Model Based Inference for Wire Chafe Diagnostics

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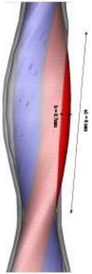
Agenda

1. Introduction & Motivation
   - Importance of Wiring Faults
   - Chafing Faults
2. Characterization of Chafing Damage
   - 3D Commercial EM Simulator
   - Experimental Methods
   - Fault Library
3. Model Based Inference
   - Bayesian Framework
   - Chafe Model



Recent EWIS Incidents

February 2009 A fire breaks out on-board an A340 Virgin Atlantic flight en route from Heathrow to Chicago, which could not be extinguished until after the plane landed and depowered. Investigators later discovered problems with the electrical wiring in a bar unit of the plane that was specifically adapted for the airline.

January 2008 American Airlines B757 Flight 1738 experienced smoking in the cockpit caused by arcing within the windshield heat system resulting in the cockpit windshield shattering during the emergency landing.

Chafing is a dominant EWIS failure mechanism

- A frequently occurring type of wiring fault
  - FAA reports 55% in one study†
  - Navy reports 37% in another study†
- Precursors to more significant problems:
  - open and short circuits (cause instrument failure)
  - arcing (causes smoking, fires, or worse!)

† *See K. Wheeler et. al., "Aging Aircraft Wiring Fault Detection Survey" for an overview of these studies and more*

Detection of Chafing Damage

- Efforts in hardware development for chafe detection have been reported, however, little attention has been focused on detectability and uncertainty
- Initial investigations on detectability suggest that chafing on unshielded (*e.g.*, power cables) wires is difficult if not impossible to detect†
- Shielded wire (*e.g.*, high-speed communication cables), however, may generate a detectable signature.

† *"The Invisible Fray: A Critical Analysis of the Use of Reflectometry for Fray Location," Griffiths et al., IEEE Sensors Journal, vol. 6, no. 3, June 2006.*

Chafing in Shielded Electrical Cabling

- Chafe first ablates outer insulation, then shield, leaving inner conductors intact

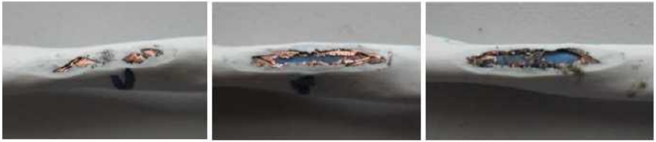
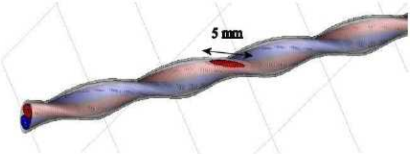


Figure: Chafe progression: 2k, 4k, and 8k cycles beyond short

- Time domain reflectometry (TDR) between active conductors and the shield is proposed for chafe detection

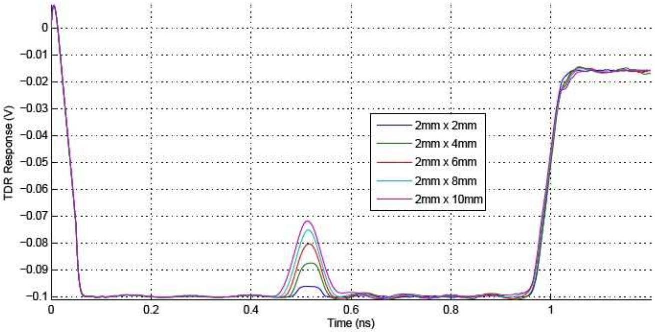
3D Commercial Electromagnetic Simulator

- Computer Simulation Technology (CST)'s Microwave Studio is used
- Wire Types:
  - Coaxial Cable
  - Twisted Shielded Pair
- Fault Types:
  - Rectangular
  - Elliptical (pictured)
  - Multiple Faults



3D Commercial EM Simulator: Representative Data

- Response of twisted shielded pair (TSP) to TDR interrogation



Experimental Methods for Chafe Characterization

- There are two fundamental modes of chafing damage
  - Wire movement versus stationary object (*e.g.*, wire rubbing on a bulkhead)
  - Wire movement versus wire movement (*e.g.*, wires in a bundle abrating each other)
- Two machines have been developed to mimic these damage mechanisms
  - Stationary rod abrasion machine
  - Wire-on-wire abrasion machine

