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METIS DESIGN CORPORATION

STRUCTURAL HEALTH MONITORING CAPABILITIES

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STRUCTURAL HEALTH MONITORING

TECHNOLOGIES OVERVIEW

Introduction

- 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

- Essentially involves integrating non-destructive evaluation (NDE) devices into a vehicle to collect prognostic data
  - can be embedded or surface mounted
  - integrate into new vehicles or retrofit ageing vehicles to facilitate CBM
  - interrogation of system can occur continuously or intermittently

- Applicable to any field – highest payoff in aerospace (labor)






Goals of SHM

- Reduce inspection and maintenance costs
  - inspections account for roughly 25% of an aircraft's life cycle cost
  - commercial airlines spend a combined $10 billion/year on maintenance
  - condition based maintenance could reduces these costs by 33%
  - integrate into new vehicles designs for need-based maintenance
  - retrofit SHM systems into existing vehicles to extend viable economic life

- Increase reliability of damage detection and failure prediction
  - much of the military and airline fleet are ageing aircraft, fatigue issues
  - can catch damage that may have occurred between scheduled intervals
  - most inspection is currently visual, overlooks many forms of damage
  - metals: corrosion and fatigue vs. composites: delamination and impact
  - damage below the visible surface is important for composites

Concept of Operations

In flight, can passively monitor for events, intermittently perform tests, or actively notify operators and ground crews

Starting from taxi, monitoring methods can 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.

System Data Utility

- Black box augmentation
  - record additional critical data in the event of an accident
  - witness maximum strain/stress in vehicle for future design/analysis use
- Supplemental inspection tool
  - expedite scheduled inspections, reduce manual labor with in-situ system
  - offer surface penetrating methods without tear-down of sub-structure
- Enable condition-based maintenance
  - continuously monitor vehicle in-flight for threshold stain/stress values
  - perform complete pre-flight diagnostic inspection for safety assurance
- Streamline supply/demand chain
  - provide component data for state-based maintenance and repair
  - smoother, quicker and cheaper supply of replacement components

Active vs Passive Sensing

- Active damage detection methods
  - actively seek out damage sites
  - requires an excitation source; major power driver
  - can be stress, vibration, electric, magnetic or light-induced
  - typically yields more detailed damage state information

- Passive damage detection methods
  - passively witness operating environment
  - damage event or environment provide necessary energy
  - record maximum strain, displacement, impact energy, etc; reduced data
  - some methods can also constantly record
  - overall these methods are used to infer damage, often model-based

Common SHM Detection Methods

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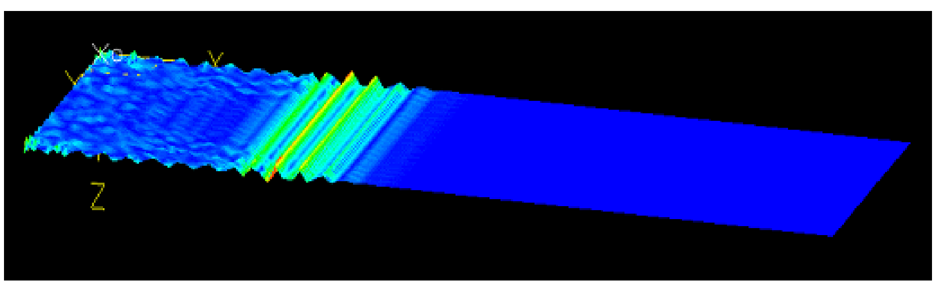
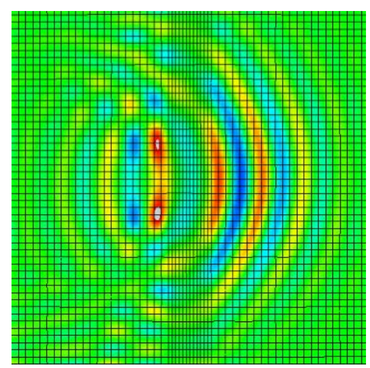
Methods	Data	Power	Strengths/Limits
Strain Gauge	2 bytes/s – 2kB/s (1Hz – 1kHz)	~70mW @5V 350 Ω Passive (P α V^2)	Inexpensive/ Only local information
Fiber Optics	2GB/s 1GHz	~10W mostly for laser (not grading dependant)	Large linear range/ Little transverse info
Eddy Current	2kB/s – 200MB/s (1kHz – 100MHz)	~800mW @5V $30mm^2$ Active (P α $A*V^2$)	Highest sensitivity/ Smallest coverage
Acoustic Emission	2MB/s – 20MB/s (1MHz – 10MHz)	~100mW @5V Passive (P α V^2)	Flexible placement/ Require event energy
Modal Analysis	200kB/s (100kHz)	~175mW @5V 25kHz Active (P α $f*A*V^2$)	Largest coverage/ Only global data
Lamb Wave	2MB/s (1MHz)	~300mW @5V 100kHz Active (P α $f*A*V^2$)	Surface penetrating/ Complex results

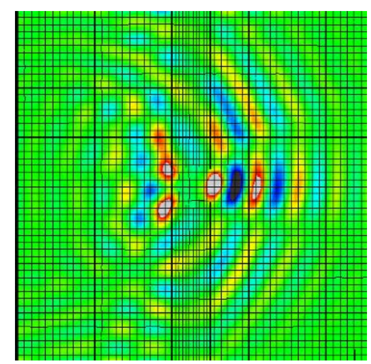
Lamb Wave Methods

- Form of elastic perturbation that propagates in a solid medium
  - excitation shape and frequency can be optimized for particular geometry
  - 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 actuator/sensor pairs

- Many advantages to Lamb waves over traditional methods
  - best damage size and range to sensor size ratios
  - sensitivity and range scales with input power level (with limitations)







Optimization of Sensor Geometry

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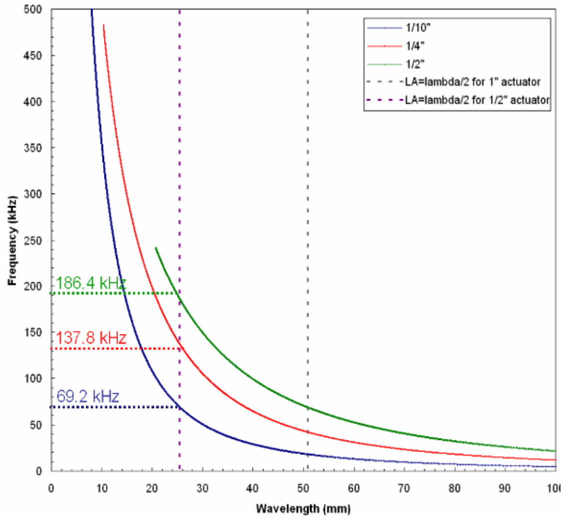
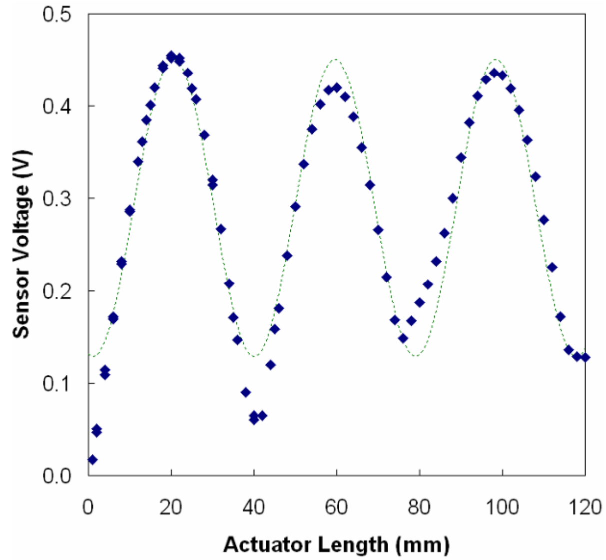
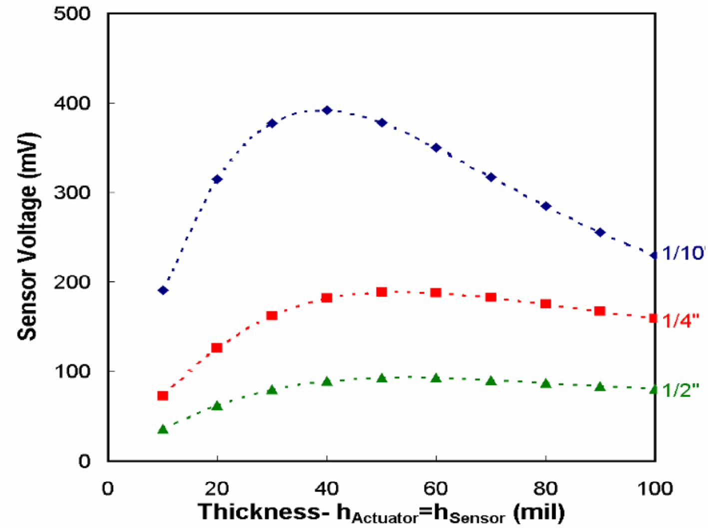
Frequency Selection



