F.L. Lewis, Fellow IEEE, Fellow IFAC, Fellow UK InstMC
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The University of Texas at Arlington

Structural Health Monitoring

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SHM

Worden et al. 2009

Rytter's Levels:

— *Level 1.* (Detection.) The method gives a qualitative indication that damage might be present in the structure.
— *Level 2.* (Localization.) The method gives information about the probable position of the damage.
— *Level 3.* (Assessment.) The method gives an estimate of the extent of the damage.
— *Level 4.* (Prediction.) The method offers information about the safety of the structure, e.g. estimates a residual life.

classification

Machine Learning

— Classification, i.e. the association of a class or set label with a set or vector of measured quantities. The set of observations may be sparse and/or noisy.
— Regression, i.e. the construction of a map between a group of continuous input variables and a continuous output variable on the basis of a set of (again, potentially noisy) samples.
— Density estimation, i.e. the estimation of probability density functions from samples of measured data.

Methods of Learning
- supervised
- unsupervised
- reinforcement

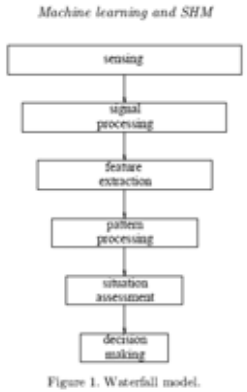
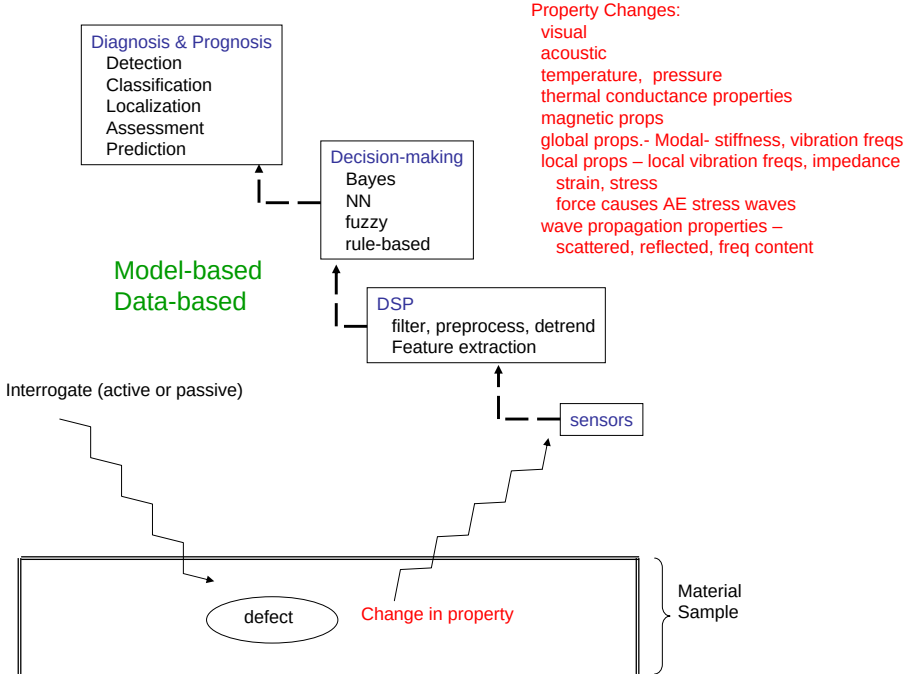


Figure 1. Waterfall model.



Fault Types

Composites
- Matrix (resin) crack
- Delamination
- Fibre breaks

Metals
- Material Defects
  - Corrosion
  - Crack
  - Fatigue
- System Defects
  - Rivet Failure
  - Surface Ice

Detection Methods

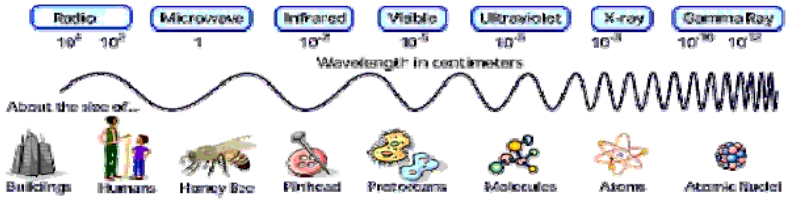
Vibration (LF- wavelength >> plate thickness)
- global- LF - changes in structural props- stiffness, vibr. freqs.
- local- HF – changes in res. freqs., impedance

Sonic
- Ultrasound (HF- wavelength << thickness)
- Acoustic Emission (mid freq.- wavelength ~ thickness)
- Wave Propagation (single freq waves)

Strain, Stress

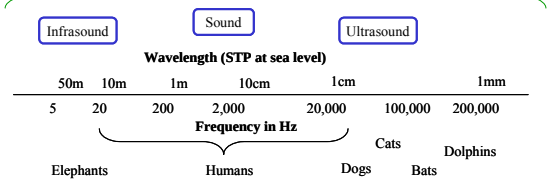
X-Ray
Visual
Thermal
Magnetic

Sensor Modalities



Electromagnetic spectrum
http://imagers.gsfc.nasa.gov/ems/waves3.html

Overlap in freqs!



