Protocol and Demonstrations of Probabilistic Reliability Assessment for Structural Health Monitoring Systems

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Verification and Validation of Structural Damage Sensing Systems

- Structural Damage Sensing is a component of SHM
- SDS System Certification requires Qualification Testing that includes Capability (Reliability) Validation

SDS System Verification and Validation:
- **Verification**: Demonstrate design requirements under *controlled conditions* (laboratory environment)
- **Validation**: Demonstrate design requirements with *representative operational environment and user*

- Required capability depends on expected application
- Validating SDS capability is a requirement for use of SHM in USAF structures managed via Aircraft Structural Integrity Programs (ASIP)
Probabilistic Reliability Assessment for SDS Systems

Protocol comprises:

- Procedure for analyzing all pertinent characteristics of the SDS system
  - Identify all critical factors that affect system performance

- Multistage approach for system validation

- Modeling and experimental methodology for efficiently addressing a wide range of damage and operational conditions

- Effective methods for evaluating metrics of capability and reliability depending on system type and function (uncertainty propagation)

Primary Protocol

1. Define SHM Application
2. Identify and Evaluate Controlling Factors
3. Design Multistage Validation Study
4. Perform Multistage Validation Study
5. Process Data for SHM Reliability Assessment
6. Economic and Probabilistic Risk Assessment
Analyzing Pertinent Characteristics of an SDS System

SDS System Characteristics
- **Type of Damage Sensing**
  - Direct / active, Passive, Indirect
- **SHM System Output**
  - Damage detection, localization, characterization
- **Coverage and Sensor Location**
  - Local, semi-global (sub-structure), or global
- **Measurement Type**
  - Eddy current, ultrasonic, vibration, pressure
- **Time of Data Acquisition (DAQ)**
  - During flight, select condition, on ground
- **Location of DAQ Hardware**
  - On the ground or onboard the aircraft

SDS Data Analysis
- **Data Classification Approach**
  - Human interpretation only (human factors)
  - Automated signal classification (software certification)

Structure Characteristics

Damage Characteristics

SDS Maintenance and Process Controls
- **System Maturity** (input data for assessment)
- **Secondary Inspections and Maintenance** (combined POD / False call assessment)
- **SHM Process Controls**
  - Maintain calibration, detect sensor failure
  - Redundant sensors systems coverage
- **SHM System Maintenance**
  - Repair scheduled or unanticipated
- **SHM Failure Modes Effects Analysis**

Impact (on ASIP)
- Criticality of the Damage State
- Credit Associated with SHM Application
  - e.g. increase in maintenance cycle
- Effect of Worst Case Occurrence
  (should SHM application fail)
Model Assisted Probability of Detection method

• Uses models to minimize the need for empirical samples, improve reliability

• Consensus protocol developed by international working group
  – Full model-assisted, transfer function based, hybrid
  – Meeting minutes and significant amount of stored data
    www.cnde.iastate.edu/MAPOD/

• Feasibility of approach demonstrated for eddy current inspection

• Project under contract (SBIR) to demonstrate feasibility for ultrasonic (TRI/Austin) and eddy current (Victor Technologies)

Demonstration Study –
Define SHM System

**SDS System Characteristics:**

- **Type:** Direct damage detection using active sensing
- **SHM System Output:** Damage detection call
- **Coverage and Sensor Location:** Semi-global (sub-structure)
- **Measurement Type:** Vibration (low frequency) response
- **Time of Data Acquisition (DAQ):** While aircraft is on the ground
  - Vary temperature (gradients), loading/unloading, boundary cond., fastener torques
- **Location of DAQ Hardware:** Onboard the aircraft

**Structure Characteristics:** Include joints in test article

- **Center joint with sites for simulating damage growth**
- **End conditions with optional shims (to change boundary)**

**Damage Characteristics:**

- **Damage Types (Failure Conditions) to Detect:** (Large) fatigue cracks
  - Approximate crack growth by cutting notches
  - Fastener removal necessary for growing flaw *(must maintain equal torque, verify damage metric change not due to changes in boundary conditions)*
Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

Parametric Study
- Frequency
- Source Excitation
  - location
  - orientation
  - distribution
- Sensor(s)
  - location
  - orientation
  - measurements
- Crack (notch) length
- Temperature
  (elastic property variation)
- Boundary conditions
  - Fastener stiffness
  - Fastener contact
  - End stiffness
- Detection algorithms / metrics
- Characterization algorithms / metrics