Diameter Selection



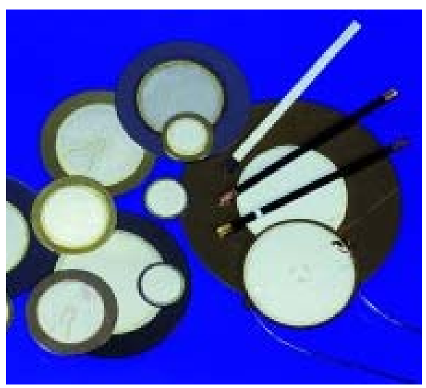
Thickness Selection



- 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)

Mechanical Design of Sensors

- SHM is predicated on the ability to intimately integrate sensors with a structure, whether surface mounted or embedded
  - exposed to many of the same loading conditions as the host structure
  - includes peak static stress and strain, as well as mechanical fatigue
  - sensor elements and adhesives can disbond, crack, soften, or decouple
- Many methods rely on high-frequency actuation
  - mechanical fatigue of actuator element can become an issue
  - electromagnetic fatigue can degrade PZT wafers and SMA over time

Durability and Packaging

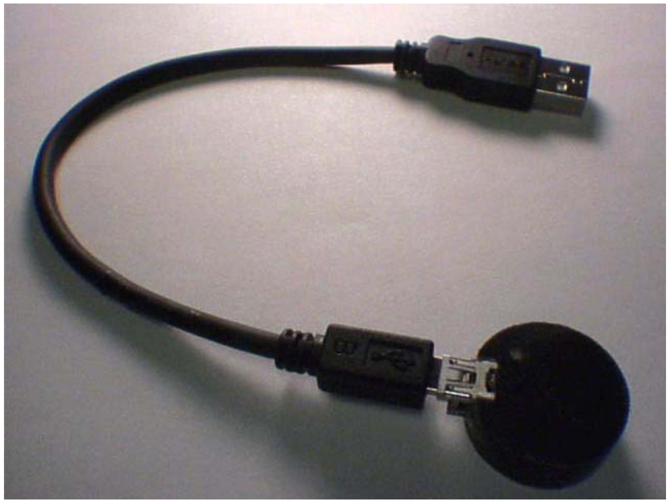
- To achieve cost benefits sensors must be sufficiently reliable
  - cannot require replacement within life of the component being monitored
  - failure of aircraft subsystems have catastrophic consequences
- Durability describes the response of a material, component or system to its operating environment over time
- Standards in place to regulate durability of aircraft components
  - DO-160E: environmental airworthiness requirements (FAR AC21-16D)
  - MIL-STD-810: guidance for environmental tests for DoD components
  - MIL-STD-461: protocols for evaluating EMI susceptibility and emissions

System Infrastructure Components

- **Connectors & cables:** attach to sensors (semi)permanently
- **Amplifiers:** improve outgoing actuation or incoming signal
- **Data acquisition:** set rate and bit-resolution for digitization
- **Computation:** control and coordinate other components
- **Memory:** storage of collected data
- **Communication:** accept external commands, pass data
- **Power:** provide excitation source, supply for electronics

Point of Measurement Electronics

- Point-of-Measurement (POM) is a MDC patented concept for local integration of all sensing infrastructure components
  - digitizing at POM minimizes EMI introduction
  - digital bus requires less cabling then analog
  - POM eliminates stray capacitance (essentially a “free” amplification)
  - achievable for nearly any sensor
  - enables active/passive, local/global & distributed computing architectures
- M.E.T.I.-Disk 3 Digital SHM Node
  - Lamb wave, modal analysis, AE capable
  - 1MHz 16-bit ADC & 1MS/s 8-bit DAC
  - self-diagnostics for electronics & sensor
  - daisy-chain compatible using CAN bus
  - network over USB or wirelessly



Wired vs Wireless SHM

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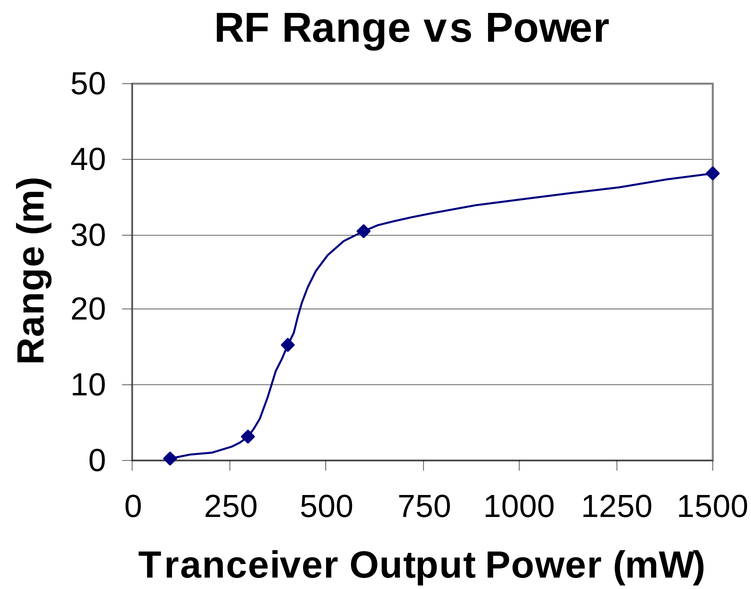


- Need for wireless SHM
  - cables & connector are fault prone
  - corrode & crack in harsh environment
  - add weight, cost, integration time
  - easily reconfigurable network
- Downsides to wireless
  - heavily regulated in several applications (FAA for EMI, DOD for security)
  - places large constraints on sensor power consumption
  - requires batteries, which carry own longevity issues, including recharging
  - transmission range is power dependant
- Hybrid system can take advantage of many of the upsides
  - wireless communication eliminates data lines, increases accessibility
  - powered from a common bus with an integrated fail-safe back-up battery