Acoustic Spectrum Transmission depends on the medium

Sensors

Based on Physical Transduction Principles

Mechanical Sensors
- **Piezoresistive Effect** converts an applied strain to a change in resistance
- **Piezoelectric Effect** converts an applied stress (force) to a potential difference. PZT
- **Capacitive Sensors** convert displacement (force) into change in capacitance

Magnetic and Electromagnetic Sensors do not require direct physical contact
- **Hall Effect.** Magnetic field applied perpendicular to current flow causes induced voltage
- **Magnetic Field Sensors** detect metallic objects
- **Eddy Current Sensors** use magnetic probe coils to detect defects in metallic structures

Thermal Sensors measure temperature or heat flux
- **Thermo-Mechanical Transduction**. Heat causes thermal expansion
- **Thermoresistive Effects**. Resistance *R* changes with temperature *T*
- **Thermocouples**. Junctions of two different metals at different temperatures causes current flow
- **Resonant Temperature Sensors.** Temp change in some materials causes a change in resonant frequency

Optical Transducers. Convert various properties to light
- **Optical fiber interferometers and gratings**– changes in length (strain), temp. cause changes in phase
- **Optical fiber accelerometers** based on time of flight

Acoustic Sensors
- **Ultrasound.** High Frequency. Can penetrate structures. Reflected and scattered from defects
- **Acoustic Wave Sensors**
  - surface acoustic wave (SAW), thickness-shear mode (TSM), flexural plate wave (FPW), or acoustic plate mode (APM)

F.L. Lewis, "Wireless Sensor Networks," in *Smart Environments: Technologies, Protocols, Applications*, Chapter 2, ed. D.J. Cook and S.K. Das, Wiley, New York, 2005.

PZT - Lead zirconate titanate

Piezoelectric
Sensor- develops a voltage difference across two of its faces when compressed
Actuator- physically changes shape when an external electric field is applied

Pyroelectric
Heat Sensor- Develops a voltage difference across two of its faces when it experiences a temperature change.
TEMP. COMPENSATION

Ferroelectric-
Has a spontaneous electric polarization (electric dipole) which can be reversed in the presence of an electric field.

Interrogation / Interaction Modalities

Group 1

X-ray
Visual
Coherent Optics
Fiber optics – no EMI, lightweight, low noise, high BW
  Interferometry
  Fiber Bragg Grating - FBG

Thermography - IR
Magnetics

Eddy current
  a coil induces eddy currents in a conductive sample
  defects cause change in the impedance of the sample

Group 2- Sonic

Sound propagation depends on the medium
Defects scatter or reflect sound waves

Ultrasound HF (5 MHz)
- wavelength << thickness
- short prop. Distance
- a single excit. freq.

Acoustic Emission AE Mid freq (100 kHz-2 MHz)
- wavelength ~ thickness
- substantial prop. dist. (a few m.)
- multiple excitation freqs. (e.g. white noise)

Lamb Wave is AE with a single excit. freq.

Group 3- Vibration Wavelength >> thickness

Monitor vibration signature- pattern recognition

LF (20 Hz – 20 kHz)
- Global- changes in physical props.
- Modal parameters (stiffness, res. freq.)

HF (100 kHz – 1 MHz)
- Local- changes in frequency content
- EM impedance
  - PZT sensors

Group 4- Strain, Stress

Force on defect causes AE stress waves

Lamb Waves wavelength ~ thickness

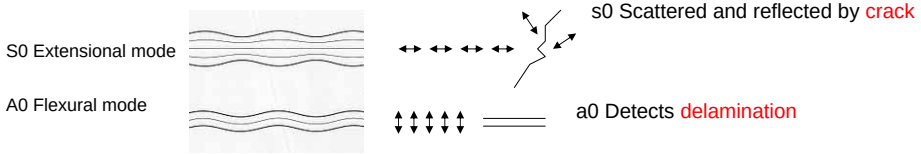
wikipedia

Irradiate entire thickness
Propagate substantial distances

Elastic waves that propagate in a solid thin plate

2-D Wave equation $\nabla^2\phi = \frac{1}{c_l^2}\frac{\partial^2\phi}{\partial t^2}$

solutions split into two sets of waves-
symmetric & antisymmetric



A major challenge and skill in the use of Lamb waves for ultrasonic testing is the generation of specific modes at specific frequencies that will propagate well and give clean return "echoes". This requires careful control of the excitation and identification of the correct waves.

Structural Health Monitoring

Overview & Aerospace Applications

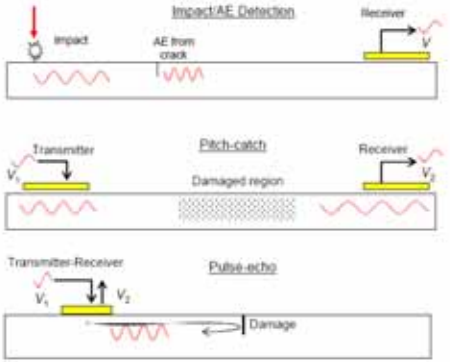
An invited lecture series for ME/MSE 568: Active and sensing materials and their devices

Presented by
Dr. Jeong-Beom ("J-B") Ihn

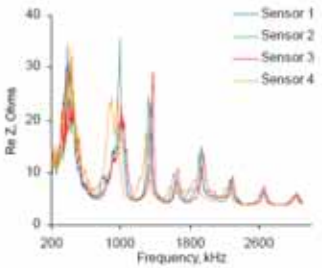
Affiliate Assistant Professor, ME, Univ. of Washington
Senior Research Engineer, Boeing Research & Technology

How are Piezo actuator/sensors used in SHM ?

