i \): dielectric displacement (charge/surface area)
Brief History of Piezoelectricity

- Pierre Curie and his brother Jacques first discovered the piezoelectricity phenomenon in quartz and Rochelle salt in 1880 and named the effect piezoelectricity (from Greek piezein, “to press”).
  - Piezoelectric effect first found in certain crystalline minerals: zinc blende, tourmaline, quartz, rochelle salt, can sugar, etc.
  - In 1940, piezoelectricity was demonstrated in the first synthetic piezoelectric substance – Barium titanate.
- For a brief history of piezoelectric materials, check out the following website
  - http://www.piezo.com/history.html
Applications for Piezoelectric Materials

- The piezoelectric effect is used in **sensing** applications, such as in force or displacement sensors.
- The inverse piezoelectric effect is used in **actuation** applications, such as in motors and devices that precisely control positioning, and in generating sonic and ultrasonic signals.
- Piezoelectric materials are also **pyroelectric**. They produce electric charge as they undergo a temperature change. So they can be used for thermometer (see the picture on the right).
Piezoelectric Materials

- Piezoelectric Crystals (natural material)
  - Quartz (SiO$_2$)
  - Rochelle salt (NaKC$_4$H$_4$O$_6$· H$_2$O): water soluble
  - EDT (ethylene diamine tartrate) and DKT (diapotassium tartrate)
  - ADP (amonium dihydrogen phosphate)
  - Perovskite family: the group of ferroelectric crystals represented by BaTiO$_3$ is called the perovskite family.
Piezoelectric Materials

- **Piezoelectric Ceramics** (man-made materials)
  - Barium Titanate (BaTiO₃)
  - Lead Zirconate Titanate (PbZrTiO₃) = **PZT, most widely used**
  - The composition, shape, and dimensions of a piezoelectric ceramic element can be tailored to meet the requirements of a specific purpose.
Piezoelectric Materials

- Piezoelectric Polymers
  - PVDF (Polyvinylidene fluoride) film
- Piezoelectric Composites
  - A combination of piezoelectric ceramics and polymers to attain properties which can be not be achieved in a single phase

Image courtesy of MSI, MA
What is Ferroelectricity?

• The phenomenon of a dipole reversing in an opposing field is called **ferroelectricity**.

• Therefore, ferroelectric materials refer to a class of crystalline materials which possess an internal polarization that can be reversed by an externally applied field, i.e., a crystalline material which can be poled.

• All of the commonly used piezoelectric ceramics are ferroelectric.
Microstructure of Piezoelectric Ceramics

- If a piece of piezoelectric material is heated above a certain temperature, called a Curie temperature (~300°C, 572°F), it will lose piezoelectric properties. After cooling below the Curie temperature, the piezoelectric material will NOT regain its piezoelectric properties.
  - Above the **Curie temperature**, each perovskite crystallite exhibits simple cubic symmetry, with **no dipoles** moment
  - Below the Curie temperature, however, each crystallite has tetragonal or rhombohedral symmetry and a **built-in dipole moment** which may be reversed or switched to certain allowed directions under an applied electric field.
Microstructure of Piezoelectric Ceramics

- Piezoelectric ceramics are **polycrystalline** ferroelectric materials with the perovskite crystal structure - a tetragonal/rhombahedral structure very close to cubic.

![Diagram of piezoelectric ceramics microstructure](image-url)

(a) cubic lattice (above Curie temperature)  
(b) tetragonal lattice (below Curie temperature)

Image courtesy of APC International, Ltd.
Microstructure of Piezoelectric Ceramics

• Adjoining dipoles form regions of local alignment called **domains**. The alignment gives a net dipole moment to the domain, and thus a net **polarization**. Each domain contains millions of unit cells.

• Before poling, the direction of polarization among neighboring domains is random, so the piezoelectric ceramic element has no overall polarization.

Image courtesy of D. Damjanovic, EPFL
The piezoelectric property of ceramics does not arise simply from its chemical composition. In addition to having the proper formulation, piezoelectric ceramics must be subjected to a high electric field for a short period of time to force the randomly oriented micro-dipoles into alignment. This alignment by application of high voltage is called "poling".