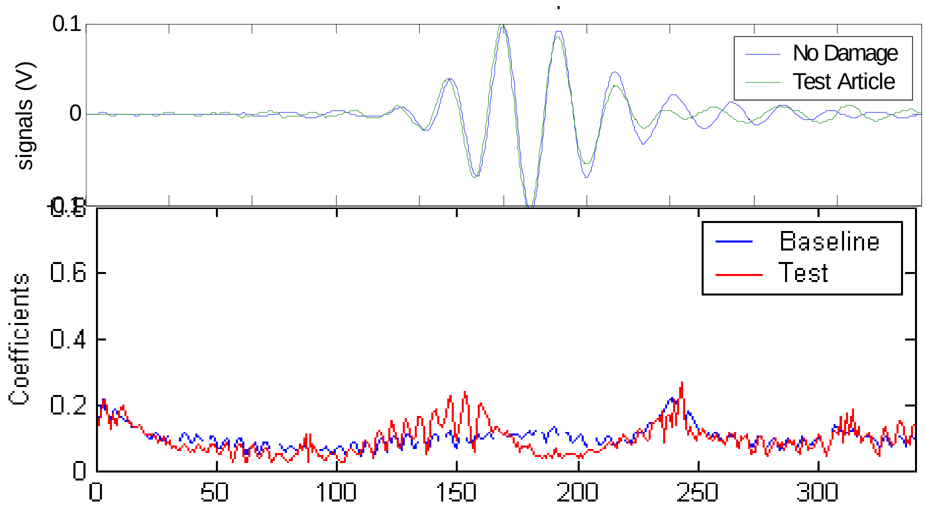
Duty-Cycle

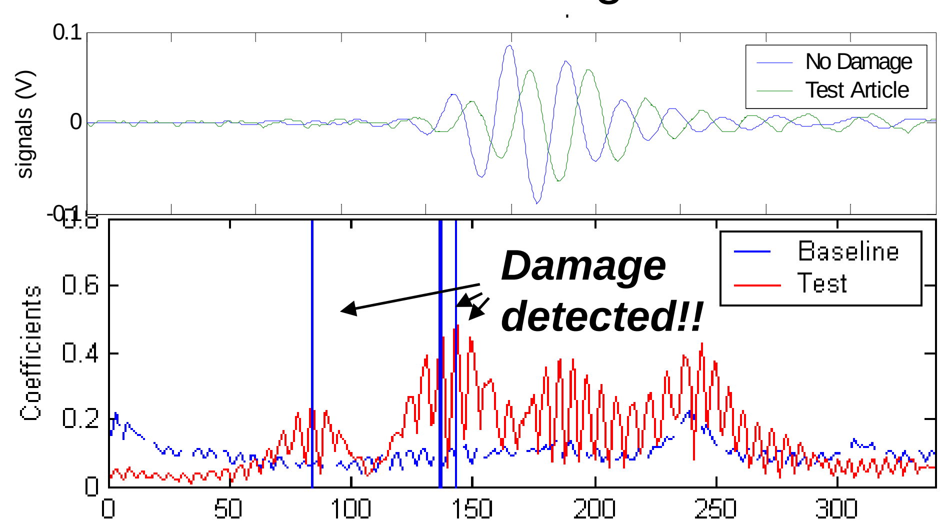
- Duty-cycle defines how often data is collected
  - scheduled: such as pre or post-flight, particular altitude or speed
  - time intervals: sample every second, minute, hour, day, etc
  - continuous: always on and collecting
- Strategic states can be used to reduce composite power draw
  - *Off*: all chips in low power mode, analog disabled, ~1mW
  - *Listening*: transceiver waiting for commands, analog disabled, ~80mW
  - *Transmission*: sending data, analog disabled, ~220mW
  - *Testing*: all chips & sensors operating, ~3mW + 0.1W to 10W for sensor

Duty-Cycle (1ms test)	**Acquisition Rate for Lamb wave**	**Time to Fill 1GB File**	**Time to Drain 1Ah Battery**
Continuous	1MHz	9 minutes	6.5 hours
1 sample/min	1MHz	1 year	0.5 year

Damage Identification Algorithms

- Several multi-physics approaches are possible
  - ➢ Time domain—compare time-of-flight of wave-packets
  - ➢ Energy domain—compare intensity of wave-packets
  - ➢ Frequency domain—compare spectrum of wave-packets
- Common features of analysis
  - ➢ pulse-echo and pitch-catch can both yield good information
  - ➢ nearly all methods rely on a baseline or undamaged characterization
  - ➢ wavelet decomposition can be used to enhance/denoise signals





Pattern Recognition Methods

Methods	Description	Strength	Limitation
Nearest Neighbor	Category of new data point determined by nearest neighbor point category	Intuitive, simple, highly adaptable	Sensitive to noise, large storage space
K-Nearest Neighbor	Category of new data point determined by average of k-nearest neighbors categories	Intuitive, simple, highly adaptable	Computationally intensive recall, large storage
Decision Tree	Series of branched questions leading to category leaves, weighting implicit in structure	Easiest to train, accommodates missing features	Rules may be complex, can be unstable
Neural Network	Machine-learning technique uses training data sets to weight input/output links	Robust to noise, multivariate & non-linear OK	Needs most training data, "black box"

Pattern recognition methods efficiently use collected training data to extract key features within multiple domains to classify "state" of health from new sensor data, including presence of damage, type and severity

Summary

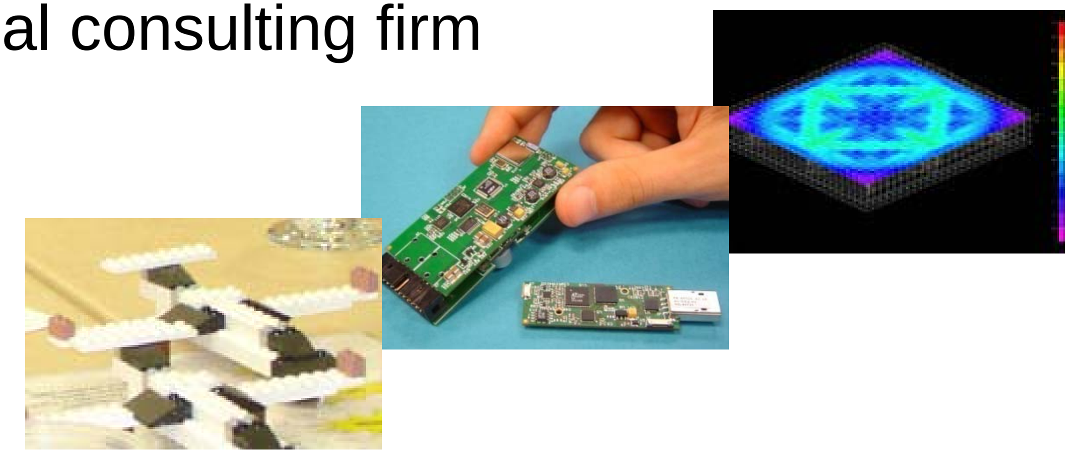
- Structural Health Monitoring (SHM)
  - reduce inspection & maintenance costs through CBM
  - increase reliability of damage detection with integrated methods
- Sensing Methods
  - active or passive, each with strengths & limitations (range/sensitivity)
  - must consider sensor mechanical design & durability to insure reliability
- Sensor Hardware
  - several components necessary (amp, DAC, ADC, memory, computation)
  - data volume and power consumption play a major role in viable systems
- Signal Processing
  - traditional analytical & model-based approaches can yield good results
  - pattern recognition for state classification with minimal data collection
- SHM System Design
  - not all architectures & approaches will work for every application
  - to date no current full scale test articles or in service examples

Monitoring & Evaluation Technology Integration

M.E.T.I.-System Damage Detection Devices

Metis Design Corporation (MDC)