Propagating Lamb waves



E/M Impedance



Actuation / Interrogation

Active vs. Passive

Passive vibration monitoring-
in-flight aircraft vibration freqs are very low
successful in a boat hull monitoring application

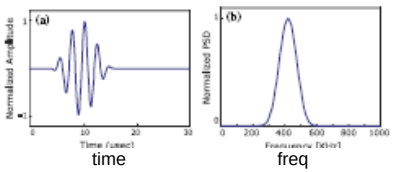
Active -

PZT actuator

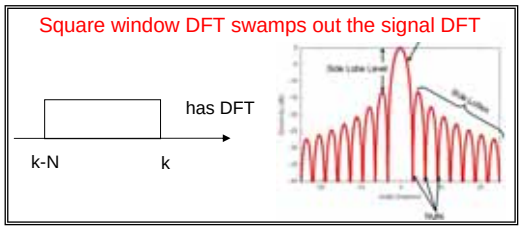
Eddy-coil EM actuator
discharges capacitor through a coil, induces pulsed magnetic field in conductive sample, generates a force
needs 1-10 J

Actuator interrogation signals

Burst sinusoids



Square window DFT swamps out the signal DFT



FFT of burst sinusoids with:

Square window

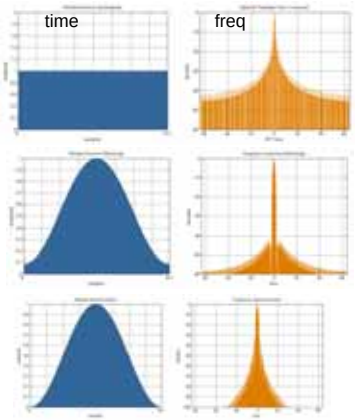
$$w(n) = 1$$

Hamming window

$$w(n) = 0.54 - 0.46\ \cos\left(\frac{2\pi n}{N-1}\right)$$

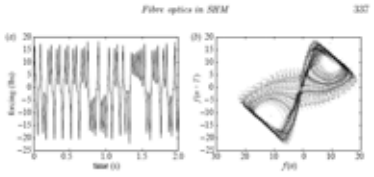
Hann window

$$w(n) = 0.5\ \left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right)$$

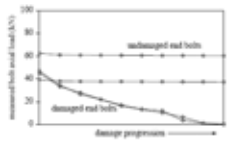


Chaotic Interrogator Actuation

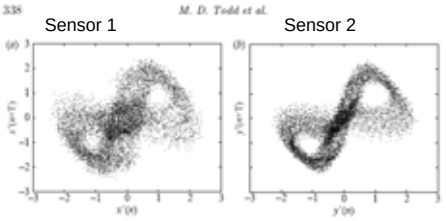
Todd et al. 2009



Actuation by Lorenz Signal



Signals received at sensors



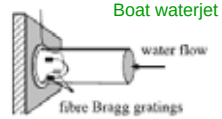
Actuator and Sensor Locations

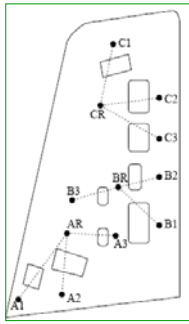
c.f. human nervous system proprioceptors

Based on Physical Models
FEA or dynamics model
Based on Engineering Knowledge

Deploy at Hot Spots
Deploy over a Large Area-
limits the frequencies and interrogation methods

Todd et al. 2009
FBG sensors on
Boat waterjet



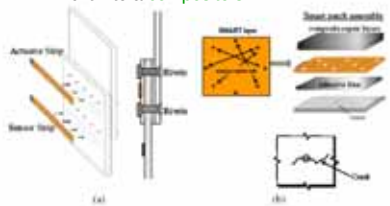


Aircraft wing

Worden & Manson 2009
CR = actuator
Ci= PZT sensors
3 sensor networks based on known damage regions

No methodical procedures

Ihn & Chang 2004
Sensors along a rivet joint and
Built into a composite skin



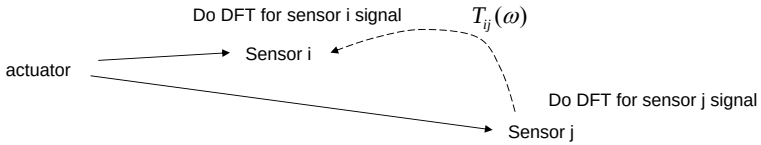
Features

Time moments
Frequency domain properties-
- Resonant freqs, sidebands
- Power content in specific frequency bands
- Transmissibilities

Strain, stress

Transmissibility from sensor j to sensor i

$$T_{ij}(\omega) = \frac{PSD_i(\omega)}{PSD_j(\omega)}$$

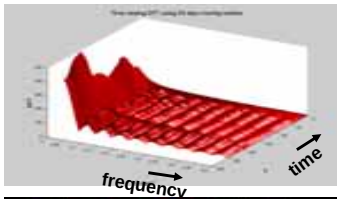


Time-Varying Frequency Content

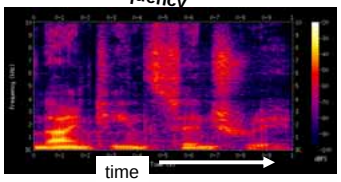
Short Time Fourier Transform – Windowed DFT

Must select window length
Must use good window w(n) - Hamming, Hann

$$X(k,t) = \sum_{n=t-(N-1)}^{t} x(n)w(t-n)\,e^{-j2\pi(k-1)(n-1)/N}$$



STFT
Spectrogram

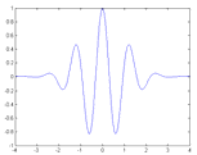


Wavelet

Does not need window
Multi-resolution analysis

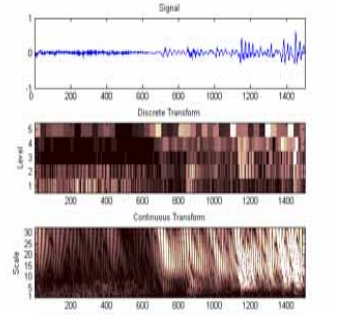
Basic or mother wavelet

$$\psi(t) = 2\,\mathrm{sinc}(2t) - \mathrm{sinc}(t) = \frac{\sin(2\pi t) - \sin(\pi t)}{\pi t}$$



$$Wf(u,s) = \int f(t)\frac{1}{\sqrt{s}}\psi^*\left(\frac{t-u}{s}\right)\mathrm{d}t = \langle f, \psi_{u,s}\rangle$$

Wavelet xform
Scaleogram



Hilbert-Huang Transform (HHT)

