Electromagnetic Imaging in Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE)

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Outline

• Introduction and motivation
  – Damage and Damage State
  – NDE vs. SHM
• Electromagnetic imaging in NDE
  – A review
  – Hybrid imaging methods
    • Eddy Current / Magneto Optic Imaging
    • Eddy Current / Giant Magneto Resistive Imaging
    • Microwave induced Thermoacoustic Imaging
• Summaries and future directions
• In the most general terms, *damage* can be defined as changes introduced into a system that adversely affect its current or future performance
  – This talk will be focused on the study of *damage identification* in structural and/or mechanical systems
  – The definition of damage here will be limited to the changes to the *materials and/or geometric properties* of these systems, including changes to the boundary conditions and system connectivity
Damage (length-scales)

• In terms of length-scales, all damage begins at the material level. Such damage:
  – usually referred to as a defect or flaw
  – present in all materials, to some degree
• Damage does not necessarily imply a total loss of system functionality
  – Two different states of a system: undamaged or operating in its optimal manner vs. damaged state
  – In reliability society, failure is a common term, which can be defined as a point that the damage grows to reach, where it affects the system operation to an unacceptable level
Damage (time-scales)

- In terms of time-scales, damage can accumulate incrementally:
  - Over long periods of time, such as that associated with fatigue or corrosion damage accumulation
  - Over short periods of time, such as scheduled discrete events (e.g. aircraft landings) and unscheduled discrete events (e.g. earthquakes)
Damage state of a system
[A. Rytter, 1993]

- **Existence**: Is there damage in the system?
- **Location**: Where is the damage in the system?
- **Type**: What kind of damage is present?
- **Extent**: How severe is the damage?
- **Prognosis**: How much useful life remains?
Five closely related disciplines

• Nondestructive Evaluation (NDE)
• Structural Health Monitoring (SHM)
• Condition Monitoring (CM) [Bentley, Hatch, 2003]
  – Analogous to SHM, but addresses damage identification in rotating and reciprocating machinery
• Statistical Process Control (SPC) [Montgomery, 1997]
  – Process-based rather than structure-based, uses a variety of sensors to monitor changes in a process
• Damage Prognosis (DP) [Farrar, Lieven, 2007]
  – Predict the remaining useful life of a system
Nondestructive Evaluation (NDE)

- Nondestructive Evaluation is the science of evaluating/assessing the integrity of material/structure without compromising its usefulness
  - Visual
  - Tap Test
  - Radiography
  - Thermography
  - Acoustic methods (Ultrasound, AE, etc.)
  - Magnetic Flux Leakage
  - Eddy current
  - Microwave
  - ...
Nondestructive Evaluation (NDE)

• NDE is:
  – necessary and critical to determine the system safety and reliability
  – primarily used for damage characterization and as a severity check when there is a priori knowledge of the damage location [CR Farrar, K Worden, 2007]
  – usually carried out off-line in a local manner, however recent NDE research development allow it as a monitoring tool for in situ structures
Structural Health Monitoring (SHM)

- Structural Health Monitoring is the process of determining and tracking structural integrity and assessing the nature of damage in a structure (or the process of implementing a damage identification strategy) [PC Chang, A Flatau, SC Liu, 2003]
  - Ideally, SHM consists of determining, by measured parameters, the location and severity of damage in structures as they happen.
Structural Health Monitoring (SHM)

- SHM usually involves:
  - the on-line observation of a system over time using periodically spaced measurements
  - Damage sensitive features extraction
  - Statistical analysis of these features to determine the current state of system health
  - For long-term SHM, obtain information regarding the ability of the structure to continue to perform its intended function with the inevitable aging and damage accumulation [Worden, Dulieu-Barton, 2004]
Global Health Monitoring

• However, the state-of-the-art SHM methods usually do not give sufficiently accurate information to determine the extend and/or nature of the damage
  – Only determine whether or not damage is present in the entire structure (global health of the structure)
    • Still critical and important by just knowing the occurrence of damage
• Further examination of the structure needs to be taken
  → Local Health Monitoring (NDE methods)
Local Health Monitoring