- Highly specialized technical consulting firm
  - mechanical design
  - custom sensor systems
  - lean enterprise solutions



- Objective
  - develop novel solutions for a wide range of real-world challenges
  - internal R&D aims to further the state-of-the-art for damage detection
  - external service to assist client transition from concept through prototype

- Diverse engineering staff
  - combine creativity with hands-on design experience
  - solid fundamental principles (>50% of the technical staff hold Ph.D.'s)
  - maintain good relationships with several top universities worldwide

Management Profile

- Seth S. Kessler, Ph.D. – President, CSS Team Lead
  - S.B., S.M. and Ph.D. in Aerospace Engineering from MIT
  - specializes in composites, high-g systems, active materials, cryogenics, damage detection and monitoring, and finite element analysis
  - worked as advanced concept engineer at Lockheed Martin Skunk Works
  - 30+ publications, SHM text co-editor, 4 issued and 5 patents pending
- Kristin Jugenheimer – Chief Engineer, Mechanical Team Lead
  - S.B. and S.M. in Mechanical Engineering from MIT, BioMedical minor
  - specializes in product design, CAD, finite element modeling, kinematics
  - worked for Boston Scientific's Microvasive Endoscopy Group, where she developed new device concepts and bench-level testing apparatus
- Hugh McManus, Ph.D. – Lean Enterprise Team Lead
  - S.B. and S.M. in Aerospace Engineering from MIT, Ph.D. from Stanford
  - specializes in aerospace industry modern product development practices
  - previously a professor at MIT and at Lockheed Missiles and Space

Client Profile

- MDC solutions span a variety of disciplines ranging from air and spacecraft applications to biomedical and consumer products
- Government Agencies (including classified applications)
  - produce customized testing or acquisition devices for field use
  - standardized software reports can be deployed for both PC and PDA
  - rapid development of custom electronics for harsh environments
- Commercial Entities
  - provide testing & evaluation hardware to demonstrate client technologies
  - outsource development to use internal resources more efficiently
  - intellectual property is completely retained by the client
- University Laboratories
  - increase quantity of integrated testing hardware at greatly reduced costs
  - improve safety by using wireless acquisition for remote experimentation

Partial Client List

- Air Force Research Laboratory
- Arizona State University
- Army Corps of Engineers
- ATK Launch Systems
- Boeing
- Boston University
- Charles Stark Draper Laboratory
- Composite Technology Corporation
- Continental Structural Plastics
- GE (Research Center & Plastics)
- Honeywell
- Massachusetts Institute of Technology
- Menasha Packaging Company
- NASA
- National Institute of Health
- National Science Foundation
- Navy
- Nova Chemicals
- NRO Office of Space Launch
- Oregon State University
- Peninsula Plastic Corporation
- Polaroid
- Raytheon
- Rockwell Collins
- Rolls-Royce
- Select Engineering Services, Inc.
- SSI Schaefer USA
- Textron
- University of Michigan
- University of Missouri-Rolla
- University of South Carolina
- Vought Aircraft

Partnerships

- MDC maintains several strategic partnerships to offer the highest quality turn-key solutions at a reasonable price

- Manufacturers
  - machining, compression & injection molding, die & laser cutting
  - PCB fabrication and assembly, flex-circuits, microfabrication, MEMS
  - electro-mechanical assembly and integration (low and high volume)

- Test facilities
  - mechanical, environmental, electrical and combined testing
  - UL, ASTM, DO-160, MIL-STD-810/461, and other certified testing

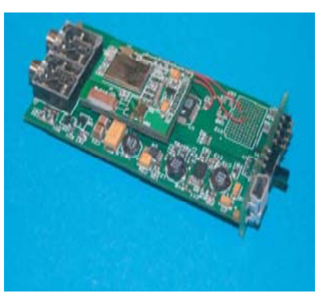
- Universities
  - professors available for specialized consulting
  - facilities available for specialized testing

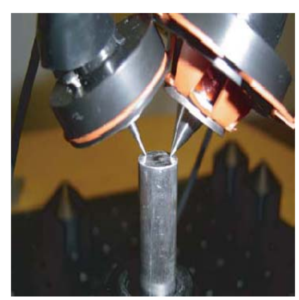
Corporate Recognition

- Inc. Magazine
  - 779th fastest growing compay in America in 2007
  - 34th fastest growing company in metro-Boston in 2007
  - 15th fastest growing consuting companin America in 2007
- Boston Business Journal
  - recognized as BBJ 2007 Pacesetter
  - top 60 fastest going companies in MA in 2007

Custom Sensor Systems (CSS)

- Unique service provides off-the-shelf instrumentation alternative
  - hardware for custom sensors, data acquisition, computation
  - communication over USB, Firewire, Ethernet, WiFi, ZigBee, Bluetooth
  - software for PC/PDA including automation, signal processing, algorithms
  - packaging designs to conform to the harshest of environments
- Each challenge is distilled to its fundamental parameters
  - can optimize design with respect to size, weight, cost or durability
  - eliminates superfluous functionality, peripherals and add-ons
- Client-owned turn-key solutions



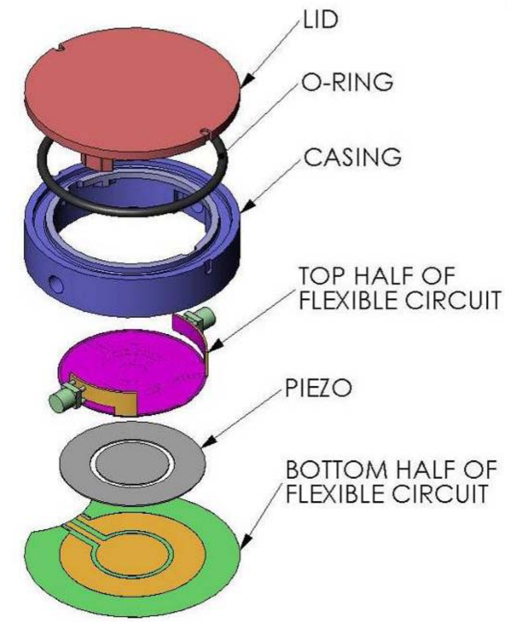


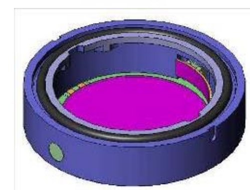
SHM Product Lines

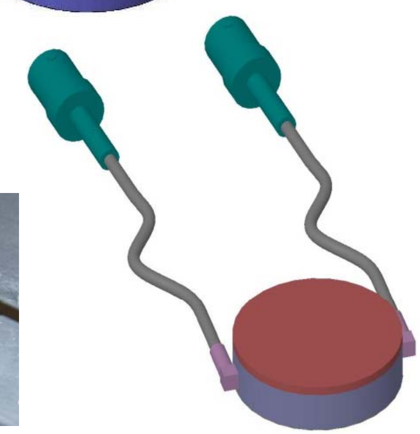
- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to reduce life-cycle costs and improve reliability
- MDC has proven to be an industry leader in SHM R&D efforts
  - methodologies that allow greatly reduced sensor densities
  - enabling technologies for data and power efficient architectures
  - low-cost devices suitable for both ageing and future vehicle integration
- MDC patented and patent-pending SHM related technologies
  - micro-electronics that digitizes analog data at the point of measurement
  - simple, highly synchronous damage detection network electronics
  - concentric piezoelectric pulse-echo actuator and sensor pair
  - method for localizing damage (angle and radius) from a single point

