Structural Health Monitoring Applications Using Piezo-Dielectric Effects

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Outline

- Overview of Current Health Monitoring Systems
- Linear Piezoelectricity
- Adaptive Piezoelectric Sensoractuator (APSA)
- Experimental Demonstration
- Conclusions and Future Work
What do we Want in a Health Monitoring System?

- Real-Time Operation
- In-Situ Operation
- Self-monitoring or autonomous
- Quantify "damage"
- Locate damage
- Scalable
- Cheap, simple, easy-to install, amenable to retrofit market

No method provides the complete answer
Brief Overview of Some Previous Methods and [Strengths] and (Weaknesses)

- Ultrasound: [detailed 3-d view of internal structure, portable], (surface delams, tedious, no measure of structural degradation)
- X-ray and Thermography [Excellent, 2-d view of defects, easy], (bulky, expensive, no in-situ or real-time)
- Acoustic Emission [can determine distance to failure, real-time, in-situ, can tell failure is imminent], (little quantification)
- Fiber Optic Array [Can pinpoint damage, in-situ, real-time], (have to create grid with adequate structural resolution, only finds cracks that break fiber-optic cables)
- Modal (Frequency) Analysis [well understood], (model based, temperature effects, eigenanalysis required to pinpoint damage - complex, computationally-intensive)
Features of Proposed Method

- Monitors Electrical Behavior of Piezoelectrics to determine mechanical properties of the structure to which it is attached
- PZT "sees" structure as a distributed elastic foundation
- Real-Time Operation
- In-Situ Operation
- Very Cheap and Simple
- Easy to Retrofit
- Can use APSA simultaneously as a transducer for active control
Linear Piezoelectric Equations

\[ T_{ij} = c_{ijkl}^E S_{kl} + e_{kij} E_k \]  
\[ D_i = e_{ikl} S_{kl} + \varepsilon_{ik}^S E_j \]

\(^S\) - Blocked Value
\(^E\) - Short Circuit Value
Monitor Permittivity (Capacitance)

- "Blocked" vs. "Free" Capacitance
  \[ \varepsilon^S = \varepsilon^T \left(1 - k^2\right) \]

- PZT-5A, \( k=0.7 \), so

\[ \frac{\varepsilon^T}{\varepsilon^S} \approx 2 \]

- Capacitance of an Electroded Piezoelectric Patch

\[ C_p = \frac{\varepsilon A}{t} \]
Adaptive Piezoelectric Sensoriactuator (APSA)

- Self-sensing piezoelectric transducer
- Provides truly collocated sensor/actuator pair
- Separates mechanical and electrical charges
- Inherently monitors capacitance of piezoelectric patch in real-time
- Health monitoring operation independent of control
- Dual-technology opportunity

Adaptive Piezoelectric Sensor-Actuator (APSA) - Schematic

V_{In} \rightarrow \text{Power Amp} \rightarrow V_{pa} \rightarrow C_p \rightarrow \text{Piezostructure} \rightarrow \text{Multiplier (AD632)} \rightarrow V_{Out}

V_{Ref} \rightarrow V_{pa} \rightarrow \text{VCA & CMR} \rightarrow V_{Out}

Low-level White Noise Training Signal

Gain Determined From LMS Algorithm

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Sets Gain Across Analog Network

$$w(k + 1) = w(k) - \mu e(k)x(k)$$  \hspace{1cm} \text{(LMS)}

Adaptive Filter Coefficient Prop. to Capacitance

$$C_p \propto w(k)$$

Looks for "abrupt" changes in capacitance

$$y(k) = w(k) - w(k - 1)$$  \hspace{1cm} \text{(Edge Detector)}
Events that can effect the strain field, Causing a change in PZT Capacitance

- Structural boundary condition change
  - Fastener Failures

- Change in Stiffness ($EI$, $EA$)
  - Impact Damage
  - Fatigue Cracking
Picture of Test Setup

Clamp #1  Beam  Clamp #2

Piezoceramic

Optical Bench
Experimental Results For Structural Boundary Condition Change

Clamp #2 Unbolted, Experiment 1

Clamp #2 Rebolted, Experiment 2

Experimental Results For Structural Boundary Condition Change
Conclusions

- A novel method of structural health monitoring using the Adaptive Piezoelectric Sensoriactuator is presented.
- The electrical properties of the piezoceramic change with varying mechanical conditions of the structure.
- The structure forms a varying elastic foundation for the piezoceramic patch.
- Capacitance of the piezoceramic transducer can be monitored in real-time using the Adaptive Piezoelectric Sensoriactuator.
- A digital edge detector (differentiator) watches for "abrupt" capacitance changes.
- The method is simple, cheap, works in-situ, works in real-time, amenable to retro-fit.
Future Work

- Ability to localization damage
- Ability to quantify damage or events
- Temperature insensitivity (electro-mechano-thermal coupling)