Fault detection & Identification

Model-Based
- make physical model using FEA or physics-based methods
- determine comparison metric
- look for departures of real measured data from the model

Data-Based
- based on moments, freq response, or statistics
- establish normal operating limits based
- establish abnormality thresholds
- departures indicate faults

Both methods look for departures from the norm
- this means Statistical Pattern Recognition
- preprocessing of data, filter, detrend
- outlier rejection

Dr. George Vachtsevanos
http://icsl.gatech.edu/icsl

Georgia Tech

Physical Modeling

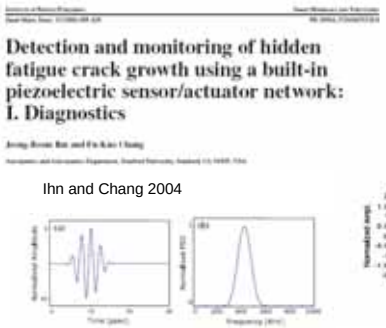
e.g. Deterministic Crack Propagation Models

- Variations of available empirical and deterministic fatigue crack propagation models are based on Paris' formula:

$$\frac{da}{dN} = C_o (\Delta K)^n$$

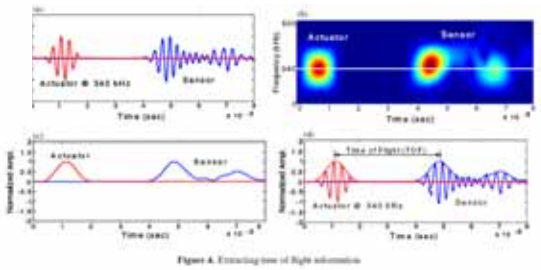
Where:

α	= instantaneous length of dominant crack
N	= running cycles
C_o, n	= material dependent constants
ΔK	= range of stress intensity factor over one loading cycle

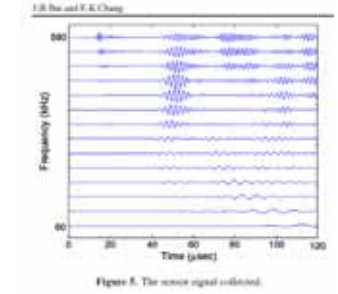

Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: I. Diagnostics

Ihn and Chang 2004

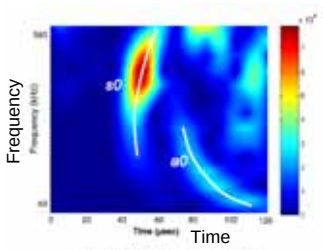
Lamb Waves



Must focus on ONE frequency

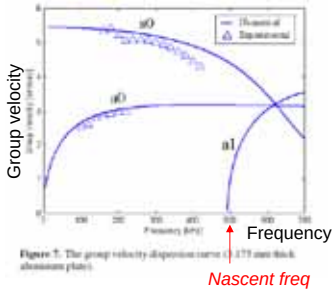


Where is the right Lamb wave?



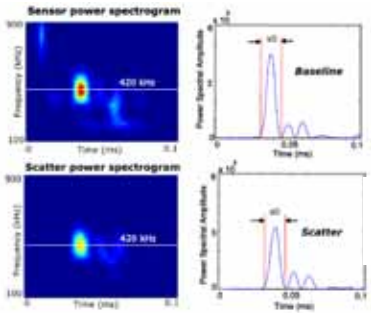
Group velocity
Dispersion

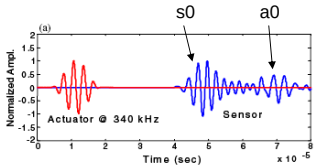
From FEA for the specific material



Nascent freq

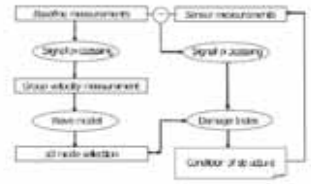
s0 arrives before a0 below 600kHz

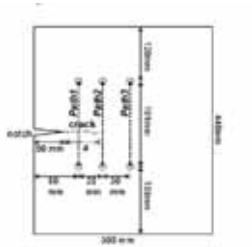




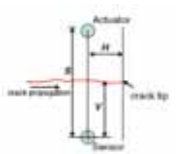
$$\text{Damage index (DI)} = \left(\frac{\int_{t_1}^{t_2} |S_{sc}(\omega_0, t)|^2 \, dt}{\int_{t_1}^{t_2} |S_b(\omega_0, t)|^2 \, dt} \right)^{\alpha}$$

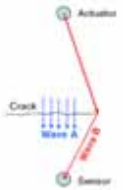
Use s0 for cracks
Use a0 for composite delamination

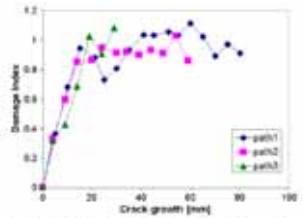




Optimal sensor location wrt crack







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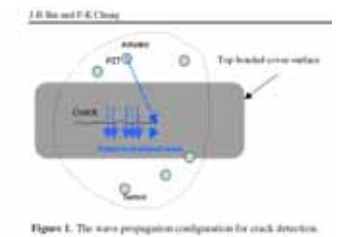
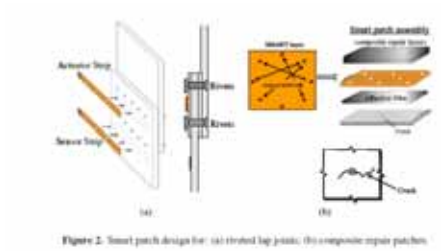
Smart Suitcase