M.E.T.I.-Disk 2 Analog SHM Device

- Four major components
  - ➢ concentric piezoceramic sensor/actuator elements
  - ➢ flexible circuit for power and shielding
  - ➢ ¾” 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
  - ➢ shielded from in and out-of-plane EMI exposure
- Device characteristics (TRL 6 demonstrated)
  - ➢ nominal drive of 20Vpp
  - ➢ nominal sense of 20mVpp
  - ➢ Lamb wave, modal analysis, AE capable
  - ➢ co-axial cable compatible







M.E.T.I.-Disk 3 Digital SHM Device

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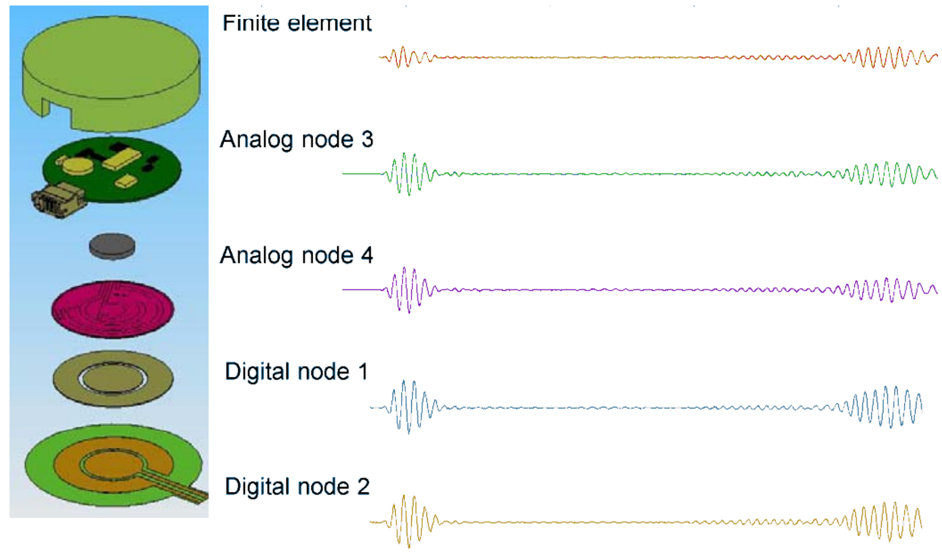
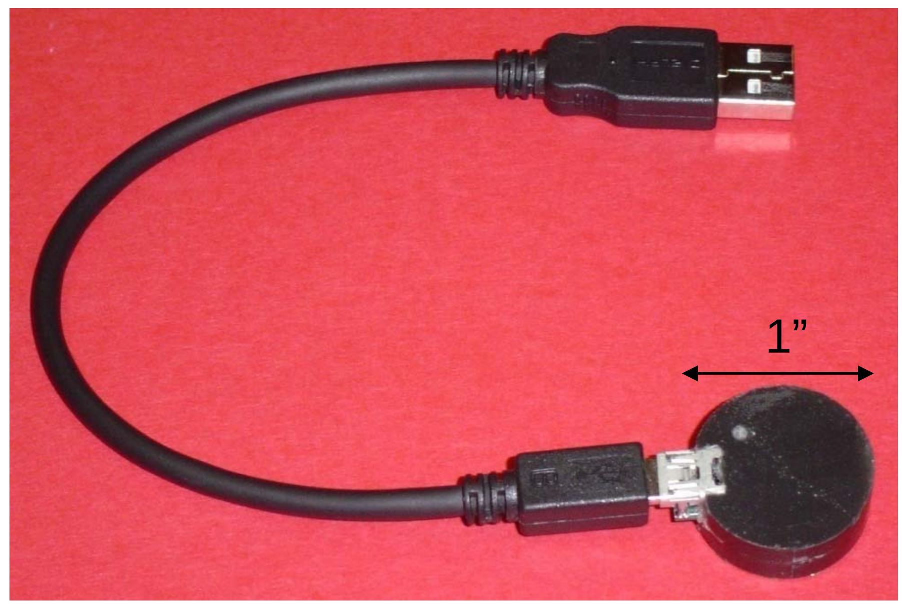
- Miniaturized instrumentation
  - ➢ concentric piezoelectric elements
  - ➢ 2 channel 1 MHz 16-bit ADC
  - ➢ 3 MSample/s 8-bit 20Vpp DAC
  - ➢ programmable waveform & gains
  - ➢ synchronous to 50ns on CAN bus
  - ➢ 1” urethane encapsulation
  - ➢ tested to MIL810/DO160 (TRL 6)
  - ➢ capable of multiple test types: Lamb wave, modal analysis, AE

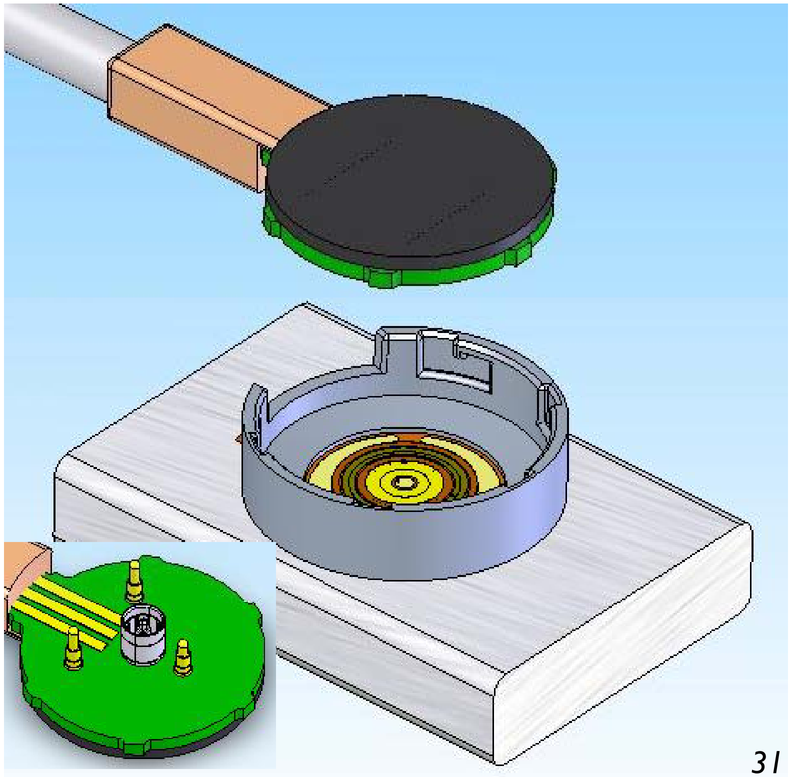


- Point-of-Measurement™ sensing
  - ➢ digitizing at POM™ minimizes EMI
  - ➢ requires less cabling then analog
  - ➢ enables local logic & computation