Picture courtesy of G Cook, EDO Electro Ceramics Products, and Sensor Magazine
Poling

- The domains are aligned by exposing the element to a strong, DC electric field, usually at an elevated temperature to accelerate the process.
- Through this polarizing (poling) treatment, domains most nearly aligned with the electric field expand at the expense of domains that are not aligned with the field.
- When the electric field is removed most of the dipoles are locked into a configuration of near alignment. The ceramics now has a permanent polarization.
- Depoling might occur if high electrical field or heat is applied to the piezoelectric ceramics material by accident.
Poling

Image courtesy of APC International, Ltd.
Piezoelectric Properties

- The **electromechanical coupling coefficient**, $k$, is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or vice versa.
  
  - $k_{xy}$, The first subscript $(x)$ to $k$ denotes the direction along which the electrodes are applied; the second subscript $(y)$ denotes the direction along which the mechanical energy is developed. This holds true for other piezoelectric constants discussed later.
  
  - Typical $k$ values varies from 0.3 to 0.75 for piezoelectric ceramics.

\[
k = \sqrt{\frac{\text{Mechanical Energy Stored}}{\text{Electrical Energy Applied}}} \quad \text{or} \quad k = \sqrt{\frac{\text{Electrical Energy Stored}}{\text{Mechanical Energy Applied}}}
\]
Piezoelectric Properties

• The **piezoelectric charge constant, d**, relates the mechanical strain produced by an applied electric field,
  - Because the strain induced in a piezoelectric material by an applied electric field is the product of the value for the electric field and the value for d, d is an important indicator of a material's suitability for strain-dependent (actuator) applications.
  - The unit is Meters/Volt, or Coulombs/Newton

\[ d = \frac{\text{Strain Development}}{\text{Applied Electric Field}} \quad \text{or} \quad d = \frac{\text{Short Circuit Charge Density}}{\text{Applied Mechanical Stress}} \]
Piezoelectric Properties

• The piezoelectric constants relating the electric field produced by a mechanical stress are termed the **piezoelectric voltage constant, g**, 
  – Because the strength of the induced electric field in response to an applied stress is the product of the applied stress and g, g is important for assessing a material's suitability for sensor applications.
  – The unit of g is volt meters per Newton

\[
g = \frac{\text{Open Circuit Electric Field}}{\text{Applied Mechanical Stress}} \quad \text{or} \quad g = \frac{\text{Strain Developed}}{\text{Applied Charge Density}}
\]
Soft Piezoelectric Ceramics

- "Soft" Piezoelectric Ceramics
  - characterized by large electromechanical coupling factors, large piezoelectric constants, high permittivity, large dielectric constants, high dielectric losses, low mechanical quality factors, and poor linearity.
  - produce larger displacements and wider signal band widths, relative to hard ceramics, but they exhibit greater hysteresis, and are more susceptible to depolarization or other deterioration. Under high drive conditions susceptible to self-heating beyond their operating temperature range.
  - Lower Curie points (generally below 300°C) dictate that soft ceramics be used at lower temperatures.
  - Generally large values for permittivity and dielectric dissipation factor restrict or eliminate soft ceramics from applications requiring combinations of high frequency inputs and high electric fields.
  - Consequently, soft ceramics are used primarily in sensing applications, rather than in power applications.
Hard Piezoelectric Ceramics

- "Hard" or High Power Piezoelectric Ceramics
  - can withstand high levels of electrical excitation and mechanical stress.
  - characteristics generally opposite those of soft ceramics, including Curie points above 300°C, small piezoelectric charge constants, large electromechanical coupling factors, and large mechanical quality factors.
  - also are more difficult to polarize or depolarize.
  - Although hard ceramics generally are more stable than soft ceramics, they cannot produce the same large displacements.
  - Hard ceramics are compatible with high mechanical loads and high voltages.
  - Generally used for actuation applications, such as piezoelectric motor or actuators.
Stability of Piezoelectric Ceramics

- **Mechanical Limitations**
  - Mechanical stress sufficient to disturb the orientation of the domains in a piezoelectric material can destroy the alignment of the dipoles.
  - *Could be a major limitation for a high stress area monitoring*

- **Thermal Limitations**
  - If a piezoelectric ceramic material is heated to its Curie point (~300°C), the domains will become disordered and the material will be depolarized. The *recommended upper operating temperature for a ceramic usually is approximately half-way between 0°C and the Curie point.*
  - Also, sudden temperature fluctuations can generate relatively high voltages, capable of depolarizing the ceramic element.
Stability of Piezoelectric Ceramics

• **Stability**
  – Most properties of a piezoelectric ceramic element degrade gradually, in a logarithmic relationship with time after polarization.
  – Exact rates of aging depend on the composition of the ceramic element and the manufacturing process.