FRF

\[ K_{z1} = \infty \quad \text{(fixed)} \]

\[ K_{z2} = \infty \quad \text{(fixed)} \]

Sensor

 crack

\[ \lambda_1, \mu_1, \rho_1 \]

\[ \lambda_2, \mu_2, \rho_2 \]

\[ F(\omega) \]

\[ F \text{ on } -y \text{ side} \]

\[ \text{(1) fixed contact on } -z \text{ side} \]

\[ \text{(2) fixed contact on } -y \text{ side} \]

\[ \text{(3) fixed contact on } +x \text{ side} \]

\[ \text{(4) fixed contact on } +y \text{ side} \]

\[ \text{(5) fixed contact on } -x \text{ side} \]
Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

TOP: Modal response on top surface comparing case 1 (icur = 49: crack = 0 in, temp = 110F, E_fastener = 1*E_1, fc=1) and case 2 (icur = 54: crack = 4.9213 in, temp = 110F, E_fastener = 1*E_1, fc=1) for select frequencies.

FRF and Difference in FRF at 4 transducer positions
Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

Determine Output Variance on Damage Measures (POD) Given Uncontrolled Environmental Variables and Uncertainty

Input Parameters with Variation
- Temperature: (elastic property variation)
- Boundary condition: Fastener stiffness

Output Results
- Damage metric ‘distributions’ as a function of transducer location and crack length

Stochastic model (FEM model + Probabilistic Collocation Method)
Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

Determine Output Variance on Damage Measures (POD) Given Uncontrolled Environmental Variables and Uncertainty

**Input Parameters with Variation**
- Temperature: (elastic property variation)
- Boundary condition: Fastener stiffness

**Output Results**
- POD for varying transducer location and crack length

**Stochastic model**
(FEM model + Probabilistic Collocation Method)

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Input crack (direction of growth)
Demonstration Study – Identify and Evaluate Controlling Factors

Primary Protocol

Define SHM Application

Identify and Evaluate Controlling Factors

Design Multistage Validation Study

Perform Multistage Validation Study

Process Data for SHM Reliability Assessment

Economic and Probabilistic Risk Assessment

Sub-tasks

Evaluate Potential Contributing Factors (Part, Environment, Loading, SHM system)

Is Variability (Range) and Uncertainty (Confidence Bounds) of Factor Known?

Can Influence of the Factor be Evaluated Using Simulated and/or Experimentation?

Assess SHM System Sensitivity to Following Factors:

A. Loading and Unloading
B. Fastener Torque
C. End Condition Variation (Stress)
D. Temperature Variation and Temperature Gradients
E. Bond Quality and Sensor Performance
F. Ambient Noise (from Test Chamber on / off)
G. Sensitivity to Flaw Growth

Approaches

- Prior work
- Elicit expert opinion
- Baseline experiments
- Designed experiments
- Simulated studies
- Inverse methods
Evaluate Controlling Factors – Temperature Variation and Gradients

**Temperature Study:** Test article placed in Thermotron temperature chamber
- Temperature testing performed from \(-20^\circ\text{F}\) to \(150^\circ\text{F}\)
- Temperature compensation algorithms are necessary for damage metric
- Significant temperature gradients also observed during study
  - Some gradients considered extreme (>\(45^\circ\text{F}\)) due to end ‘thermal sinks’
  - Need to make estimate of expected gradients ‘in the field’ (10-20\(^\circ\text{F}\)?)

Thermocouple locations

![Thermocouple Locations](image)

**Temperature Response on Plate during Cooling and Heating**

**Peak Temperature Difference across Plate during Study**

![Temperature Response Graph](image)

![Peak Temperature Difference Graph](image)
Temperature Compensation Algorithm

**Issue 1:** Varying shift wrt frequency in FRFs with temperature changes

- **Fit nonlinear model** with bias and slope corrections:  
  \[ f_{\text{new}}(f) = f + \left( \frac{\phi}{1000 \text{ Hz}} \right) f + \phi_0 \]

**Issue 2:** Temperature variation also produces shape changes in FRFs

- **Use three references** (FRFs) addressing different temperature bands

**Study:** Vary Temperature - Up to 112°F, Down to 32°F, Return to 75°F

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Evaluate Controlling Factors – Bond Quality and Sensor Performance

Observations:

• Several accelerometer bonds failed during temperature testing
• Failure was observed at prolonged exposure to 150°F
• Coherence measures can be used to track sensor failure (example below)
  — Differences were observed with sensor ‘in partial contact’ and ‘in air’
• One of the sensor failures was the reference accelerometer (#1)
• Losing the reference sensor is especially detrimental to performance of vibration-based SDS system (FRF)
• SHM computer algorithms need to detect failures and schedule repairs
• Validation studies should include bond failure and repair as varying condition
Observations:

- Damage grown at 1/16" increments up to 0.688" at only one site to verify sensitivity (thin saw blades provided by NIAR)
- Simulated flaw growth (SFG) attempted to mimic forcing of plate structure without creating damage – *no significant effect on damage metric*
- Sensitivity observed to certain notch increases, but trend not linear
  - sensitive to first notch cut
  - significant drop after fastener installed and removed (FIR)
  - Metric grows with larger notches
- Jump observed after two week delay in testing – 'still in noise'
- Larger cuts will be applied for validation studies
Design of Validation Study

Demonstration Study:  Focused on Single Stage

- Phase II – Laboratory Testing of Relevant Structures / Environment
- Assumption: Key SDS Factors can be Demonstrated in Single Study

Factors in Study:

- Flaw growth (notch):
  - First cut: 0.063", Second to 0.125", repeat 0.125" cuts to 1.00" (10 levels)
  - At two fastener locations with relief notches
- Environmental conditions: (ambient 72°F)
  - Temperature variation (32°F to 112°F)
  - Temperature gradients (<10°F)
  - Ambient noise (chamber on / off)
- Boundary conditions:
  - Loading / unloading mass on structure (10 lb)
  - Fastener removal and reinstall (75 in-lbs +/- 10 in-lbs) – 'simulate maintenance'
- Sensor conditions: Evaluate accelerometer bond reinstallation (ref., second)
Measurement / POD Model

1) Model Flaw Length and Location:
   • Length: \( dm = \beta_0 + \beta_1 \cdot a_1 + \beta_2 \cdot a_1^2 + \beta_3 \cdot a_1^3 \)
   • Sensitivity to location must be addressed in model
     [Compare combined and separate measurement model fits]

2) Model for Secondary (Envir.) Variables:
   • Normalized mean temperature \((a_3)\), and absolute value \(|a_3|\)
   • Normalized temperature gradients \((a_4)\),
   • Abs. difference between temp. and nearest reference \((a_5)\)
   • Ambient noise level \((a_6)\),

3) Model Impact of Random Conditions (Change from Before vs. After):
   • Sensor failure*
   • Sensor bond degradation
   • Sensor replacement
   • Minor fastener loosening
   • Local maintenance action (fasteners uninstall/install)
   • Added mass
   • Structure load / unloading
   [Perform separate statistical tests for significance]
Measurement ‘Model’ and POD Evaluation Process

Input Parameters Types:
- Controlled Parameters, $a_j (N_j)$
  - Flaw size
  - Flaw location
  - Temperature Conditions
  - Ambient noise
- Uncontrolled Parameters, $a_k (N_k)$
  - Boundary conditions
  - Flaw morphology

Input Parameter Characteristics:
- Expected Variation Represented as a Distributions (ex. Gaussian, Uniform, Gamma, Beta)
- Uncertainty in Distribution Parameters (Not Addressed)

Level 1. Input Parameter Variability

Temperature (normalized)

Temperature Gradients (normalized, 10°F)
Measurement ‘Model’ and POD Evaluation Process

Fit Measurement ‘Model’ (Using Empirical Data)

- Flaw length \(a_1\): \[ dm = \beta_0 + \beta_1 a_1 + \beta_2 a_1^2 + \beta_3 a_1^3 \]
- Flaw location \(a_2\)
  - Evaluate both ‘combined’ and ‘separate’ flaw location scenarios fits
- Normalized mean temperature \(a_3\), and absolute value \(|a_3|\)
- Normalized temperature gradients \(a_4\),
- Abs. difference between temp. and nearest reference \(a_5\)
- Ambient noise level \(a_6\),
- Sensor status (active, failed)

Level 2: Uncertainty in Model Parameter Estimate

Regression Analysis Example (R)

```r
Code:
data.tmp <- read.csv('analy_ref1_flaw3.csv', header=FALSE)
x1 <- data.tmp$V1
x2 <- data.tmp$V2
x3 <- data.tmp$V3
x4 <- data.tmp$V4
x5 <- data.tmp$V5
x6 <- data.tmp$V6
x11 <- x1*x1
x111 <- x1*x11
y1 <- data.tmp$V14
frame1 <- data.frame(y=y1, x1=x1, x2=x2, x3=x3, x4=x4, x5=x5, x6=x6, x7=x11, x8=x111)
y.vs.x <- lm(formula = y ~ x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8, data=frame1)
summary(y.vs.x)
```