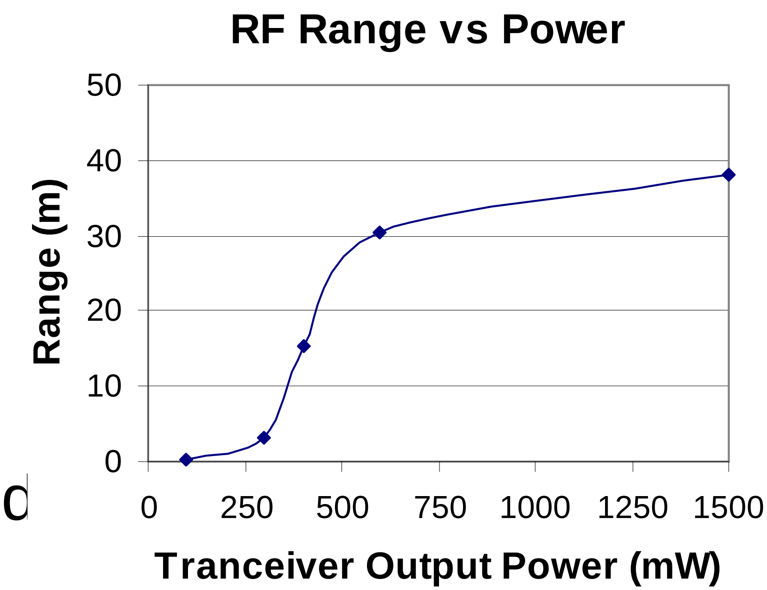
Intelli-Connector™ & Intelli-Harness™

- Intelligent SHM infrastructure embedded into a 1" connector
  - connector-less Firewire mating option
  - cable harness for distributed network
- Acquisition features
  - maintains all MD3 characteristics
  - diagnostic mode reports on sensor impedance, temp, continuity (tamper)
  - voltage protection for actuator/sensor circuits from mechanical backdrive
- Communication features
  - multiple interrupt lines allow 10ns sync and remote re-programming
  - Ethernet connection from hub to PC with standard or wireless router

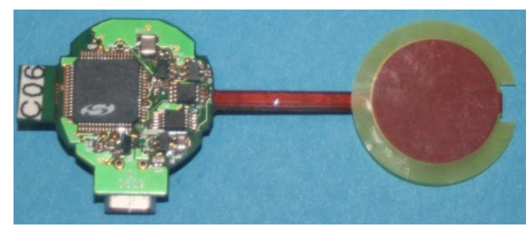


M.E.T.I.-Disk 4 Wireless SHM Device

- Need for wireless SHM
  - cables & connector are fault prone
  - corrode & crack in harsh environment
  - add weight, cost, integration time
  - easily reconfigurable network

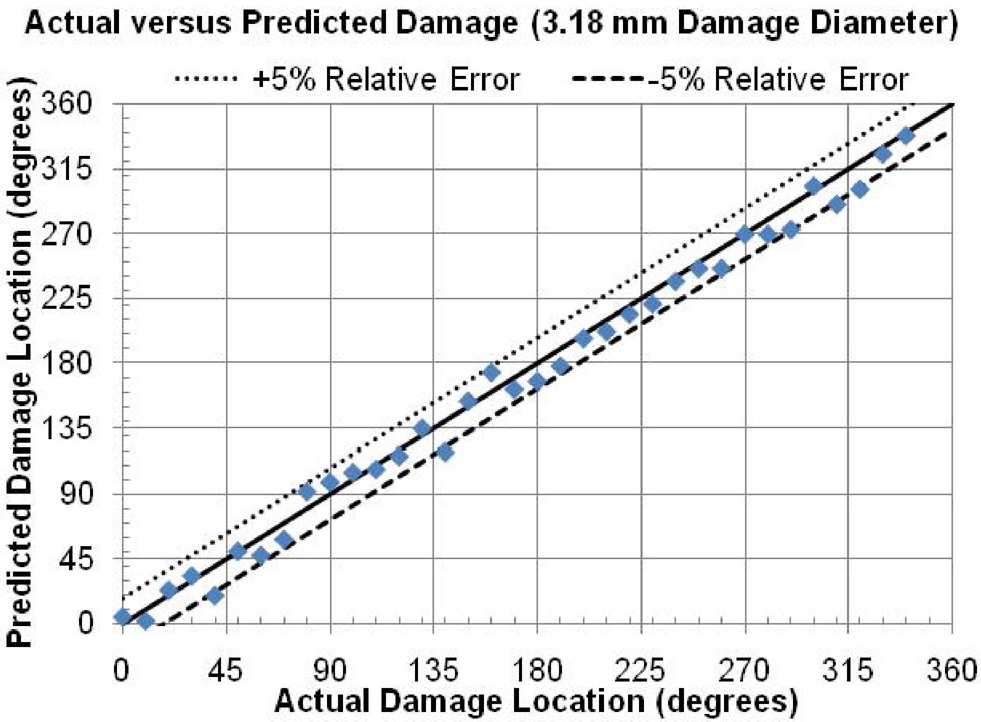


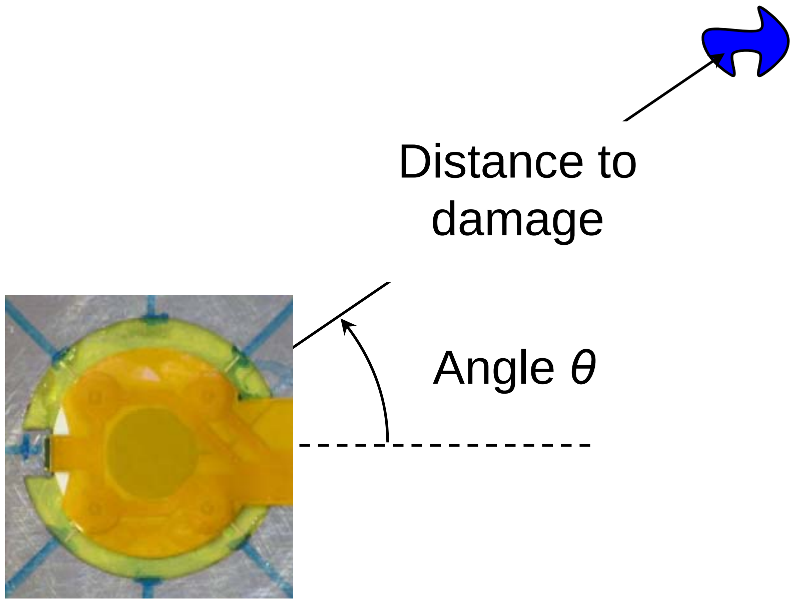
- Device design (TRL 4 demonstrated)
  - same form-factor, ZigBee chip added
  - mini-USB connector used for power input
  - power with USB or Lithium polymer battery



- Hybrid system can take advantage of many of the upsides
  - wireless communication eliminates data lines, increases accessibility
  - powered from a common bus with an integrated fail-safe back-up battery
  - NASA Phase II SBIR research underway to integrate power harvesting

