Structural Health Monitoring by Based on Piezoelectric Sensors

Wiesław Ostachowicz
wieslaw@imp.gda.pl
General Overview on SHM and NDT Methods

- NDT methods
- Extended NDT methods
- SHM methods
- General definitions
NDT methods

- Conventional ultrasounds with frequency analysis
- Nonlinear ultrasounds
- Laser excited ultrasounds
- Eddy current
- Strain gauges

General Overview on SHM and NDT Methods
Extended NDT methods

- Active thermography using optical excitation
- Active thermography using ultrasound excitation
- THz technology
- Electro–mechanical impedance
Extended NDT Methods

Guided waves monitoring by 3D laser scanning vibrometry

Active thermography
Damage detection

Energy distribution

16.5 kHz

35 kHz

100 kHz

952.1 kHz

850 kHz

500 540
PZL – WA Stabilizer

A0 Wave 35 kHz
Damage detection

Thermal damage in GFRP

Additional masses detection

Notch detection
Extended NDT Methods

Electro-mechanical impedance

Piezoelectric transducer
Impedance analyzer
Mechanical structure
Vibrothermography

Other applications:

Pulse thermography
SHM methods

- Vibration based methods
- Guided wave methods
- Fiber Optics Techniques
- Acoustic Emission
- Comparative Vacuum Monitoring
- Electromagnetic layer
There is a need for SHM methods capable of comprehensive, real-time condition monitoring.
Guided waves propagation
L – Shape

A0 Wave  75 kHz
Wing Section
A0 Wave  75 kHz
Experimental vs. numerical results

Laser vibrometry

Spectral Finite Element Method (numerical calculations)

Lateral Velocities

Glass fibers/epoxy, laminate [0/90/0/90]
Spectral Finite Element Method
– Damage Detection and Localization

Numerical Simulations – Geometry
Spectral Finite Element Method
– Damage Detection and Localization

Aluminium plate, detection and localization of additional mass–IMV (Integral Mean Value) Maps

IMV Maps for displacements $u$, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms

IMV Maps for displacements $w$, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms
Spectral Finite Element Method
– Damage Detection and Localization

Aluminium plate, detection and localization of additional mass–RMS (Root Mean Square) Maps

RMS Maps for displacements $u$, for the following periods: 0.125 ms; 0.25 ms; 0.375 ms; 0.5 ms

IMV Maps for displacements $w$, for the following periods: 0.125 ms; 0.25 ms; 0.375 ms; 0.5 ms
Sheathing of a small aircraft wing – detection and location of a failure

RMS (Root Mean Square) maps

RMS maps for displacements $w$ | time: 0.125 ms; 0.25 ms; 0.375 ms; 0.5 ms

Weighted RMS maps for displacements $w$ | time: 0.125 ms; 0.25 ms; 0.375 ms; 0.5 ms
Spectral Finite Element Method
– Damage Detection and Localization

Part of the fuselage shell, detection and localization of fatigue cracks

RMS (z ang. Root Mean Square) Maps

RMS Maps for amplitudes of displacement $a$, for the following periods: 0.125 ms; 0.25 ms; 0.375 ms; 0.5 ms
SHM METHODS
Experimental stands located on ship yacht Dar Młodzieży
(Maritime University | Gdynia)

The ship's route
29 May – 6 June 2011

Fokmast with FBG sensors

Source: http://www.am.gdynia.pl/
Problems:

Sensors cannot measure damage

Size of detectable damage versus sensor size

Size of detectable damage versus sensor power

Levels of health monitoring
Sensors cannot measure damage.

Feature extraction though signal analysis and statistical classification are necessary to convert sensor data into damage information.

The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

Levels of Health Monitoring

- **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 diagnostics.
- **Level 6**: Self healing.

