3. Data Acquisition II: Piezoelectric Devices

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Outline

- Piezoelectric Devices
- Structural Health Monitoring Techniques using Piezoelectric Transducers
  - Guided waves (More in Lecture 7)
  - Electro-Mechanical Impedance methods
  - High frequency response functions
  - Time series analysis
- Commercially Available Systems
- Current Status and Issues in Active-Sensing
  - Sensor self-diagnostics
  - Hardware development
- Acoustic emission
- Summary
Piezoelectric Devices

- Piezoelectric materials

\[
\begin{bmatrix}
S \\
D
\end{bmatrix}
= 
\begin{bmatrix}
S' \\
D'
\end{bmatrix}
\begin{bmatrix}
T \\
E
\end{bmatrix}
\]

- Materials produce an electric charge when mechanically stressed \(\text{(direct effect)}\)
- These materials also deform (produce a mechanical strain) when an electric field is applied to them \(\text{(converse effect)}\)

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Piezoelectric Devices

- The use of piezoelectric materials in structural dynamics problems (as sensors and actuators) is an active research area. The applications include vibration testing, control, and SHM
- Integrated with control algorithms (and/or with other active materials), this field is called “smart structures” or “intelligent material systems”.
- Natural fix for SHM applications ➔ Capabilities in both sensing and actuation
- Known and repeatable inputs can be applied and used in SHM algorithms (Active-sensing)

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Advanced Piezoelectric Sensors

- Drawbacks of Piezoceramic sensors
  - Brittle
  - Do not conform to curved surfaces

- Recent studies showed there are advanced piezoelectric materials to overcome such limitations.
  - Macro-fiber Composites (MFC)
  - Active-fiber Composites (AFC)

Damage Sensing Methods: Wave Propagations

- What is the wave?
  - A disturbance or variation which travels through a medium
  - Waves transfer energy without transferring particles
  - Types: longitudinal, transverse, surface waves (Raleigh, Lamb), etc
  - Traditionally widely used in NDT testings, now in structural health monitoring using piezoelectric patches.

Figures from http://www.kettering.edu/~drussell
Damage Sensing Methods: Wave Propagation

- When a crack is present in a wave path, wave deflection, reflection, and transmission occurs.
- Amounts of each of these will be dependent on size/nature of damage.
- A matrix of info on *damage sensitive feature* can be created.
- Need to create a relationship between wave info and damage location, size, and orientation.
- Lamb waves are widely used in SHM applications.

### Piezoelectric Devices for Wave Propagation

- Piezoelectric (PZT) patches can serve as a sensor and an actuator for wave propagation.
- Can be directly mounted (or even embedded) on the structure.
- Intelligent selection of
  - Size of PZT patches
  - Driving frequency
  - Sensor-actuator spacing
  - Pulse shape
- Development of signal processing algorithms for efficient damage identification is also an important research issue.
- This is a hot topic of SHM research and will be detailed on another lecture.
Damage identification through Wave Propagation

• An example: Broken rail detection
  (http://www.ndt.net/article/wcndt00/papers/idn270/idn270.htm)
• The detection of a broken rail is made possible by utilizing energy propagating from the train wheel in contact with the rail.
• The rail is a wave guide that permits certain wave modes and frequencies to travel efficiently
• If a break were to occur between the two sensors,
  – Sensor 1: increase in magnitude as a result of both impinging elastic wave energy and reflected elastic wave energy from the broken rail.
  – Sensor 2: Decrease in magnitude consisting of a noise pattern.

Damage Sensing Methods: Electromechanical Impedance Method

• Piezoelectric (PZT) patches are used to couple the electrical impedance and mechanical impedance of structures.
• The mechanical impedance of a structure is a function of the structure’s mass, stiffness, and damping.
• Therefore, if any of these quantities changes, it can be seen through the electrical impedance of a PZT patch.
Impedance-based Structural Health Monitoring

- Self-sensing: Excite a structure and measure impedance change (> 30 kHz) with co-located PZTs.
- The co-location requires less than 1V to produce useful impedance excitations.
- As a structure is damaged, K, M or C changes and impedance changes

\[
Y(\omega) = \frac{I}{E} = i\omega \frac{w}{I_c} \left( \frac{1}{Z_{\omega}} \frac{Z_{\omega}^2}{Z_{\omega}^2 + \left( \tan \frac{\omega t}{k} \right)^2} \right) \quad \text{(Sun, 1996)}
\]

Composite reinforced concrete walls* (Park et al.2000)

- To monitor
  - Debonding between composite plate and concrete wall
  - Crack growth under the composite plate

* This work was performed at Virginia Tech under the direction of Drs. Daniel J. Inman and Harley H. Cudney supported by CERL.
Observations