Stationary Rod Abrasion Machine

Specifications	Range	Optimal Setting
Stroke Length	1 - 3 cm	1 cm
Stroke Frequency	1-100 Hz	10 Hz

- 200g mass used to pressure wire against diamond coated chafing rod
- Average chafe to inner conductor time for TSP is $\sim 12k$ cycles

Wire-on-Wire Abrasion Machine†

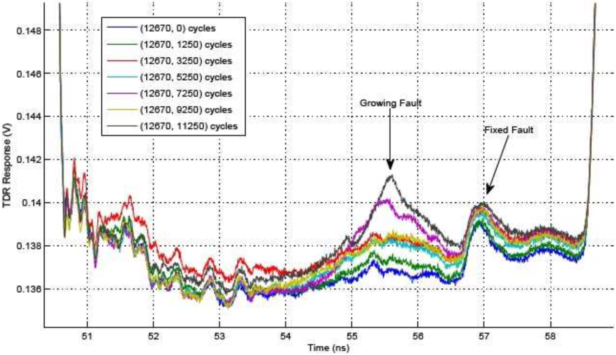
Specifications	Range	Optimal Setting
Stroke Length	1 cm	1 cm
Stroke Frequency	1-20 Hz	10 Hz

- 500g mass used to pressure wire against diamond coated chafing rod
- Average chafe to inner conductor time for TSP is $\sim 25k$ cycles

† *Thanks to AFRL for the design*

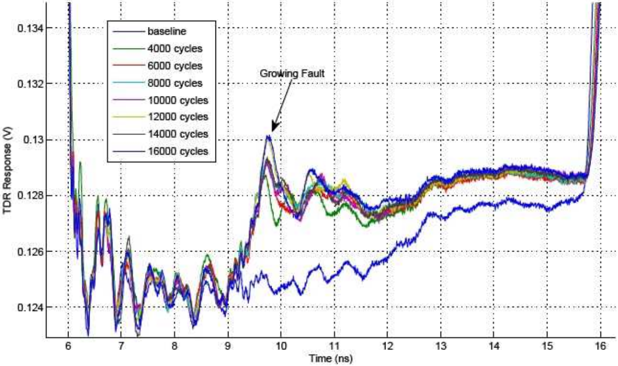
Rod Abrasion Machine: Representative Data

- Two fault example, one fault fixed and the other growing in size



Wire-on-Wire Abrasion Machine: Representative Data

- Growing braid on wire TDR data set



Overview of Fault Library

- Contains TDR response signals from both simulations and lab experiments
  - Formatted in ASCII and Matlab binary files (.mat)
  - Simulated data was collected by growing fault length and simulating the TDR response
  - Experimental data was collected by growing faults under controlled chafing conditions and measuring the TDR response

Library Available Online:

http://ti.arc.nasa.gov/project/wiring/

Why Use Probability Theory for Wire Fault Detection?

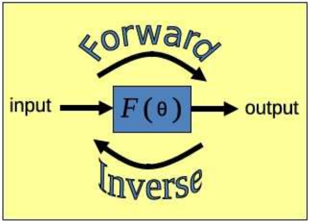
- Want to infer variables of interest from noisy reflected electrical signals:
  - fault location(s)
  - fault size(s)
- Want to automatically cope with sources of uncertainty:
  - electrical noise from equipment and environment
  - unknown or uncertain cable parameters (*e.g.*, dielectric permittivity, finite conductivity)
  - geometric distortions (*e.g.*, bends, wiggles)
  - other reflection sources (*e.g.*, splices)
  - unknown number of faults all mixing together
- Specifically, the *Bayesian* approach provides a systematic approach to incorporating these effects and more...