- Nondestructive evaluation methods are used to locate the damage and determine its nature
  - In contrast to the “global” and “continuous” monitoring that detects the general location of the damage, NDE methods will find the exact location and characteristics of the damage (size, shape, material types, etc.)
  - *In situ* evaluation capability with advanced sensing/imaging and signal/image processing techniques
  - Several advanced imaging sensors (*imaging physics, image processing techniques*) will be introduced during this talk
- When we talk about imaging sensors, it is more about the “local” HM rather than the “global” HM techniques.
Damage detection methods: SHM/NDE for a wind turbine system
[C. C. Ciang, 2008]

- Acoustic emission events detection
- Thermal imaging
- Ultrasonic
- Modal-based approaches
- Fibre optics
- Laser Doppler vibrometer
- Electrical resistance-based damage detection
- Strain memory alloy
- X-radioscopy
- Eddy current
  - “no promising strategy in scanning an in-service wind turbine blade”, limited to the CFRP component
Electromagnetic Imaging

- All electromagnetic methods in nondestructive evaluation involve the Maxwell’s Equations

Deng, PhD Thesis, 2009
Applications of NDE
Forward and Inverse Problems in NDE/SHM

Forward: Mathematical Models

Object Space:
Materials Characterization, Damage Identification

Inverse: Image Processing, Pattern recognition, Reconstruction, Visualization, Classification

Image Space:
Measured or Simulated Data

Deng, PhD Thesis, 2009
Qualitative vs. Quantitative

What I can see in the images?
Good Image Quality?
What does image value mean?
Quantitative evaluation?
Useful information (both Qualitative and Quantitative) in physics, physiology, pathology, biology...
Better Interpretation of Images
(Mathematical Models/ Techniques

(Inverse problem!)

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EM Imaging in NDE/SHM: A Review

- Usable EM frequencies cover almost the entire spectrum
  - **Static methods:**
    - EIT (Cheney1999; Borcea2002; Lionheart2004; Stacey2006)
    - ERT (Kemnaa2002); ECT (Yang2003, Soleimani2005)
  - **Quasi-static methods:**
    - **Pulsed EC** (Dai1990; Bowler1997; Giguere2001; Tian2005; Yang2010)
    - EC-MOI, EC-GMR (Will be covered in this talk)
    - MIT (Griffiths2001)
    - GMI (Vachera2007)
EM Imaging in NDE/SHM: A Review

- High frequency time varying methods:
  - **Millimeter and THz** ([Zimdars 2005; Kharkovsky 2007; Hor 2008, Zoughi 2009, Kemp 2010])
  - **Millimeter acoustic** ([Redo-Sanchez 2009])
  - **Microwave TAT** ([Deng 2011])
  - **Magneto acoustic** ([Xu 2005, Li 2007])
MOI-Motivation

• Multi-site damage

Aloha Airlines B-737-200 lost part of its front fuselage during a flight in Hawaii, 1985.

Southwest Airlines B-737-300 had a section of fuselage tear during a flight from AZ to CA, April 1st, 2011.
Magneto Optic Imaging Physics

\[
\theta \approx \theta_f \frac{(k \cdot M)}{|k||M|}
\]
Typical MO Rivet Images

[Courtesy of PRI R&D Corp]
Challenges and Accomplishments

- 2D binary image of 3D magnetic field
- Domain Noise while object of interest is moving!
- Analog images with various size and shape, need quantification
- Imaging multiple rivets, Large FOV, Subjective and Tedious

Courtesy of PRI R&D Corp
Forward Models Results:
Calibration of the System

Binary Image Generation at different threshold values $T$

3D Magnetic Field results using FEM
Image formation simulated at different sensor biased level
Simulated and measured images comparison (two different source excitation)
Image Object Detection
(Recursively Morphological)

Choose the structure element size recursively and carefully.

