Validation of a Lamb Wave-Based Structural Health Monitoring System for Aircraft Applications

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Background

- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to reduce life-cycle costs and improve reliability.

- Much SHM research has focused on detection methods; most demonstrations have been limited to laboratory-scale.

- Presently MDC is developing infrastructure for which several methods can be implemented for military or civil applications.

- MDC has focused primarily on piezoelectric-based methods.

- Several collaborators from industry, government and academia.
Lamb Wave Methods

• Form of elastic perturbation that propagates in a solid medium
  ➢ excitation shape and frequency can be optimized for particular geometry
  ➢ can favor $A_0$ wave for long travel distances and to minimize clutter

• Damage can be identified in several ways
  ➢ group velocity approximately $\propto (E/\rho)^{1/2}$, damage slows down waves
  ➢ reflected wave from damage can be used to determine locations

• Present research utilizes concentric piezoelectric actuators and sensors to measure characteristics of reflected waves
Stiffened Plate FEA Results

- Figures on left show FEA results for stiffened plate without damage
- Figures on right show FEA results for rib with 1” disbond
- Simulations show through-thickness displacements over 1ms
- Disbond yields fringe pattern in both reflected and transmitted wave
Design of M.E.T.I.-Disk 2 SHM Node

- Four major components
  - concentric piezoceramic sensor/actuator elements
  - flexible circuit for power, ground and shielding
  - casing encapsulates components for protection
  - micro-connectors provide strain relief, connectivity

- Overall design packaged for practical usage
  - nominal temperature range of -20°F to 180°F
  - sealed from moisture exposure
  - protected against incidental impact
  - resistant to a variety of chemicals and fuels
  - shielded from in and out-of-plane EMI exposure

- Device characteristics
  - nominal drive of 20Vpp
  - nominal sense of 20mVpp
  - Lamb wave, modal analysis, strain, AE capable
  - co-axial cable compatible
Optimization of Sensor Geometry

- Model-based tools developed to optimize sensor geometry
- Specimen property range needed for design (E, v, rho, t)
- Fundamentals described by dispersion curve, resonance
- Specimen configuration also useful (cores, ribs, boundaries)
• M.E.T.I.-System is a suite of damage detection infrastructure products
• Single node can cover ~1m diameter, dependant on structural configuration
• Wired version, M.E.T.I.-Disk 2, currently working to commercialize
• Digital version, M.E.T.I.-Disk 3, nearly completed, moving to test phase
• Wireless version, M.E.T.I.-Disk 4, expected completion by end of 2005
• Perform SHM using variety of passive and active methods, various sensors
In flight, passive monitoring is used with intermittent active method acquisitions. Up to 16 hours of data collection.

Starting from taxi, passive monitoring methods begin collecting data on state of structural health.

Upon landing, flight data is collected during normal pre-flight servicing time. Complete active method diagnostic is also performed for on time, safe take-off.
Prior Testing

Have validated the system for simple composite structures
Validation for Aircraft Structures

- Plate of 1/8” thick 6061-T6 Aluminum chosen to represent skin
- Four 18” square quadrants formed by c-channel ribs
- Experiments performed for both bolted and bonded ribs
- One M.E.T.I.-Disk 2 sensor placed in center of each quadrant
Experimental Procedure

• Once the plates were assembled, baseline measurements were collected for each plate configuration in a pristine state

• Data was collected from quadrants with no damage to determine false positive statistics for the system

• Data then was collected from quadrants with simulated damage represented by 1.5kg masses over a 4x6cm area

• Tests conducted using baseline measurements from other quadrants to demonstrate algorithm flexibility

• MDC software with embedded algorithms and damage criteria used to identify presence and location (if any) of masses
Hardware Configuration

- **Arbitrary Function Generator (AFG)**
  - necessary to excite actuators
  - 20Vpp signal used with custom sinusoidal function
  - frequencies varied between 60 and 100 kHz
  - Agilent 33220A used, many other options available including NI

- **Oscilloscope**
  - used as datalogger to collect voltage response of sensors
  - 20mVpp nominal signal level, range of 2-200mV
  - data collected for 0.5ms at 1MHz
  - Tektronix TDS3014 used, many other options available including NI

- **Processor**
  - standard Dell workstation used to run Metis software
  - both test command and analysis performed remotely over LAN

- **M.E.T.I.-Disk 3** incorporates AFG and datalogging capabilities
Damage Identification Algorithms

• Baseline measurements
  ➢ a dozen independent measurements collected in a brief time period
  ➢ perform statistical analyses on data to define limits for damage criteria
  ➢ creates a composite view of pristine state to compare with tests
  ➢ for aircraft, will likely collect over multiple days for multiple vehicles

• Damage determination in 3 phases
  ➢ Energy packet analysis—presence of damage from increased reflections
  ➢ Normalized difference analysis—location of damage from key reflection
  ➢ Continuous wavelet transformation—method to minimize false positives
  ➢ for composite materials, frequency criteria also used for damage type

• Calibration constants
  ➢ each phase utilizes a sensitivity factor to be tuned by application
  ➢ “safe regions” can be defined for known features (bolts, ribs, etc.)
Results from Algorithms

Undamaged plate

Plate with simulated damage

Damage detected!!
Overall Results

- 1000 tests on undamaged specimen without any false positives
- 2500 tests on simulated damage, 100% capture of damage
- Location prediction with better than 0.5” accuracy from 0.5-8.0”
- Calibrated baseline measures from one quadrant could be used in other quadrants without degradation of accuracy
Sources of Error

- Largest source of error in wavespeed calculations
  - plot displays theoretical front and back of weight
  - wavespeed error dependant on frequency, resolution capabilities
- Difficult to measure damage within 0.5” of sensor due to overlap of transmitted and reflected waves
Summary

• M.E.T.I.-Disk 2 designed, optimized and packaged to facilitate damage detection using Lamb waves and other methods
• Aluminum testbed with ribbing created to validate operation of MDC SHM system on aircraft structures with simulated damage
• 3 phase algorithm to compare test data with statistical undamaged data embedded in software along with test control
• Test results were better than expected
  ➢ 1000 tests on undamaged specimen without any false positives
  ➢ 2500 tests on simulated damage, 100% capture of damage
  ➢ Location prediction with better than 0.5” accuracy from 0.5-8.0”
• Working to minimize/eliminate sources of error
Advantages to M.E.T.I-System

• Software-centric design
  - uses customized software to tailor the system to any application
  - allows generic hardware to be mass-produced cheaply, installed easily
  - flexible infrastructure accepts multiple sensor types, detection methods
  - hardware-centric designs add complexity, time, cost and risk

• Lamb waves methods
  - can query larger area than other methods, reducing sensor density
  - reduced costs, weight, complexity and computational needs

• Surface mounted sensors
  - devices can be retrofitted onto ageing aircraft
  - allow for easy removal without damaging the structure
  - embedded sensors can initiate damage themselves, repairs are difficult

• Embedded intelligence/logic in software
  - self-calibrating, uses adjacent sensor to calculate wavespeed
  - self-compensating for hygral/thermal changes using updated wavespeed
  - self-diagnostic, uses impedance to confirm piezoelectric functionality
Continued Research

• Further refinement, validation, & software integration underway
  ➢ improve accuracy of damage location prediction
  ➢ focusing on alternate wavespeed calculation algorithms

• Impedence methods for close damage (<0.5”)

• Characterization of day-to-day signal changes

• Improvement of computational efficiency

• Durability testing for sensing nodes

• M.E.T.I.-Disk 3 & 4 completion and testing