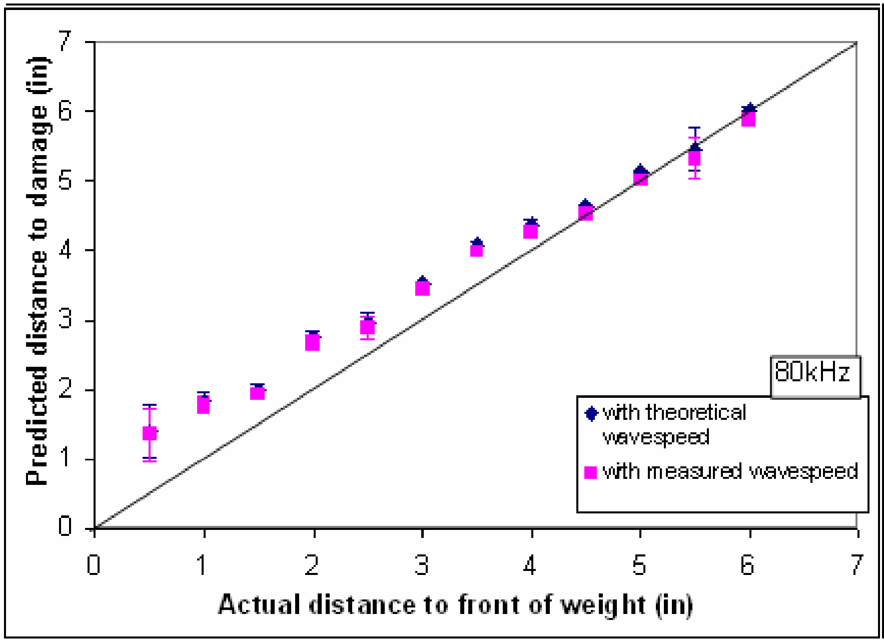
M.E.T.I.-Disk 5 "Locator" Device

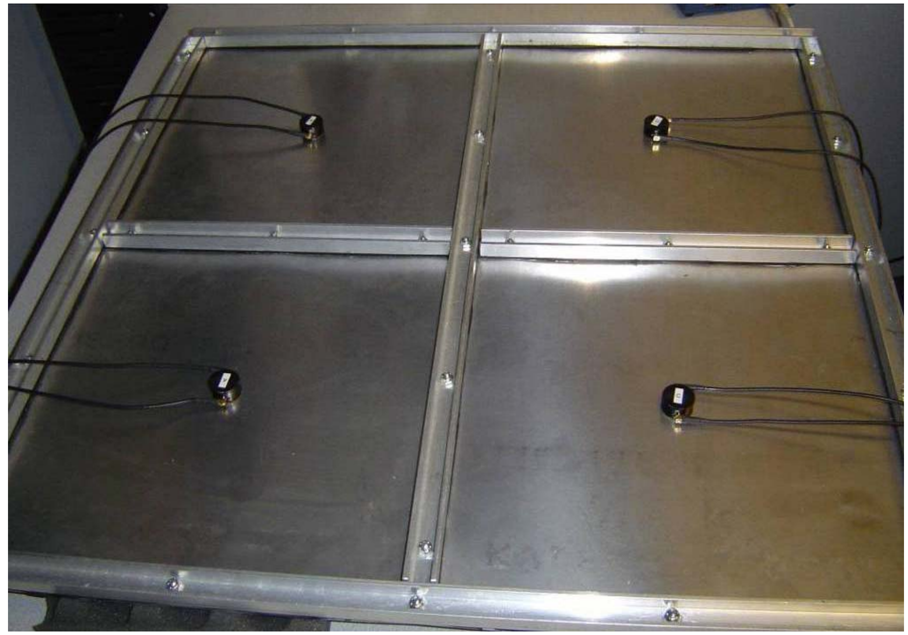




- Patent-pending method to measure angle from a single point
  - accuracy <±5% for angle and ± 5mm location (specimen dependant)
  - can be implemented using analog or digital infrastructure
- Active mode (pulse & listen) to seek damage (not phased array)
- Passive mode (sit & listen) for location of impact event

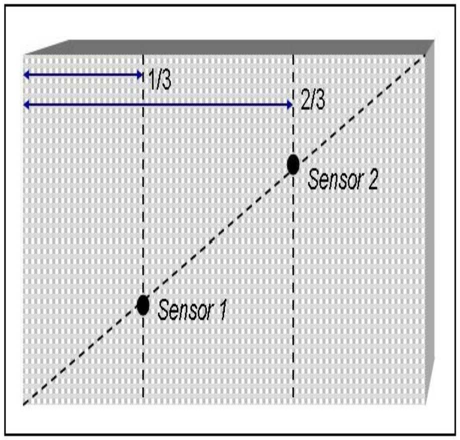
Sample Results for Aluminum





- 18” square 1/8” Aluminum quadrants formed by c-channel ribs
- Lamb wave tests performed in pulse-echo mode, 80kHz
- 2000 tests on undamaged specimen without any false positives
- 5000 tests on simulated damage, 100% capture of damage
- Location prediction with better than 0.5” accuracy from 0.5-8.0”

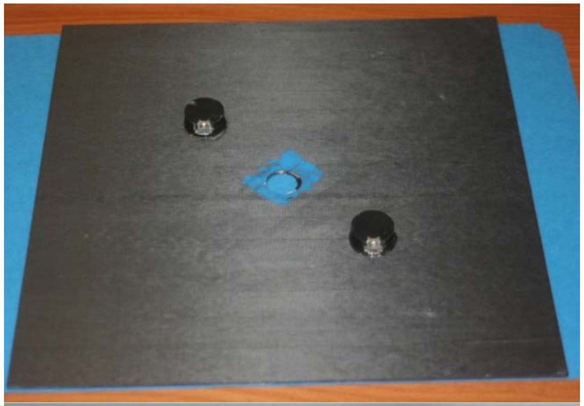
Sample Results for Composite

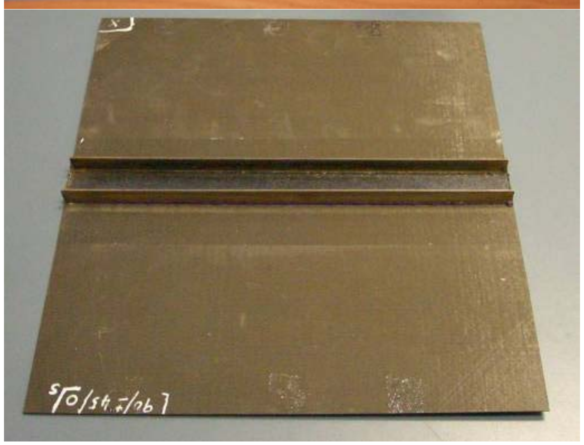


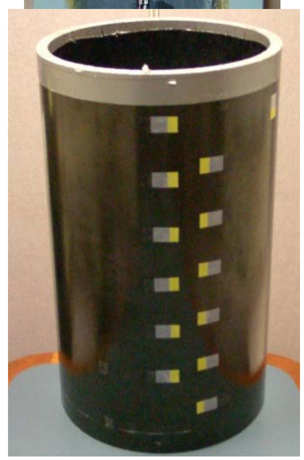
Plates	Damage Type	Damage Severity
3	Impact (5 lbs dropped weight)	4", 8", 16", 32"
3	Hole (center drilled)	$^1/_{32}$", $^1/_8$", ¼", ½"
3	Delamination (corner cut)	¼", ½", 1", 1.5"

- 11.75" square 0.1" thick quasi-isotropic composite laminates
- Lamb wave tests performed in pulse-echo mode at 100kHz
- Total of 9000 undamaged & damaged data sets collected
  - 100% presence accuracy without any false positives or missed damage
  - 100% type of damage accuracy without any mis-classifications
  - 99.9% severity prediction including adjacent levels (77% without)
  - results using an optimized K-Nearest Neighbor code
  - achieved using separate plates for training and testing
  - accommodates sensor placement variability and "real" damage

Other Validation Tests







- Analog sensors have been tested with algorithms on a variety of metals and composite materials, including sandwiches
- Digital sensors have been tested with algorithms on built-up aluminum, titanium and composite skins, and are slated for more advanced testing on large aircraft components in 2008

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
- Pulse-echo Lamb wave methods
  - can query larger area than other methods, reducing sensor density
  - pattern recognition can accurately predict presence, type & damage size
- Surface mounted sensors
  - devices can be retrofitted onto ageing aircraft
  - allow for easy removal without damaging the structure
- Embedded intelligence/logic
  - POM™ architecture allows maximum power & computational efficiency
  - self-compensating for hygral/thermal changes using updated wavespeed
  - self-diagnostic, uses impedance to confirm piezoelectric functionality