• **Electrical Limitations**
  – Exposure to a strong electric field, of polarity opposite that of the polarizing field, will depolarize a piezoelectric material. (between 500 V/mm and 1000 V/mm for continuous operation)
  – An alternating current will have a depolarizing effect during each half cycle in which polarity is opposite that of the polarizing field.
Integrated Piezoelectric Sensor Layer

- Smart layer is a thin dielectric film with built-in piezoelectric sensor networks for monitoring of the integrity of composite and metal structures developed by Prof. F.K. Chang and colleagues and commercialized by the Accellent Technology, Inc. The embedded sensor network are comprised of distributed piezoelectric actuators and sensors.

SMART (Stanford Multi-Actuator Receiver Transduction) Layer

Image courtesy of FK Chang, Stanford Univ.
SHM System Elements

(1) Data Collection
   - Sensors (passive and active)
   - Data acquisition and Integration

(2) Information Processing
   - Understanding wave propagations
   - Signal Processing

(3) Diagnostics – Defining current state
Data Acquisition and Integration

- The data-acquisition portion of the structural health monitoring process involves:
  - selecting the types and dimensions 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.

**Optimization and customization** for a specific application & performance requirements (Cost Benefit Analysis)
SHM System Elements

(1) Data Collection
   - Sensors (passive and active)
   - Data acquisition and Integration

(2) Information Processing
   - Understanding wave propagations
   - Signal Processing

(3) Diagnostics – Defining current state
Need for Information Processing

• A Sensor for Directly Measuring Structural Health Does Not Exist!

• Partial Information is Provided By Each Sensor:
  – Strain and Acceleration
  – Corrosion Environment Parameters (Moisture, pH, etc.)
  – Crack Detection and Growth
  – Acoustic Emission (AE) Events
  – Piezoelectric-Induced Vibration Signature Characteristics
  – many more ...

• Significant Information Processing is Required to:
  – Convert Raw Sensor Data into Meaningful Information
  – Fuse Multi-Sensor Data into Comprehensive Health Summary
Understanding Wave Propagations

- PZT actuator can induce a vibration to structure and generate elastic wave propagations
- PZT sensor can sense the elastic perturbations (due to impact, crack initiation, other transducer excitations)

- Elastic Wave Classifications
  - Body or Bulk waves
    - Longitudinal waves
    - Transverse waves
  - Guided waves
    - Rayleigh waves (surface)
    - Stonley waves (interface)
    - Lamb waves (plate)
Elastic Wave Equations

- 6 independent strain displacement equations
  \[ \varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \]

- 6 independent constitutive equations
  \[ \sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2 \mu \varepsilon_{ij} \]

- 3 equations of motion
  \[ \sigma_{ji,i} + \rho \ddot{f}_i = \rho \ddot{u}_i \]

- Tensor notation of Navier equation
  \[ (\lambda + \mu) \nabla \nabla \cdot \mathbf{u} + \mu \nabla^2 \mathbf{u} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \]

Lamé constants: elastic properties
Elastic Wave Equations

- **Equation of Motion**
  \[(\lambda + \mu)\nabla \nabla \cdot \mathbf{u} + \mu \nabla^2 \mathbf{u} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}\]

- **Displacement vector decomposition** *(Helmholtz theorem)*
  \[\mathbf{u} = \nabla \phi + \nabla \times \psi, \quad \nabla \cdot \psi = 0 \quad \text{(divergence-free)}\]
  - **Dilatational property**
  - **Distortional property**

- **Decomposed wave equations**
  \[
  \nabla^2 \phi = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2}, \quad C_L^2 = \frac{\lambda + 2\mu}{\rho} \quad \text{Speed of plane longitudinal waves}
  \]
  \[
  \nabla^2 \psi = \frac{1}{c_T^2} \frac{\partial^2 \psi}{\partial t^2}, \quad C_T^2 = \frac{\mu}{\rho} \quad \text{Speed of plane transverse waves}
  \]