Call: lm(formula = y ~ x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8, data = frame1)

Residuals:
Min 1Q Median 3Q Max
-0.035835 -0.007133 0.001119 0.006437 0.026368

Coefficients:

| Estimate | Std. Error | t value | Pr(>|t|) |
|----------|------------|---------|----------|
| (Intercept) 0.018921 | 0.003902 | 4.849 | 6.8e-06 *** |
| x1 -0.081361 | 0.041766 | -1.948 | 0.05526 . |
| x2 -0.003323 | 0.003465 | -0.959 | 0.34072 |
| x3 0.010309 | 0.003690 | 2.794 | 0.00665 ** |
| x4 -0.009321 | 0.005813 | -1.603 | 0.11315 |
| x5 0.032816 | 0.010755 | 3.051 | 0.00318 ** |
| x6 0.005763 | 0.013645 | 0.422 | 0.67402 |
| x7 0.373822 | 0.109798 | 3.405 | 0.00108 ** |
| x8 -0.205131 | 0.072407 | -2.833 | 0.00596 ** |

Residual standard error: 0.01303 on 73 degrees of freedom
Multiple R-squared: 0.9133, Adjusted R-squared: 0.9037
F-statistic: 96.07 on 8 and 73 DF, p-value: < 2.2e-16

Significant Factors:
- x1 <- data.tmp$V1: Flaw size \(a_1\) (Part of flaw size model)
- x3 <- data.tmp$V3: Normalized mean temperature \(a_3\)
- x5 <- data.tmp$V5: Normalized temperature gradients \(a_4\)
- x7 <- x1*x1: Flaw size model term: \(a_1^2\)
- x8 <- x11 <- x1*x11: Flaw size model term: \(a_1^3\)
POD Evaluation Process:

- Apply threshold for call criteria ($d_m > 0.06$)
- Use second order probability analysis
  - Use two-level Monte Carlo simulation
  - Sample from Input Parameter Distributions (Level 1)
  - Perform Measurement Model Evaluation and Estimate Single POD Curve
  - Repeat Evaluation for Different Samples due to Uncertainty in Model Parameters (Level 2)
  - Obtain ‘Set’ of POD Curves (Uncertainty / Credibility Bounds on POD Curve)
- Probability of False Call corresponds with POD curve result at $a_1 = 0$. 
POD Results – Sensitivity to Flaw Location

POD Results: Dependency on Flaw Location

Can Improve POD by Choosing **Optimal Sensor Configuration**: 

Only use damage metric for accelerometer #6 (with reference #1)
POD Evaluation Must Address Known Sensor Durability Issues:

- Issue demonstrated by percent of C–17 in-service strain gauge failures as a function of time [Ware et al]
- Bathtub Curve Model [Meeker and Escobar]

Evaluation of Impact of Sensor Failure:

- Evaluate changes in POD due to random sensor failure over time
- Explore failure of two sensors (25%) over first six years of service life
- Distributions of Time to Failure Considered in Evaluation
POD Results –
Impact of Sensor Durability

• Sensor Scenarios with Corresponding Changes in POD and False Call Rate:

  **Approach 1: (Best Sensitivity)**
  - Use accel. #1 as reference
  - Use accel. #6 as source

  **Approach 2: (Accel.#6 Failure)**
  - Use accel. #1 as reference
  - Use median of active sensors

  **Approach 3: (Accel.#1 Failure)**
  - Use accel. #8 as reference
  - Use median of active sensors

  **Approach 4: (Accel.#8 Failure)**
  - Use accel. #3 as reference
  - Use median of active sensors
POD Results – Impact of Sensor Durability

Evaluation of Impact of Sensor Failure:
- Evaluate changes in POD due to random sensor failures over time
- Distributions of Time to Failure Considered in Evaluation

Results: Mean expected POD and POFC at a flaw size of 1.0 in as a function of time
Concluding Remarks

General SHM Validation:

• Draft protocol and demonstration complete
• Thorough factor evaluation is critical for quality assessment
• Uncertainty bounds in POD tied to measurement model quality

Global SHM Systems:

• Must ensure changes in SHM metric are truly damage growth
  — Include stochastic structural variation, time delays in study
• Feasible to evaluate impact of sensor failures on performance
  — Data is generally available, demonstration shown here
• Necessary validation steps can be resource intensive
  — Certain flaw locations may require separate POD models
  — Use model-assisted approach to cover all damage scenarios
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