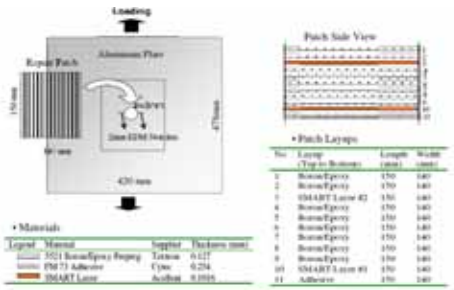


Ihn and Chang 2004

Acellent Technol. Smart patch



Rivet failure



Damage index

a0

debond

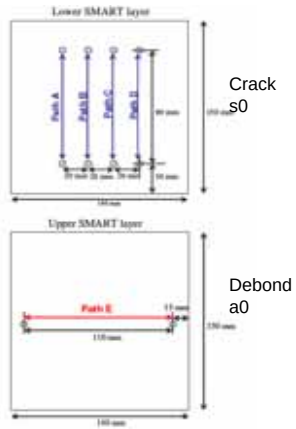
Damage index

s0

crack

Composite faults

Acellent Smart Layer



TECHNICAL NOTE

Structural health monitoring of composite structures using Lamb wave tomography

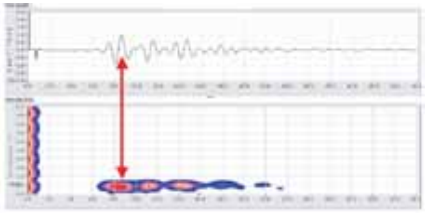
S Mahadev Prasad, Krishnan Balasubramaniam and C V Krishnamurthy

Tomography- imaging by sections using wave energy
2D or 3D images
x-ray CT
gamma
electron

Reconstruction algorithms
filtered back projection
iterative reconstruction
ART- algebraic reconstruction techniques
(Kaczmarcz algorithm)

Cardiac CT scan

wikipedia



s0 energy- compute energy up to MAXIMUM Peak
Use RMS value for tomographic reconstruction

Freq = 500 kHz

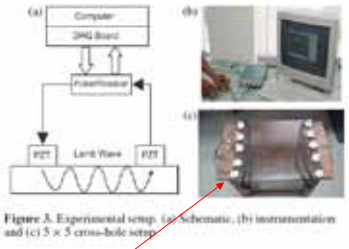


Figure 3. Experimental setup. (a) Schematic, (b) instrumentation and (c) 5 × 5 cross-hole setup.

Sticky gum to hold sensors?

Split plate into a uniform grid
Mount sensors at grid points
400 sensors!

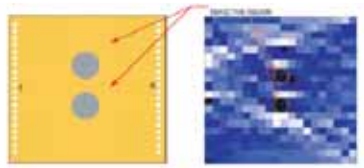
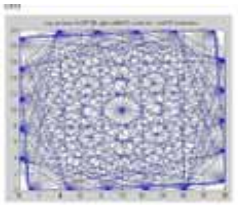


Figure 6. Tomogram of quasi-isotropic laminate with two defects.

Improved sensor placement



Uniform angular sampling of plate with few sensors

ELSEVIER

Thin-Walled Structures 43 (2005) 553–563

www.elsevier.com/locate/tws

Neural network method based on a new damage signature for structural health monitoring

Shenfang Yuan*, Lei Wang, Ge Peng

Used Kohonen NN to classify damage

Wide band Lamb waves

Excitation – rectangular impulse 10 microsec wide
Excites Lamb waves covering a broad frequency spectrum

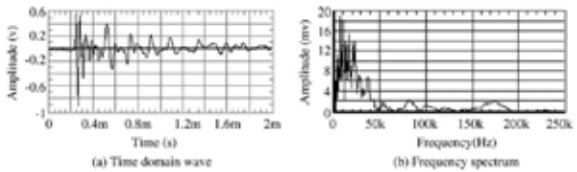


Fig. 2. Wide-band Lamb wave signal excited in honey-comb sandwich beam and its frequency spectrum.

Compensate for Propagation- amplitude A with distance x

$$A = A_0 e^{-\alpha x} \quad (1)$$

where A = the peak amplitude of the monitored signal, x = the distance of signal propagation, α = attenuation coefficient, A_0 = the initial peak amplitude value at the point of excitation. To reduce the propagation distance effect on peak value, a new signature can

Application of Smart Structures to Aircraft Health Monitoring

G.A. Hickman, J.J. Gerardi and Y. Feng

Journal of Intelligent Material Systems and Structures 1991; 2; 411
DOI: 10.1177/1045389X9100200308

Hickman et al. 1991

Select Features?

LF vibration 1-5 kHz

Defects cause energy redistribution in freq. spectrogram

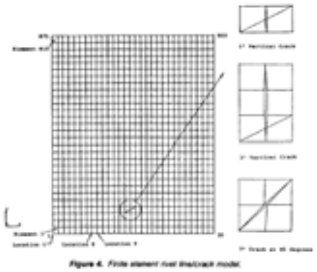


Figure 4. Finite element rivet line/crack model.

FEA

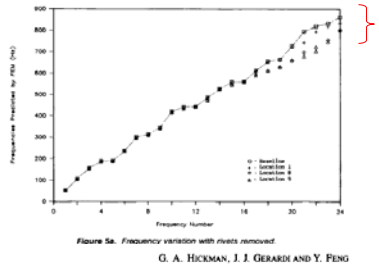


Figure 5a. Frequency variation with rivets removed.

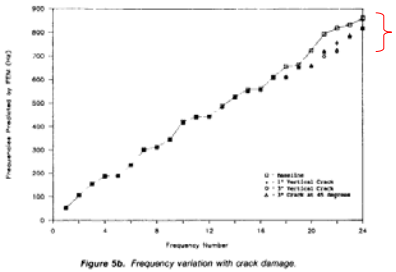


Figure 5b. Frequency variation with crack damage.