- The longitudinal and distortional waves propagate without interaction
- Coupled only at the boundary of the elastic body
Dilatational (longitudinal) Waves

Transverse Waves

Animation courtesy of Dr. Dan Russell, Kettering University
Examples of Longitudinal + Transverse Waves

Water waves

Rayleigh surface waves

Animation courtesy of Dr. Dan Russell, Kettering University
Classification of Guided Waves

- Rayleigh waves are free waves on the surface of a semi-infinite solid
- Stonely waves are occurred at an interface between two media
- Lamb waves are waves of plane strain that occur in a free plate
  - Many aircraft parts are plate-like structure
  - Good interactions with structural flaws
- Unlike bulk waves, a guided wave problem must satisfy the governing equation as well as some physical boundary conditions
Waves in Plates (Lamb Waves)

- Wave equations in a plain strain condition

\[
\nabla^2 \phi = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2} + \frac{1}{c_T^2} \frac{\partial^2 \phi}{\partial t^2} = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial x_1^2} + \frac{1}{c_T^2} \frac{\partial^2 \phi}{\partial x_3^2}
\]

- Assuming solution type

\[
\phi = \Phi(x_3)e^{i(k_1x_1 - \omega t)} \quad \Phi(x_3) = A_1 \sin(px_3) + A_2 \cos(px_3)
\]

\[
\psi = \Psi(x_3)e^{i(k_2x_1 - \omega t)} \quad \Psi(x_3) = B_1 \sin(qx_3) + B_2 \cos(qx_3)
\]

- Displacement & Stress in a plain strain

\[
\begin{align*}
  u_1 &= \frac{\partial \phi}{\partial x_1} + \frac{\partial \psi}{\partial x_3} \\
  u_3 &= \frac{\partial \phi}{\partial x_3} - \frac{\partial \psi}{\partial x_1}
\end{align*}
\]

\[
\begin{align*}
  \sigma_{11} &= \frac{1}{c_L^2} \left( \frac{\partial^2 \phi}{\partial x_1^2} - \frac{\partial^2 \psi}{\partial x_3^2} + \frac{\partial^2 \psi}{\partial x_1 \partial x_3} \right) \\
  \sigma_{33} &= \frac{1}{c_T^2} \left( \frac{\partial^2 \phi}{\partial x_3^2} - \frac{\partial^2 \psi}{\partial x_1 \partial x_3} \right) + 2 \mu \left( \frac{\partial^2 \phi}{\partial x_3^2} - \frac{\partial^2 \psi}{\partial x_1 \partial x_3} \right)
\end{align*}
\]

Then

\[
\begin{align*}
  u_1 &= \left[ ik\Phi + \frac{d\Phi}{dx_3} \right] \\
  u_3 &= \left[ \frac{d\Phi}{dx_3} - ik\Phi \right] \\
  \sigma_{33} &= \left[ \lambda \left( -k^2 \Phi + \frac{d^2 \Phi}{dx_3^2} \right) + 2 \mu \left( \frac{d^2 \Phi}{dx_3^2} - ik \frac{d\Phi}{dx_3} \right) \right] \\
  \sigma_{11} &= \mu \left( 2ik \frac{d\Phi}{dx_3} + k^2 \Psi + \frac{d^2 \psi}{dx_3^2} \right)
\end{align*}
\]
Symmetric and Anti-symmetric Modes of Lamb Waves

Final displacement field

**Symmetric modes**

\[
\begin{align*}
 u_1 &= ikA_2 \cos(px_3) + qB_1 \cos(qx_3) \\
 u_3 &= -pA_2 \sin(px_3) - ikB_1 \sin(qx_3) \\
 \sigma_{31} &= \mu [-2ikpA_2 \sin(px_3) + qB_1 \cos(qx_3)] \\
 \sigma_{33} &= -\lambda (k^2 + p^2)A_2 \cos(px_3) - 2\mu [p^2 A_2 \cos(px_3) + ikqB_1 \cos(qx_3)]
\end{align*}
\]