Benefits to the Bayesian Approach

- Clearly represents uncertainty inherent within measurements
- Includes uncertainty in known prior information or expertise
  - *e.g.*,"known"' values, such as permittivity of wire insulation, are often better represented as random variables known only to a certain accuracy
- Quantifies the uncertainty in the inferred parameters
- Avoids taking direct inverse in finding optimal model parameters by seeking the estimate that maximizes the probability of the observed information

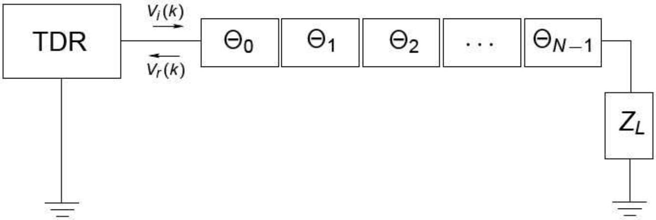
Conducting Research in two areas:

- Forward model development:
  - LTI Convolution Models
  - Analytical models
  - Behavioral models (how things change)



- Optimization Techniques to retrieve parameters (find most likely parameters that explain the observed input and output).
  - Convex Optimization & Expectation Maximization
  - Markov Chain Monte-Carlo (MCMC)
  - Reversible Jump MCMC

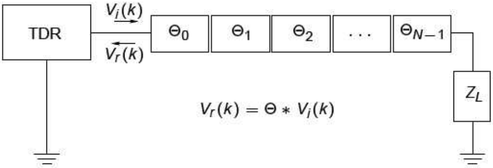
Example: LTI System Model



$$V_r(k) = \Theta_0 V_i(k) + \Theta_1 V_i(k-1) + \ldots + \Theta_{N-1} V_i(k-N+1)$$

- The reflection coefficients Θ_k and input $V_i(k)$ are given
- Motivated through physics by assuming the line is lossless and linear time invariant (LTI)

Example LTI System Model



$$V_r(k) = \Theta * V_i(k)$$

- $\Theta \in \mathbf{R}^N$ is the variable we want to estimate
- $F(\Theta) = \Theta * V_i = H\Theta$ represents our model
  - $H \in \mathbf{R}^{N \times N}$, is a convolution matrix
- $y = F(\Theta) + \nu$, where $\nu \in \mathbf{R}^N$ is Gaussian noise
- Prior information is that Θ is sparse, since chafing damage is small and localized

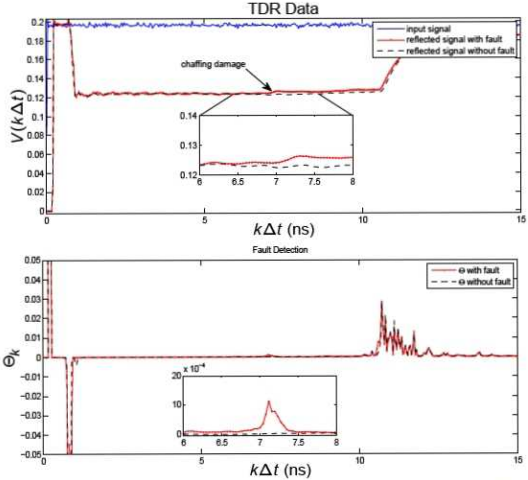
- Likelihood: $\mathbf{Prob}(y|F,\Theta) \propto e^{-\frac{1}{2\sigma^2}\|F(\Theta)-y\|^2}$
- Prior: $\mathbf{Prob}(\Theta|F) \propto e^{-\sum_{k=0}^{N-1}\lambda_k|\Theta_k|}$
  - A heuristic for prior information that Θ is sparse
- Solve: $\text{maximize}\;\; \mathbf{Prob}(\Theta|F,y) \propto \mathbf{Prob}(y|F,\Theta)\,\mathbf{Prob}(\Theta|F)$, which is equivalent to,

$$\text{minimize}\;\; \frac{1}{2\sigma^2}\|F(\Theta)-y\|^2 + \sum_{k=0}^{N-1}\lambda_k|\Theta_k| \tag{1}$$

- For fixed λ_k, (1) is a convex optimization problem, and thus solvable *globally* and efficiently, even for large N.
- The Expectation Maximization algorithm can be used to automatically find the best “tuning” parameters λ_k.