Rivet removal and cracks both lower the HF content

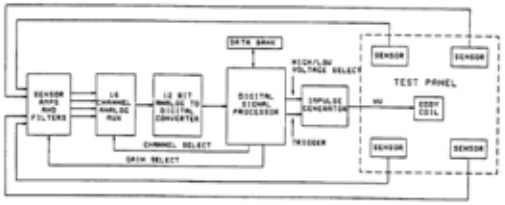


Figure 2. Block diagram of the HMS system.

Compute features for each sensor

24" sq. plate, 0.08" thick

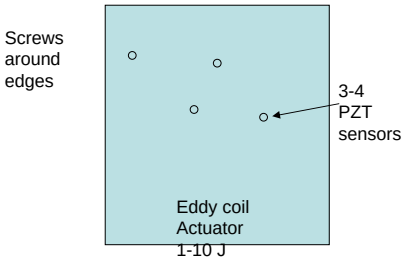


Table 1. Features extracted from piezoelectric sensor signals.

Feature	Description
1	local damping coefficients
2	one-half of the modulation signal period
3	standard deviation of signal
4	kurtosis of signal
5	skewness of signal
6	time at 90% decay
7	amplitude ratio of two biggest peak values
8	frequency of the biggest peak value
9	frequency difference of two biggest peaks
10	2nd largest peak value
11	partial power in relevant frequency bands between 1–10 kHz
12	ratio of smallest and largest partial power
13	number of peaks exceeding a given threshold
14	frequency at which 25%, 50%, and 75% of accumulated power was observed
15	transfer ratio of partial power in frequency bands between 1–10 kHz

Sensor placement determined experimentally!

Best Features:
Energy distribution- Power in specific freq bands

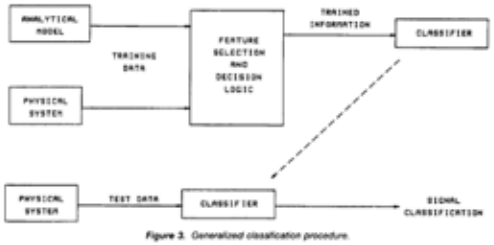
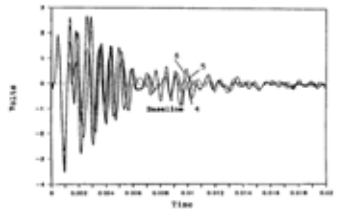


Figure 3. Generalized classification procedure.

NN classification?



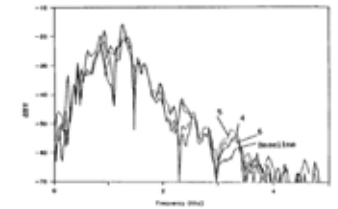


Figure 9. Rivet line ground tests using eddy-coil impulse excitation: rivet line 4, 5, 6 and baseline.

Features-
Energy distribution- Power in specific freq bands

1-1.5 kHz

1.5-3 kHz

Aircraft Monitoring

Rivet failures
Cracks
icing

Figure 1. Health monitoring system concept.

Wing cuff

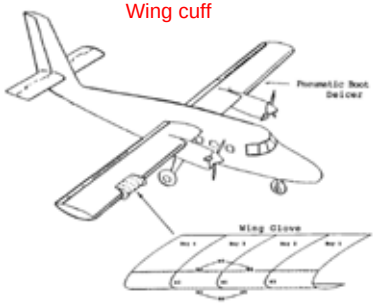


Figure 7. Twin Otter wing cuff testbed.

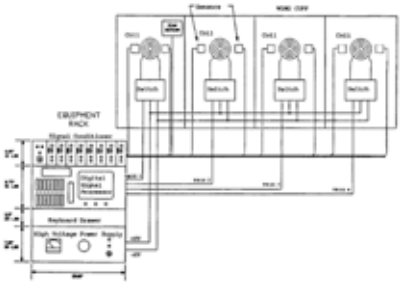


Figure 8. HMS Twin Otter hardware test configuration.

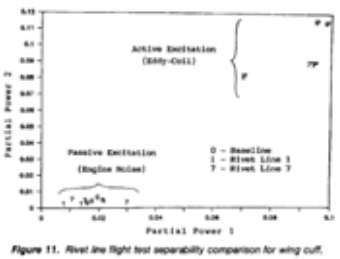


Figure 11. Rivet line flight test separability comparison for wing cuff.

Power in freq range 1.5-3 kHz

Power in freq range 1-1.5 kHz

The application of machine learning to structural health monitoring

Keith Worden and Graeme Manson

Phil. Trans. R. Soc. A 2007 **365**, 515-537
doi: 10.1098/rsta.2006.1938

Figure 2. Goat aircraft and acquisition system.

1. Damage detection

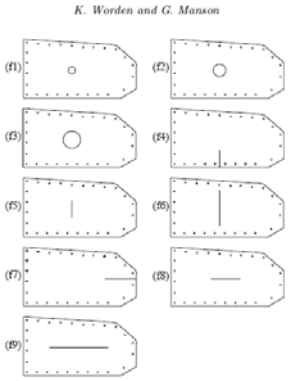
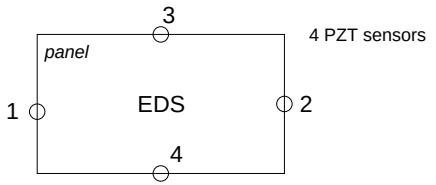


Figure 3. Schematic of damage states.

Damaged panels



EDS= Electrodynamic shaker
LF EM Vibration at 1-2 kHz
Compute DFT

Transmissibility from sensor j to sensor i

$$T_{ij}(\omega) = \frac{PSD_i(\omega)}{PSD_j(\omega)}$$

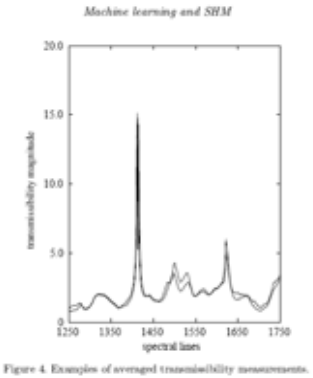


Figure 4. Examples of averaged transmissibility measurements.