**Anti-symmetric modes**

\[
\begin{align*}
 u_1 &= ikA_1 \sin(px_3) - qB_2 \sin(qx_3) \\
 u_3 &= pA_1 \cos(px_3) - ikB_2 \cos(qx_3) \\
 \sigma_{31} &= \mu [2ikpA_1 \cos(px_3) + (k^2 - q^2)B_2 \cos(qx_3)] \\
 \sigma_{33} &= -\lambda (k^2 + p^2)A_1 \sin(px_3) - 2\mu [p^2 A_1 \sin(px_3) - ikqB_2 \sin(qx_3)]
\end{align*}
\]
Symmetric and Anti-symmetric Modes of Lamb Waves
Symmetric Mode of Lamb Waves
Anti-Symmetric Mode of Lamb Waves
While wave speed is independent of frequency in bulk (body) waves, wave speed varies with frequency in Lamb wave propagation. This dispersion carries important implications for Lamb wave analysis. The analysis is further complicated by the coexistence of at least two modes at any given frequency.
• Fundamental symmetric mode for crack detection
• Fundamental anti-symmetric mode for composite delamination detection
SHM Elements To be Covered

(1) Data Collection
   – Sensors (passive and active)
   – Data acquisition and Integration

(2) Information Processing
   – Understanding wave propagations
     – Signal Processing

(3) Diagnostics – Defining current state
Signal Processing

• Signal Representation
  - Time
  - Frequency
  - T & F (STFT, WTF)
• Noise filtering
• Mode Identification / Decomposition
• Feature extractions (Damage Indexing)
Signal Representation

- Different ways of looking at a problem
  - Interchangeable: no information is lost in changing from one domain to another
  - Benefits from changing perspective: the solution to difficult problems can often become quite clear in the other domain
Time Domain Analysis

• The traditional way of observing signals is to view them in the time domain. Record in the time domain typically describes the variation of system output or system parameter over time.

• Solution techniques in time domain
  – Analytical solution of differential equations
  – Numerical simulation
  – and more
Time Domain Analysis

- **Peak**
  - $\text{Peak} = \max(|x(t)|)$

- **Peak-to-Peak**
  - $V_{pp} = \max(x(t)) - \min(x(t))$

- **Root Mean Square (RMS)**
  - $\text{RMS} = \sqrt{\frac{1}{T} \int_0^T |x(t)|^2 \, dt}$

- **Mean**
  - $\text{Mean} = \frac{1}{T} \int_0^T |x(t)| \, dt$
Frequency Domain Analysis

• It was shown over one hundred years ago by Jean B. Fourier that any waveform that exists in the real world can be generated by adding up sine waves.

\[ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} \, dt \]
Signal Characteristics Plane

- Short time but wide band
- Long time but narrow band
- Short time & narrow band
- Time varying narrow band
Limitations of the FFT

- No information about how frequencies evolve over time
- Not suitable for analyzing impulsive signals
- A power spectrum does not contain time information
Transients

- It is difficult to detect presence of transients in a signal by its power spectrum
Time-Frequency Analysis

- The short-time Fourier transform (STFT) is the most popular time-frequency analysis algorithm (Windowed FFT)

\[
S(\omega,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega \tau} s(\tau) h(\tau - t) d\tau
\]
Advantages of Time-Frequency Analysis

- Time-frequency representation shows how frequency components of a signal evolve over time

FFT

Reversed in time domain

Time
Wavelet vs Sine Wave

- Wavelet = Wave (Oscillatory) + Let (Compact)
Multi-Resolution

- A higher scale wavelet has larger time duration but lower frequency and smaller bandwidth.
Wavelet Transform vs STFT

- A wavelet transform has adaptive time-frequency resolution
Bandwidth

- **Bandwidth** is a measure of frequency range of signals (or systems), measured in hertz
  - bandwidth would be the range of frequencies that the signal's Fourier transform has a power above a certain threshold, say 3 dB within the maximum value, in the frequency domain.
Filter

• In signal processing, the function of a filter is to remove unwanted parts of the signal, such as random noise, or to extract useful parts of the signal, such as the components lying within a certain frequency range.
• The response curve or cut-off of a filter describes how well the filter blocks or passes a band of frequencies.
Filter

- Filter types: Low-pass, high-pass, band-pass, and band-reject filters
  - The purpose of these filters is to allow some frequencies to pass unaltered, while completely blocking other frequencies. The passband refers to those frequencies that are passed, while the stopband contains those frequencies that are blocked. The division between the passband and transition band is called the cutoff frequency.
Filter