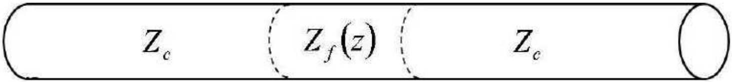
Example LTI Convolution Model Estimation Result

- $N = 1024$, $\Delta t = 0.04$ ns



Mathematical Predictive Chafe Model: Impedance Layering

- Assume that chafe can be thought of as one or a series of impedance disturbances
- Once impedance of fault is known, it is relatively straightforward to find the response of the cable in frequency or time domains



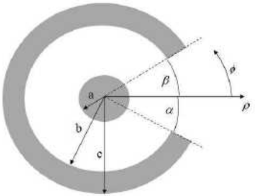
Computing Capacitance and Inductance

- Capacitance:

$$
\begin{aligned}
\nabla \cdot \epsilon \nabla \phi &= 0 \\
Q_l &= \iint \nabla \cdot D \, ds \\
&= \oint -\epsilon \nabla \phi \cdot (n \times z) \, dl
\end{aligned}
$$

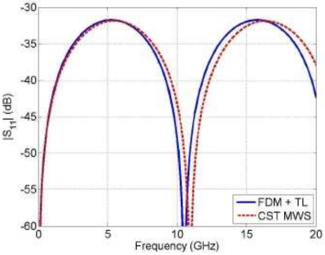
- Inductance:

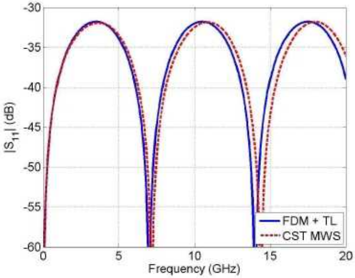
$$L_l = \frac{\mu_0 \epsilon}{C_l}$$



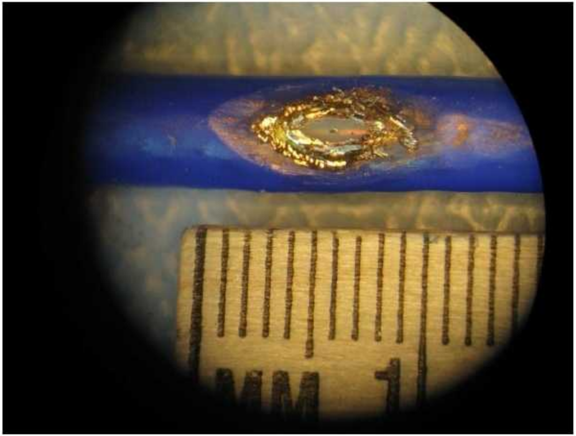
Frequency Domain Verification : Comparison with CST MWS

- Predicted Return Loss from a 2 × 10 mm chafe (left) and a 2 × 15 mm chafe (right) in coaxial cable.

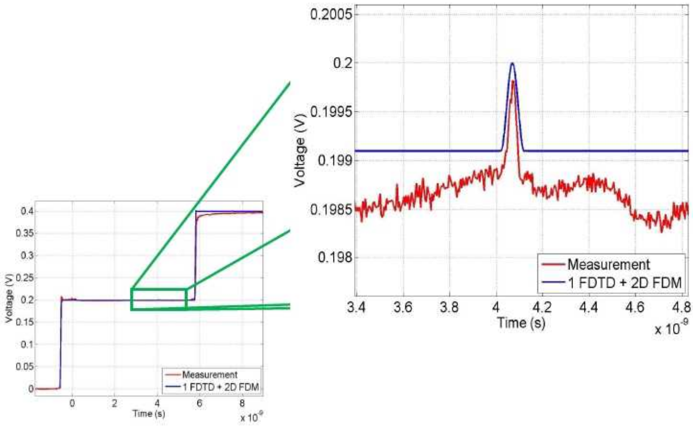




Experimental Verification: Chafe in Coaxial Cable



Experimental Verification: Comparison to Lab TDR



Conclusions

- Machines – Developed two chafing machines used to mimic effect of chafing on cables.
- Datasets – Development of publicly accessible electrical signature fault datasets.
- Algorithms:
  - Development of probabilistic Bayesian algorithms for understanding and characterizing electrical signatures of faults
  - Development of compact and efficient electromagnetics based forward models for chafe signature

Future Work

- Incorporation of forward models within a Bayesian framework is underway
- “Real-life” experimental platforms (NASA wind tunnel and vertical motion simulator) are being used
- Live communication cable interrogation (CAN bus) is being modeled and contemplated as representative platform.

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