Hybrid Passive/Active Impact Detection & Localization for Aerospace Structures

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Introduction

• Aerospace vehicles are subject to impact damage
  ➢ foreign object debris (FOD)
  ➢ battle damage (and bird strike)
  ➢ ground handling (or mishandling)

• Recording of damage event and/or resulting damage provides for timely & cost effective repairs (or prevents unnecessary ones)

• MD7 Digital SHM System
  ➢ passive mode (acoustic emission recording)
  ➢ active mode (guided wave propagation)
  ➢ witness mode (differential voltage measurements)
• **Traditional SHM methods require high sensor density**
  - many methods only detect below sensor (fiber optic, Eddy current, CVM)
  - wave-based methods can cover large areas with small sensors, however acoustic emission & scatter methods need 3+ sensors in close proximity

• **Most wave-based methods require knowledge of wave velocity**
  - challenging to compensate for velocity in non-isotropic laminates
  - complications arise due to inhomogeneity (tapers, stiffeners, drop-offs)
MD7 VectorLocator™

- Analog sensor base for impact/damage detection
- 1 PZT actuator & 6 PZT sensors in small package
- Facilitates both active/passive beamforming
MD7 Motivations: Digital Network

• **Current SHM strategies are analog, do not scale practically**
  - individual cables to each element adds mass, cost, reliability concerns
  - centralized processing can limit the total quantity of sensors on structure, required to handle significant data volume synchronously

• **Analog cables not ideal for precision measurements**
  - susceptible to conducted & radiated EMI (long wires = antenna)
  - shielded signals attenuate linearly with length due to stray capacitance
MD7 IntelliConnector™

- Digital node for distributed acquisition & computation
- Facilitates both active/passive detection methods
- Flat Flexible Cable (FFC) bus for up to 200 nodes
Installed MD7 SHM System

Total System Weight 160 g

Total System Weight 100 g

CAN Terminator

FFC Bus Power/Data

RJ-45 Adapter

0.5 m

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Each node processes phase-coherent, location independent “sonar-scan”

Sum scans incoherently to form composite image

Logic imposed to compensate for view area obstacles

Color represents # of standard deviations above mean of damage-free data
 Experiment designed to evaluate performance of hybrid system
- detection/localization of impact events
- detection/localization of damage induced by impact events
- detection/localization of loosened fasteners

Specimen selected to be representative of aircraft/rotorcraft skin
- Aluminum sheet 2 mm thick, 0.6 x 0.6 m square
- 20 fasteners evenly spaced across the center, tightened to same torque

Single MD7 sensor/node used
- bonded with AE-10 using 24-hour room temperature cure cycle
- centered half-way between edge of plate and row of rivets
- flat flexible cable (FFC) used to connect to hub (command & data storage)
Representative Aerospace Specimen

- MD7 sensor/node
- Row of fasteners
- Wood simple-support
- Aluminum plate
- 0.6 m
Test Procedure

• **Falling-mass low-velocity impacts**
  - 1 cm semi-spherical impact head
  - ~20 J of energy per impact
  - strike on side opposite and at least 2 cm from sensor/node
  - simply-supported perimeter with wooden frame
  - active guided wave scans performed with 50 kHz excitation

• **36 impact events monitored passively that triggered active scans**
  - 18 impacts randomly distributed on same side of fastener line as nodes
  - 18 impacts randomly distributed on opposite side of fastener line as nodes

• **42 active scans were triggered manually**
  - 6 scans followed the loosening (hand-tight) of a random fastener
  - 36 scans without impact or loosened fastener (false positive check)
Passive Mode Impact Detection Results

• System showed excellent sensitivity to impact events
  - 100% detection (36/36) following impact events
  - no false triggers at pre-programmed threshold
  - phase coherent scan produced for each AE result
  - Cartesian coordinates distilled for maximum likelihood centroid of scan

• Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - predictions cluster relatively closely near origin relative to size of plate
  - mean error for AE localization ~ 25 mm
  - no trend observed for results obtained on one side of fastener line vs other
Re-Centered Passive AE Impact Detection Results
Active Mode Impact Detection Results

• System showed good sensitivity to impact damage
  ➢ 100% detection (36/36) of ~0.5 mm deep dents following AE detection
  ➢ no false positives indicated (0/36) following non-impact scans
  ➢ phase coherent scan produced for each AE result
  ➢ Cartesian coordinates distilled for maximum likelihood centroid of scan

• Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  ➢ more scattered than AE, but predictions still group relatively close to origin
  ➢ mean error for GW localization ~ 50 mm
  ➢ no trend observed for results obtained on one side of fastener line vs other
  ➢ some error may be accumulated due to each subsequent dent introducing additional scatterers into structure; while subtracted in algorithm, still redistributes ultrasonic energy through structure in inhomogeneous pattern
Re-Centered Active GW Impact Detection Results
Active Mode Fastener Detection Results

- System showed excellent sensitivity to loose fastener detection
  - 100% detection (6/6) of hand-tightened fasteners
  - no false positives indicated (0/36) following non-loosened scans
  - phase coherent scan produced for each AE result
  - Cartesian coordinates distilled for maximum likelihood centroid of scan

- Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin
  - more scattered than AE, but predictions still group relatively close to origin
  - mean error for GW localization ~ 5 mm
  - essentially translates to localization within ±1 fastener position
Re-Centered Active GW Fastener Detection Results
Summary

• Paper present results for a controlled experiment investigating the use of an SHM system for hybrid passive/active operation
  - Aluminum plate with row of fasteners instrumented with a single sensor
  - 36 impact events using falling mass, AE + GW detection & localization
  - 36 manually-triggered active scans to check false-positives
  - 6 manually-triggered active scans with loosened fasteners

• Results indicate good sensitivity for both active/passive modes
  - 100% AE-based ~20 J impact detection, 25 mm mean localization error
  - 100% GW-based ~0.5 mm dent detection, 50 mm mean localization error
  - 100% GW-based loose fastener detection, 5 mm mean localization error
  - no false positives for active or passive modes with appropriate thresholds

• Hybrid beamforming approach provides an efficient & accurate means for impact/damage detection, possible to add DC sensors
## Technology & Transition Readiness

### Naval Applications
- **Surface Vessels – TRL 7**
  - 14 sensors installed on USS Independence
  - continuously operating since 2/2012
  - monitoring weld-line cracks & temperature
- **Submarines – TRL 5**
  - underwater testing
  - scaled testing planned

### Fixed-Wing Aircraft
- **Unmanned – TRL 6**
  - full-span test conducted on Triton wing assembly
  - full-span test conducted on Predator wing spar
- **Manned – TRL 6/7**
  - C-17 empennage tests
  - F-22 lug fatigue tests
  - C-130 hot-spot flight test planned for 2014

### Rotorcraft
- **BlackHawk – TRL 6**
  - 100+ subcomponent impact/damage tests
  - ongoing subassembly testing w/SIK
  - tail gearbox spin-stand crack-tracking tests
- **CH-53K – TRL 5**
  - relevant material tests
  - environmental tests
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