- An ideal filter has a "brick wall" response. That is, it has an infinite transition ratio. However, this is never the case in real word applications. The steeper the roll-off, the higher the 'Q' or quality factor of the filter. And the higher the Q, the more complex the filters design. High Q's can lead to filter instability and self-oscillation at the desired corner frequency.
Filter

- The Butterworth filter has the flattest passband region, meaning it has the least attenuation over the desired frequency range.
- The Bessel filter has a more gradual roll-off but its key advantage is that it has a linear phase response, meaning each frequency component is delayed by an equal amount of time as it passes through the filter.
- The Chebyshev filter has a steeper rolloff but more ripple in the passband.
Digital Sampling

• Sampling is the process of converting a signal (in continuous time) into a numeric sequence (in discrete time). The process is also called analog-to-digital conversion (ADC), or simply digitizing.
  • More precisely, ADC actually consists of the combination of two processes: sampling, which involves converting the domain of the signal from continuous-time to discrete-time, and quantization, which involves converting the amplitude of the signal from a continuous infinite range of values to a finite set of discrete values.
Digital Sampling

• Shannon-Nyquist sampling theorem
  – The maximum frequency component a sampled data system can accurately handle is its Nyquist limit (i.e., Nyquist frequency).
Aliasing

- The sampling rate must be greater than or equal to two times the highest frequency component in the input signal. When this rule is violated, unwanted or undesirable signals appear in the frequency band of interest. This is called "aliasing."
- When "aliasing" happens, frequency components greater than half the sampling rate "alias" (shift) into the frequency band of interest.
  - Most of the time, aliasing is an undesirable side effect, so the "under-sampled" higher frequencies are simply filtered out before the A/D stage.
Aliasing

- A very easy, convenient, and practical way of illustrating the disguising of higher frequencies as lower frequencies that is inherent in aliasing is by sampling sinusoidal signals. This is because pure sinusoidal signals have spectrums consisting only of spikes (delta functions) at the respective frequency; aliasing with pure tones is seen as the spike moving from one location to another.
Anti-aliasing Filter

- One way of avoiding the problem of aliasing is to apply an anti-aliasing filter to the signal, prior to the sampling stage, to remove any frequency components above the "folding" or Nyquist frequency (half the sampling frequency).
- An anti-aliasing filter is a low-pass filter.
(1) Data Collection
   - Sensors (passive and active)
   - Data acquisition and Integration

(2) Information Processing
   - Understanding wave propagations
   - Signal Processing

(3) Diagnostics – Defining current state
Levels of Diagnostics

- Level 1: *detect* the existence of damage
- Level 2: *detect* and *locate* damage
- Level 3: *detect, locate* and *quantify* damage
- Level 4: *estimate* remaining service *life* (prognosis)
- Level 5: self-healing
An echolocating bat (Eptesicus fuscus) pursuing and attempting to capture a moth in dark in the flight room of the Auditory Neuroethology Laboratory at the University of Maryland. The picture is provided courtesy of Professor Cynthia Moss. The photograph was taken by Ms. Jessica Nelson with a still camera.
Input sweeps—a 1st harmonic from 45 to 22 kHz and a 2nd harmonic from 80 to 45 kHz—that
A Damage Detection/Imaging Scheme

Develop visualization method to pinpoint the damage location and estimate size by locating wave scattering point(s) which define the damage boundary.

Point like damage \( d \ll \text{Wavelength} \)

Estimated crack length/location

Damage with area (i.e. composite delamination)

Estimated damage area/location
Diagnostic Input Wave

- Five peak narrow-banded burst signal as an input signal
- Narrower band of frequency contents -> less distortion
Damage detection/Imaging Scheme

Healthy structure

Firing at sensor $i$
Echoes are measured at sensor $i \ldots N$

Baseline data $R^0_{ij}(t)$

Ampl.