**Increasing degree of complexity. Greater need for analytical models.**
ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

- Continuous models
- Discrete - continuous models
- Discrete models
  - Boundary Element Method
  - Transition Matrix Method
  - Graph Method
  - Analogue Method
  - Finite Element Method

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

Continuous models

A fatigue crack is represented by additional spring-like elements, compliance of which is calculated according to the laws of fracture.

This method can successfully be used for modelling fatigue cracks in one-dimensional constructional elements (rods, beams, shafts, columns and pipes) or in constructions made of such elements (frames and trusses).

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

Discrete models

Finite Element Method

Markstrom & Storakers, (1980)
Zastrau, (1985)

Krawczuk & Ostachowicz, (1990s)

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

Composite beam finite element with a crack

Shaft beam finite element with a crack

Composite beam finite element with a delamination

Title: Dynamics of cracked Composite Material Structures

US Army Grant
No N68171-94-C-9108
Duration: 1994 – 1996
ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

US Army Grant
No N68171-94-C-9108
Duration: 1994 – 1996

Title: Dynamics of cracked Composite Material Structures

Modelling for Detection of Degraded Zones in Metallic and Composite Structures,

in: Encyclopedia of Structural Health Monitoring,

Boller, C., Chang, F. and Fujino, Y. (eds).

Changes of dynamic properties i.e.:

- mode shapes,
- natural frequencies,
- amplitudes of forced vibrations,
- damping

Low frequency method
Changes:
- first (a)
- second (b)
- third (c)

natural frequencies of the cantilever composite beam as a function of damage location (delamination): beam axis
Changes:
- first (a)
- second (b)
- third (c)

natural frequencies of the simple supported composite beam as a function of damage location (delamination): beam axis
# Summary of Detection Methods

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<th>Limitations</th>
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<td>Embeddable</td>
<td>Expensive</td>
<td>Requires laser localised results</td>
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<td>Simple results</td>
<td>High data rate</td>
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<td></td>
<td>Very comfortable</td>
<td>Accuracy??</td>
<td></td>
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<td>Eddy current</td>
<td>Surface mountable</td>
<td>Expensive</td>
<td>High power</td>
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<td>Most sensitive</td>
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<td>Surface mountable</td>
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<td>Good coverage</td>
<td>Linear scans</td>
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Arrays of distributed piezotransducers:

- applicable to most structures
- can monitor structural condition throughout the life of the structure
- can detect changes in:
  - stiffness
  - inertial and damping characteristics
  - stress levels

can focus on damage
Damage identification methods:

- Deterministic (based on Time of Flight, amplitude changes)
- Non-deterministic:
  - Neural Networks
  - Evolutionary Algorithms
  - Genetic Algorithms
Use theoretical, classical finite element and spectral finite element methods

Produce data to train the expert system

Model of the structure

Neural Networks

Genetic Algorithms
Elastic Waves

Longitudinal waves – particle motion is in the direction of travel

Longitudinal (P) Wave

Shear waves – particle displacement at each point in the material is perpendicular to the direction of wave propagation

Shear (S) Wave
• Lamb waves are waves of plane strain that occurs in a free plate.
• Complex wave mechanism – shear vertical (SV) waves form modes in connections with the longitudinal P wave; these P+SV waves are known as Lamb waves.
• Infinite number of dispersive modes which can propagate in structures.

\[
\begin{align*}
\tan(qh) &= -\frac{4k^2 pq}{(q^2-k^2)^2} \\
\tan(ph) &= -\frac{(q^2-k^2)^2}{4k^2 pq}
\end{align*}
\]
LAMB WAVES

- Dispersion equations are given by Rayleigh-Lamb frequency relations.
- Lamb wave velocity is a function of the frequency-thickness (f*d) product.
- Fundamental modes – $S_0$ and $A_0$ modes.

Wave propagation modelling

- Finite element Method
- Finite Difference Method (LISA)
- Semi-analytical methods
- FFT-based Spectral Element Method (Doyle)
- Hybrid methods
- Spectral Element Method (Patera 1984)