Current Research Areas

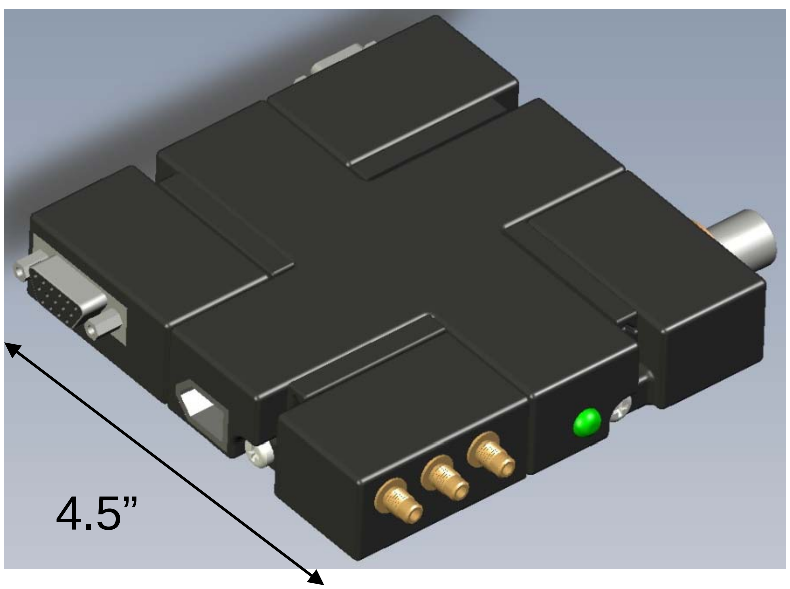
- Sensor Hardware Development
  - extended range for wireless M.E.T.I.-Disk 4
  - networking for wireless M.E.T.I.-Disk 4
  - incorporating power harvesting in wireless M.E.T.I.-Disk 4
  - packaged version of single point “localization” sensor
  - further miniaturization (80% volume reduction) for M.E.T.I.-Disk 3 &4
  - high temperature (500 °F) versions of M.E.T.I.-Disk 3 &4
- Algorithm Development
  - model-augmented pattern recognition (FEA-based state definition)
  - ageing-adaptive pattern recognition module (accounts for ageing/repair)
  - adjusted localization (for composite and type-based feature selection)
- System customization & deployment for a relevant application (both hardware & algorithms modified to meet customer needs)

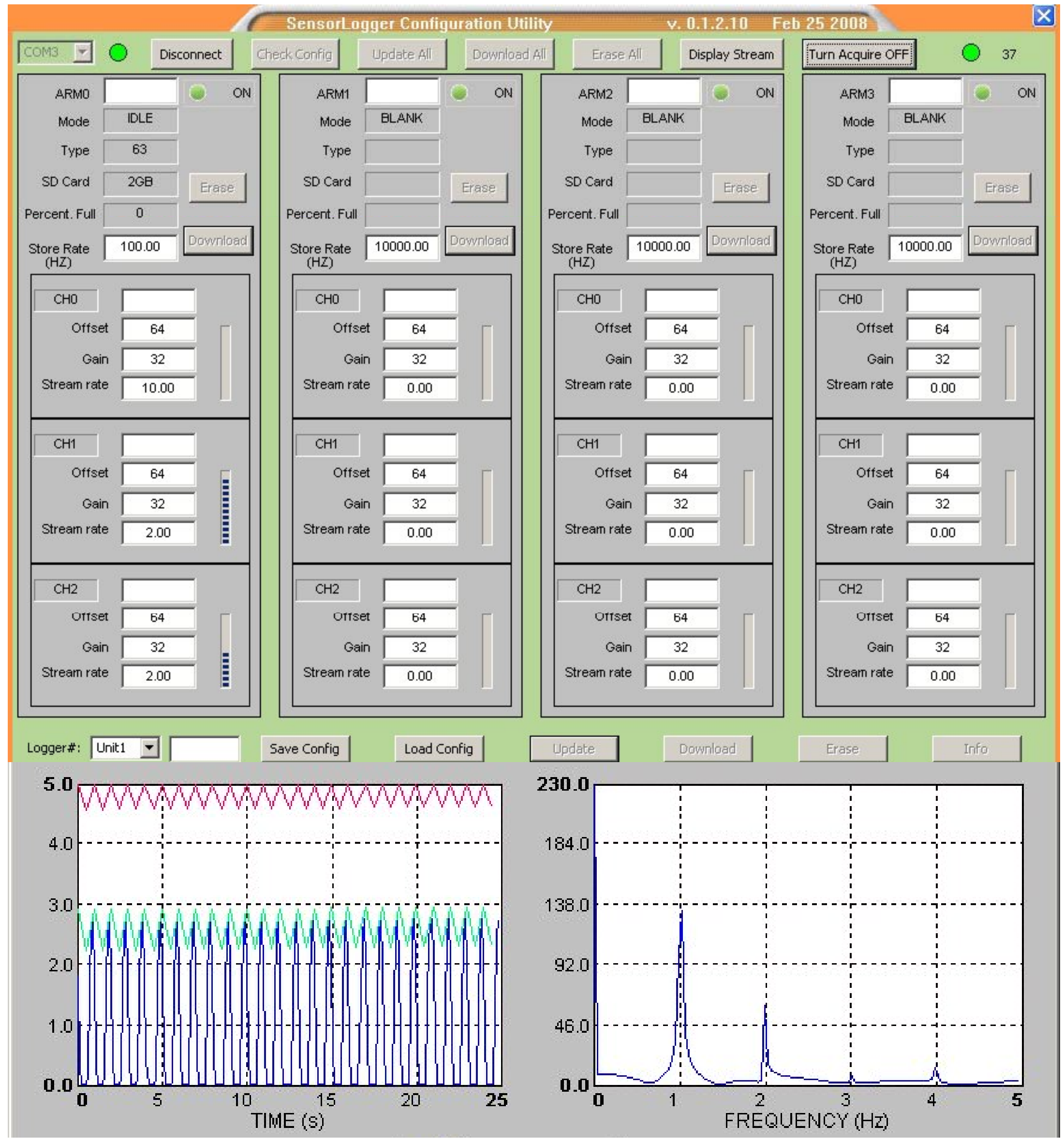
HUMS Product Lines

- Health & Usage Monitoring Systems (HUMS) is an emerging field where operation and exposure data is collected to formulate efficient condition-based maintenance actions
- MDC has played an active role developing innovative HUMS
  - modular, remotely configurable devices to log multiple sensors locally
  - novel methodology that greatly increases signal-to-noise fidelity
  - low-cost architectures that reduce instrumentation complexity
  - rugged devices that survive high-g and thermally extreme environments
- MDC patented and patent-pending HUMS related technologies
  - electronics to minimize EMI in analog data collection
  - "radio-free" wireless protocol that can penetrate thick metal walls
  - "through-wall" wireless powering/recharging technique for sensors

Wireless Aircraft SensorLogger

- Local data acquisition hub
- Anodized aluminum enclosure
- 12-channels, 100 KHz @16bit
- 48GB static memory (max)
- RS-485/232 telemetry link
- 2W draw, 2mW ¼hr duty-cycle
- Strain gauges, accelerometers, pressure and thermocouples





MDC Value Proposition

metis design

- Improve existing internal resources
  - minimize the wires necessary for instrumenting specimens
  - remove test matrix limitations imposed by COTS equipment
  - eliminate delays caused waiting for equipment availability
  - reduce precious space taken by hardware in testing areas
  - increase engineering resources by outsourcing prototype development
- Enhance existing product lines
  - introduce wireless and/or PDA capabilities to increase flexibility
  - ruggedize products to operate in harsh environments
- Introduce new products
  - mitigate proof-of-concept risk by using a proven engineering team
  - demonstrate new technology for investors using custom electronics
  - transition breakthrough products previously developed by MDC

Why Settle for off-the-Shelf?

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