$R^0_{12}$

Time
Damage detection/Imaging Scheme

Firing at sensor $i$
Echoes are measured at sensor $i \ldots N$

Data w/damage $R_{ij}(t)$
Scattered signals = Data w/damage - Baseline

\[ s_{ij}(t) = R_{ij}(t) - R_{ij}^0(t) \]
Damage detection/Imaging Scheme

- Assuming velocity, $c$ is known or can be measured

\[ \tau_d = \tau_{1d} + \tau_{d2} \]
\[ \tau_{d2} = \frac{l_{d2}}{c} \]
\[ \tau_{1d} = \frac{l_{1d}}{c} \]
Damage detection/Imaging Scheme

\[ \tau_p = \tau_{1p} + \tau_{p2} \]

\[ \tau_{p2} = \frac{l_{p2}}{c} \]

\[ \tau_{1p} = \frac{l_{1p}}{c} \]

\[ I(p) = s_{12}(\tau_p) \approx 0 \]

Plot \( I \) or \( s_{12}(\tau_p) \) at arbitrary \( p \) for known \( c,l \)

\( I \) becomes maximum when \( p = d \)
Damage detection/Imaging Scheme

Plot I for all other paths

\[ I^{sum} = \sum s_{ij}(\tau_p) \]

Problems:
1. Oscillating raw data-muti-peaks
2. Other reflected waves
3. Other cross over locations
   \( \rightarrow \) insufficient resolution to pinpoint the scatterer (damage)
Signal processing

To increase the resolution:
1. Convert raw data into clean and efficient waveforms
2. Use the correlations (product) of the scattered waveforms

\[
S(\omega,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\tau} s(\tau) h(\tau - t) d\tau
\]
Signal processing

Convert raw data into clean and efficient waveforms

Group velocity = \frac{\text{Sensor spacing}}{\text{TOF}}
Diagnostic Imaging Formulation

**Raw measurements (scattered)**

**Processed data**

**Imaging Formulation**

\[
P(x, y)_{|\omega = \omega_0} = \prod_{i=1}^{N} \prod_{j=1}^{N} S_{ij}(\omega_0, \tau)
\]

\(\omega_0\): Input frequency

\(\tau\): Time shift, flight distance/velocity
Imaging Method Verification – Added mass

- Added mass location is clearly identified
Imaging Method Verification – Added mass

- Added mass location is clearly identified
- The method highlights the edges of the mass where the wave scatters the most
Imaging method verification – Crack

- Crack location is clearly identified. If you zoom in the cracked area...
Imaging method verification – Crack

- Crack tip where wave scattering occurs was clearly highlighted
- Actual crack length = 4mm, estimated crack length = 5.2mm
Auto Focus

- Can we generate diagnostic imaging without knowing group velocity?
- Auto Focus finds the velocity that gives the most focused image (assuming constant velocity)

focused velocity = 5.1 km/sec
Measured velocity = 5.06 km/sec
Technique Verification – Delamination

Ultrasonic Scan

Piezoceramics

Delamination

Diagnostic Imaging (No Impact)

Sandwich panel from an aerospace company w/ integrated SMART layer
Technique Verification – Crack

- Tested on an aluminum plate (508 x 508 x 1.02 mm) with four PZT transducers

**Beamforming based**

**Convolution based**

- Group shape resolution
  - Higher contrast
  - Group location resolution
Technique Verification – Crack from a Hole

Beamforming based

Convolution based
Technique Verification – Crack Orientation

Crack at -90 degree from a hole

Crack at +8 degree (not from a hole)

Orientation of crack can be identified
How are Piezo actuator/sensors used in SHM?

**Propagating Lamb waves**

- Impact/AE Detection
- AE from crack
- Impact
- Sensor 1
- Sensor 2
- Sensor 3
- Sensor 4
- Receiver

**E/M Impedance**

- Re $Z$, Ohms
- Frequency, kHz
- Sensor 1
- Sensor 2
- Sensor 3
- Sensor 4
How are Piezo actuator/sensors used in SHM?

Ultrasonic Phased Array for SHM

2 in (50 mm)

42 kilocycles: 50 mm crack

Data taken was while under cyclic loading simulating in-flight recording
SHM Elements
Much More to Cover

SHm

Data Collection
- Sensors
- Data Acquisition Hardware
- Visual Inspection
- NDI/NDE
- Other Data (reports of damage events, fleet history ...)
- Loads & Environments

Data Processing
- A1
- A2
- An
- A1, A2, An = Multiple algorithms for SHM information processing

Information Processing to Define Current State
- Data Fusion & Integration
- Material State Awareness
- Structural State Awareness

Decision Making & Dissemination
- Capability analysis
- Margins
- Prognosis
- Maintenance & Operations Recommendations

Multi-scale Physics based Modeling
Q & A!

For further questions, please send me an email to jbihn@u.washington.edu or Jeong-beom.ihn@boeing.com