\[
\begin{align*}
\Theta &= \bigcap_{i=\nu} \bigcap_{j=\nu} I(x+i, y+j) \cup E(i, j) \\
O(x, y) &= \bigcup_{i=\nu} \bigcup_{j=\nu} I(x+i, y+j) \cap E(i, j)
\end{align*}
\]
Quantitative Methods-Classification

Edge images

Noisy subsurface images
Real Time MO Imaging System

(Group led by Dr. L Udpa)
Giant Magneto Resistive Imaging

Biased GMR Sensor

GMR System Schematic

$B$ field $\rightarrow$ Voltage output

Quantitative 3D measurement available! $\rightarrow$ More image processing challenges
Challenges and Accomplishments

Rich 3D information
(Time consuming in image processing)

Subjective interpretation
(Quantification and pattern recognition)

Operator variability
(Sensor optimization, POD analysis)

More accurate mathematical models needed
Forward Model: System Optimization

Innovative sensor design by image feature extraction and pattern recognition from both Model and Measurement:

Sensor array size, configuration, lift-off, operating frequency, tilt angle,…

Reduce the R&D cost, More sensitive sensor, …
Inverse Problems: Optimum Detection

Enhanced image is generated again using: \( S_\alpha(\alpha) = S_0 \cos(\alpha) + S_{\pi/2} \sin(\alpha) \)
Image SNR Improvement

\[ SNR_M = \sqrt{\sum_{i=1}^{M} (F_i - m_{0i})^2 / \sigma_{0i}^2} \]

Before

After

\[ F_{MAE} = \frac{1}{N} \sum_{i=1}^{N} \left| L_D[i] - \frac{1}{M} \sum_{j=1}^{M} L_{ND,j}[i] \right| \]

\[ F_{MSE} = \frac{1}{N} \sum_{i=1}^{N} (L_D[i] - \frac{1}{M} \sum_{j=1}^{M} L_{ND,j}[i])^2 \]
Hybrid electromagnetic imaging

- Microwave induced thermoacoustic imaging
  - High contrast (microwave) and high resolution (ultrasonic)
  - Active SHM sensors, non-contact data acquisition
  - Relatively easy interpretation (US images)
Experimental Results

- Acoustic and EM properties of solutions are different
- Higher conductivity ($\sigma$) yields greater acoustic wave amplitude.

**Table: Experimental Results**

<table>
<thead>
<tr>
<th>Sol’n</th>
<th>% micro bubble</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
<th>$v_A$ (m/s)</th>
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<tr>
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<td>100</td>
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<td>NA</td>
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</tr>
</tbody>
</table>

Side by Side Comparison

- Model reproduces experimental results very well
- Experimental data is based on averages of 200 wave forms
Dielectric vs. Acoustic Effects

Experiment: acoustic and dielectric differences

Simulation: dielectric differences only

- Different waveform between solutions results from different dielectric properties
- In agreement with paper conclusions
Non-uniformity of E-field in Dielectric

Integration of $|E|^2$ over microwave pulse

Total Energy is 18065610.8933 a.u.

$\lambda_0 = 1; \lambda_d = 0.6$

- Most works assume power deposition is uniform
- Modeling and analytical solutions show that power deposition has a unique geometric signature

$\lambda_0 = 100 \text{ mm}; \lambda_d = 26 \text{ mm}$

[Petersen, Ray, Mittra, Computational Electromagnetics. 1998, p. 64]
Summaries and Future Directions

• For SHM of wind turbine systems, innovative electromagnetic sensing may be a promising technology
  – Active sensors (operating in adverse environments, not just limited to CFRP component)
  – Self-validating sensors (HM of sensors)
  – Large number of sensors deployment (global and local)

• SHM/NDE research at CU-Denver
  – Advanced numerical and statistical modeling capability
  – Extensive experience in imaging sensors/systems/prototypes research
  – Data analysis algorithms/software development

• Multi-disciplinary research
  – Sensing, structural dynamics, signal/image processing, pattern recognition, computational hardware (GPU), data telemetry, smart materials, etc.
Thank you! Questions?