Damage Comparison

- Qualitative damage assessment
  - A damage metric is computed
  - Damage comparisons are made using this scalar number
    \[ M = \sum_{i=1}^{n} |\text{Re}(Y_{i,1}) - \text{Re}(Y_{i,2})|^p \]

- This value will be compared against all other damage to assess the state of structures
- A compensation technique has been established to be stable under various types of environmental condition changes
Observation – Damage Metric PZT 1-5

- Multiple damage at different locations could be identified

Three story bookshelf example

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Thin Plates Example

- 100-mm diameter, 0.8 mm thick circular plates
- Changes in impedance signatures with different types of damage introduced (Girugiutiu and Zagrai, 2001)

Current status of the impedance methods

- There are more than 20+ research institutes worldwide investigating this method for various SHM applications
- Pros:
  - Low power consumption
  - Localized SHM sensing capability
  - Sensor diagnostic capability
- Cons:
  - Not ideal for highly-damped structures
  - Difficulties in localization for very low-damped structures
  - Difficulties in frequency selection
Damage Sensing Methods: High frequency response function

- FRF contains unique dynamic characteristics, which can be used for monitoring and tracking the changes in structural integrity.
- With piezoelectric active-sensors, FRF can be measured at higher frequency ranges (>5 kHz) to improve the sensitivity.
- One PZT patch is designated as an actuator, exerting a random input, and the remaining patches can be used as sensors.

Damage Sensing Methods: Time Series Models

- Most of the active-sensing methods have been based on frequency domain (impedance) or other approaches for damage sensitive feature extraction.
  - Excessive averaging, intensive computation
- However, predictive models of time series data can also be directly used in piezoelectric active-sensing SHM.
The autoregressive model with exogenous input (ARX) predicts the current time point in a series as a linear combination of $p$ previous time points and $q$ previous input points:

$$x_i = \sum_{j=1}^{p} \alpha_j x_{i-j} + \sum_{j=0}^{q} \beta_j y_{i-j} + e_i$$

An ARX ($p,q$) model is used to capture the input/output relationship, utilizing the information associated with a “known and repeatable” input provided by a piezoelectric active-sensing system.

Damage sensitive features:
- ARX Parameters: $\alpha_j$ and $\beta_j$ in
- Residual Errors: Use a model estimated from the baseline condition to predict newly measured responses.

Section of a Wind turbine Blade

- CX-100 Turbine Blade 1-m Section
- Simulated damage was introduced
Frequency Response Testing Results

- **Real Component Magnitude**
- **Imaginary Component Magnitude**

Time Series Analysis

- **Actual and Predicted Undamaged Signals (Path 1)**
- **Actual and Predicted Undamaged Error (Path 1)**
- **Actual and Predicted Damaged Signals (Path 1)**
- **Actual and Predicted Damaged Error (Path 1)**
Time Series Analysis

- Path 1
  - Detected Damage

RMSE Plot

Advantages of Piezoelectric active sensing in SHM

- Can detect incipient damage
- Sensors are low-cost and non-intrusive
- Require low power
- Usually non-model based methods
- Can be used in inaccessible locations
- Multi-scale sensing capability
- Localized sensing - unaffected by changes in boundary and environmental conditions or operational vibrations

- Very active research area in the SHM field.
Then, what are the issues?

- Localized sensing requires too many sensors and actuators.
- Installation of piezoelectric active sensors are not always straightforward.
- Long term reliability of PZT sensors and associated installation condition has not been substantially investigated.
- Application specific processes
- Data acquisitions systems are not designed for SHM.
- Automated signal processing algorithms

Piezoelectric sensor failure identification

- The sensor-self diagnostic procedure is a critical component to successfully implementing active SHM.
- Most SHM systems are not intelligent enough to differentiate signal changes caused by structural damage from sensor failures
- Recently, Several researchers turn their attention on sensor validation,
  - U of South Carolina: tracking the resonances of PZT sensors
  - KAIST: Tracking the time reversal properties in wave propagations
  - LANL: tracking the admittance of PZT sensors
  - Many others

*Giurgiutiu and Zarai (2002)*
Piezoelectric sensor failure identification

- Typical piezoelectric sensor failure modes are
  - Sensor breakage
  - Degradation of mechanical and electrical properties of PZT
  - De-boding between PZT and a host
- The impedance/admittance responses provide critical information regarding sensors’ health.
- Both sensor functionality and bonding condition can be efficiently monitored.