Features = power in specific freq bands

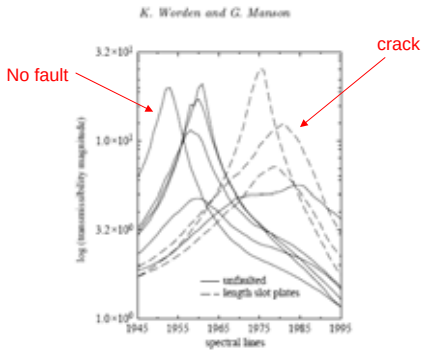


Figure 5. Novelty detection feature to detect length-spanning cuts.

Band 1 Band 2

Classification and departure detection
NN
clustering (K-means, NN)
outlier analysis using norm distance measure

Training data Set and Validation Set

Unsupervised learning for fault detection

2. Damage Location

Network of sensors

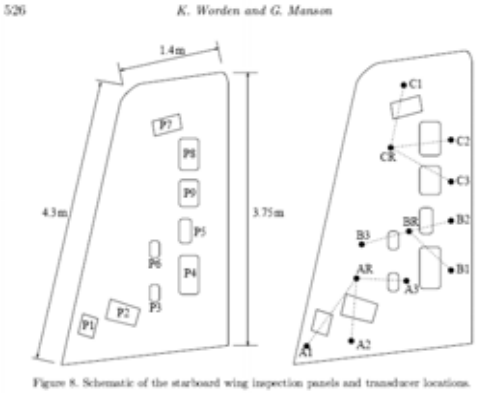


Figure 8. Schematic of the starboard wing inspection panels and transducer locations.

CR = PZT actuator
Ci = PZT sensors

Actuator and sensor locations based on KNOWN possible fault locations

4 networks with
1 actuator and 3 sensors

Damage = remove panels
NN MLP classifier – competitive learning

Supervised learning for fault classification or fault location

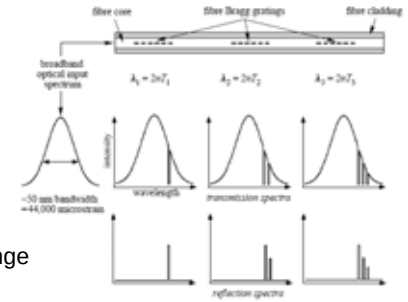


Figure 1. Wavelength-encoded multiplexing.

Fiber Bragg Grating – FBG

Interrogate length scales in the mm range
No EMI
Lightweight
Can be directly photo written into silica fiber using UV
Embed inside composites

$\lambda_r = 2nT$ about 0.1-0.3 nm

n= fiber core model index, T= grating period

Axial compression or tension changes T – can measure strain

Boat Hull Monitoring – passive wave excitation
Joint Degradation – active excitation - EDS

Boat Hull Monitoring

A-K= 11 sensor arrays
56 sensors in all
Rosette= 3-D sensor?

Passive excitation

Sensor placement
hull monitoring
waterjet monitoring

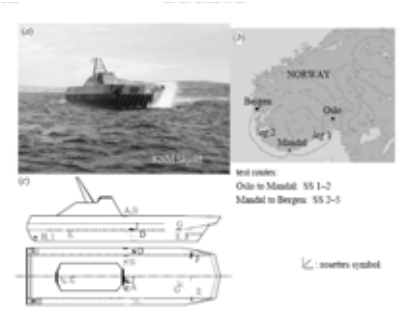


Figure 8. (a) A photograph of the KNM Skjold, (b) the test routes and (c) the sensor locations; rosettes are indicated by small rosette symbols.

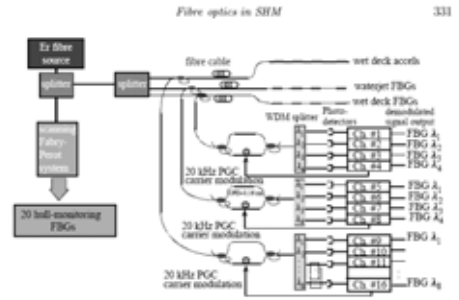


Figure 9. Complete ship monitoring system, including both SFP and WDM architectures required for hull and waterjet monitoring.

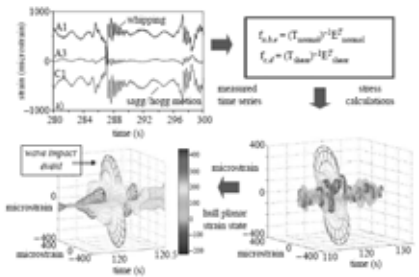


Figure 10. Characterisation of primary boat motions and using rosettes to determine real-time state of strain in hull.

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NDT&E International 34 (2001) 31–37

www.elsevier.com/locate

Ultrasonic NDE of composite material structures using wavelet coefficients

S. Legendre*, J. Goyette, D. Massicotte

$$Wf(u,s) = \int f(t)\frac{1}{\sqrt{s}}\psi^*\left(\frac{t-u}{s}\right)dt = \langle f, \psi_{u,s}\rangle$$

Discrete wavelet transform
Set scale factor equal to 2^j

tions at the scale 2^j. In that case, the orthonormal basis is defined by

$$\left\{\psi_{j,n}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^j n}{2^j}\right)\right\}_{(j,n)\in Z^2} \quad (4)$$

for $n = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, J$ with $N = 2^J$. The signal $f(t)$ can be decomposed over this basis

$$f(t) = \sum_{j=-\infty}^{+\infty}\sum_{n=-\infty}^{\infty}\langle f, \psi_{j,n}\rangle\psi_{j,n}(t) \quad (5)$$