Sensor diagnostic procedure (Park et al 2006a, 2006b)

- The method tracks the capacitive value of PZT, which is manifested in measured electrical admittance.
- Electrical admittance of a PZT bonded to a structure (Sun, et al 1996)

\[
Y(\omega) = \frac{I}{V} = \frac{w}{l_e} \frac{\varepsilon}{d_{33}} (1 - i\delta) + d_{31} \varepsilon \frac{Z_m(\omega)}{Z_m(\omega) + Z_s(\omega)} \tan \left( \frac{\tan kl}{k l} \right)
\]

Geometry constants
PZT’s electrical and mechanical properties

- Degradation in these properties causes a change (downward shift in the slope) in the imaginary part of electrical admittance
Sensor diagnostic procedure

The effects of bonding layer

- Electrical admittance of a free-free PZT
  \[ Y_{\text{free}}(\omega) = \frac{w_f}{t_c} \left( \varepsilon_{33} \tau (1 - i\delta) \right) \]

- Electrical admittance of a PZT bonded to a structure
  \[ Y(\omega) = \frac{w_f}{t_c} \left( \varepsilon_{33} \tau (1 - i\delta) - d_{33}^2 Y_P^2 + \frac{Z_s(\omega)}{Z_s(\omega) + Z_f(\omega)} d_{33}^2 Y_P^2 \left( \tan k_l t \right) \right) \]

- The effect of bonding on the electrical admittance \( (Z_s(\omega) \gg Z_f(\omega)) \)
  \[ Y(\omega) = \frac{w_f}{t_c} \left( \varepsilon_{33} \tau (1 - i\delta) - d_{33}^2 Y_P^2 \right) = Y_{\text{free}}(\omega) - i\omega \frac{w_f}{t_c} d_{33}^2 Y_P^2 \]

- The bonding layer also affects the measured electrical admittance

Experiments:

- Several PZTs (5A)
  - 1x1x0.01"

- The bond causes a 38% decrease in measured capacitance
  - Free-Free: 29.1 nF
  - Bonded condition: 18.9 nF

- Sensor failures, including fracture, degradation of sensor quality, and debonding can be efficiently identified by measured admittance
Test setup and procedure

- Objectives: Check the sensor functionality and diagnostic capability with impact loadings
- Two PZT and Macro-fiber composites (MFC) are bonded on one side of a 24 x 24 x 0.25 composite plate.
- A series of impact (as high as 40 m/s) was given using a steel projectile with a gas gun facility.

Sensor Diagnostics Results

- Sensor failures are discernable from structural damage.
Sensor Validation after Installation (.25d, .01t in sensor)

Effects of bonding on Lamb waves (.25d, .01t in sensor)

- With the identified bonding defects
  - Changes in magnitude,
  - Changes in arrival time (velocity)
Sensor Validation after Installation (.5d, .02t in sensor)

Effects of bonding on Lamb waves (.5d, .02t in sensor)

- With the identified bonding defects
  - Significant changes in magnitude, shape, arrival time
  - These changes become more pronounced as the size of sensor increases
- Without the efficient sensor-diagnostic process, these changes can be mistakenly considered as structural damage
- Sensor diagnostic technique, which is insensitive to temperature variation is also developed (Overly et al. 2008)
Effects of bonding defects on Electro-mechanical impedance measurements

- With the bonding defects, the identified resonances and magnitudes are different.
- The sensor diagnostic process is required to assess the quality of the sensor condition.

Hardware Development for Active Sensing (Overly et al 2006, Mascarenas et al 2006)

- Capable of measuring impedance up to 100 kHz.
- 12 bit resolution, 180 mW power consumption, a single sensor per node
- Can be used for electromechanical impedance method, sensor diagnostics
Evolution of the Wireless Impedance Device

- The first generation WID1 was a breadboard prototype capable of monitoring 1 PZT sensor
  - This evolved into a packaged PCB form with the WID1.5
- The WID2 integrated a set of multiplexers, increasing the number of sensors per node to 7, and also provided more triggering options
- The WID3 builds upon the WID2, providing more stable wireless communication, networking capabilities, and an integrated power conditioning circuit

Hardware Development for Active Sensing (Overly et al 2007)

- Capable of measuring impedance up to 100 kHz.
- 50 mW power consumption, 7 sensors per node, new triggering options.
### WID 3.0 Integrates WID2 with a low-frequency vibration data acquisition capability

- All the function of WID2 +
  - Improved networking capability
  - Power conditioning circuit for energy harvesting and wireless energy transmission
  - More user-friendly functionalities

AD7924 A/D converter: 12 bit resolution with a sampling frequency up to 40 kHz (6 mW of power consumption)

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### Concluding Remarks

- Examples have been presented in the area of structural health monitoring using piezoelectric sensors.

- A key aspect of this method is the use of sensing and actuation capabilities of piezoelectric materials at high frequency ranges

- The methods have been successfully applied to variety of configurations and situations.

- Currently, lots of research efforts underway to handle real-life field applications
Useful References


- www.muravin.com

- www.ndt-ed.org