Feature selection
Select specific levels only

No defect

Defect

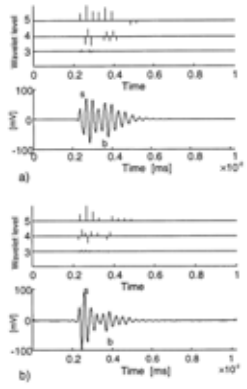

Fig. 3. Feature extraction from ultrasonic signals $H = 3$, $L = 5$ and $M_j = 4$ for $j = 3, 4, 5$ (Eq. (8)): (a) defect-free region; and (b) region with defect

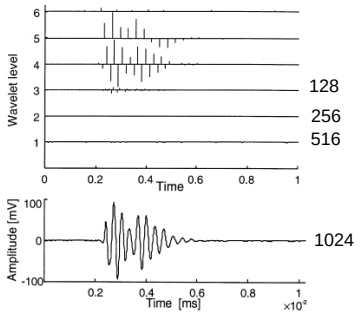

Fig. 2. Wavelet levels of an ultrasonic A-scan signal generated in a glass/epoxy composite structure compared to the original signal in the lower part of the figure.

SAW Devices as Wireless Passive Sensors

L. Reindl, G. Scholl, T. Ostertag, C.C.W. Ruppel, W.-E. Bulst, and F. Seifert*

1996 IEEE Ultrasonics Symp.

SAW + RFID

Interrogation freqs 434MHz = 5-10 m RFID range
2.5 GHz = 1-2 m RFID range

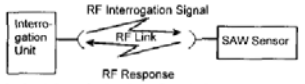

Fig. 1: Schematic drawing of a wireless sensor system based on passive SAW sensors.

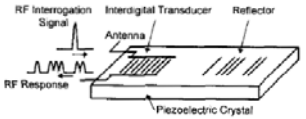

Fig. 2: Schematic layout of a passive SAW device used for identification and sensor applications.

Changes in time delay and freq due to physical quantity y(t)

$$\tau(y_0+\Delta y) = \tau(y_0)\left[1+S_y\Delta y\right] \quad (1)$$

$$f(y_0+\Delta y) = f(y_0)\left[1-S_y\Delta y\right] \quad (2)$$

Sensitive to y(t) = temp., displacement
y(t)= strain, force, accel. needs proper packaging

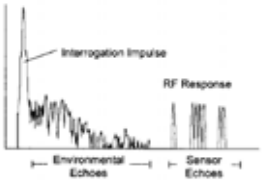

Fig. 3: Interrogation pulse, environmental echoes, and RF response of a SAW reflective delay line.

Gate this part = 1-2 micro sec

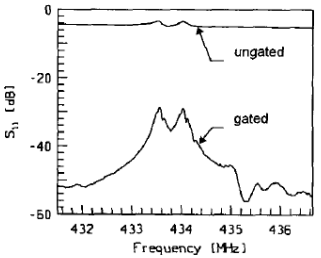

Fig. 6: Measured RF response of the resonator sensor (upper line: original frequency response, lower line: after gating in time domain).

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Smart Mater. Struct. 18 (2009) 000000 (9pp)

UNCORRECTED

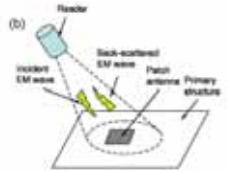
Bio-inspired sensor skins for structural health monitoring

Haiying Huang, ME Dept, UTA

Uday Tata[1], S Deshmukh[1], J C Chiao[2], Ronald Carter[2] and H Huang[1]

(Ed.)

Patch Antenna



Passive induction coupling-remote interrogation

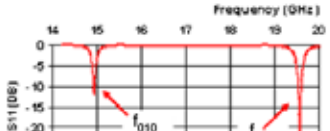


Figure 3. Simulated S_{11} of dual frequency patch antenna.

Strain causes
Res freq shift

$$\frac{\Delta f}{f_r} = \frac{f_r - f_{r0}}{f_r} = \frac{L_{r0} + C_2 h_0}{L_{r0} + v_s C_2 h_0}\varepsilon_L = C\varepsilon_L.$$

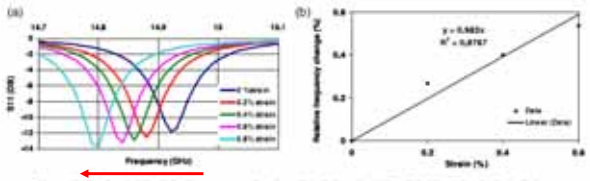


Figure 4. Simulated shift of f_{010} frequency as a function of applied strain: (a) Parallel shift of S_{11}; (b) linear fitting.

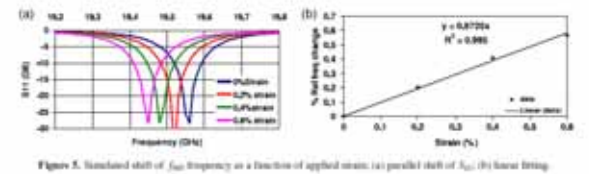
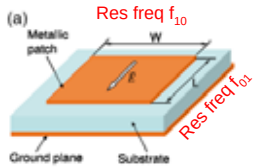


Figure 5. Simulated shift of f_{001} frequency as a function of applied strain: (a) parallel shift of S_{11}; (b) linear fitting.



Crack Monitoring

Haiying Huang, ME Dept, UTA

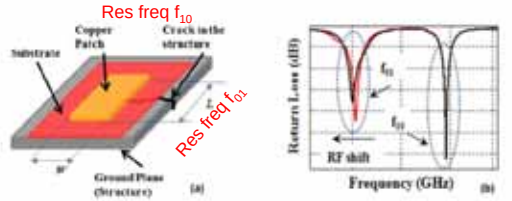


Figure 1: Principle of antenna sensor for crack monitoring; (a) Diagram of a patch antenna with width direction crack; (b) reduction of f_{01} frequency due to width direction crack.