Understanding Wire Chafing: Model Development and Optimal Diagnostics Using TDR

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   - Chafing Faults
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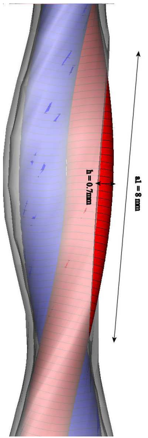


Wiring, what's the big deal?

- Wiring problems most likely led to the TWA 800 (1996) and Swissair 111 (1998) tragedies
- On average 3 fire and smoke events occur each day on jet transport aircraft in the US and Canada (1999)
- Recently, American Airlines Flight 1738 experienced smoking in the cockpit (January 2008)
  - official cause was arcing within the windshield heat system
  - cockpit windshield shattered during the emergency landing
  - no injuries

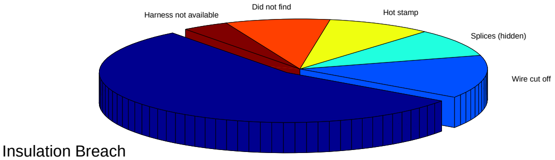
Chafing Fault Definition

Localized damage to the insulation and shielding of a wire.

- Typically caused by wires rubbing against each other or their fixtures over long periods of time
- Becoming an increasing problem in aging aircraft

Why chafing faults?

- A frequently occurring type of wiring fault
- Precursors to more significant problems:
  - open and short circuits (cause instrument failure)
  - arcing (causes smoking, fires, or worse!)
- Successful detection of these faults would allow us to:
  - identify fault's location and severity
  - track fault progression and estimate remaining useful life



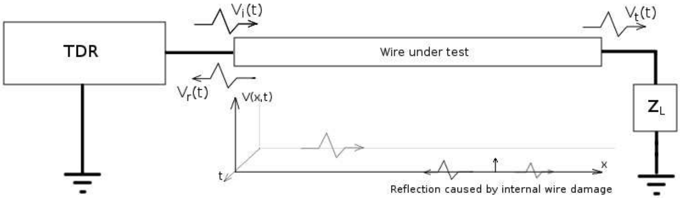
FAA Wiring Fault Survey Results

Detecting chafing faults

- Time Domain Reflectometry is an industry standard method.

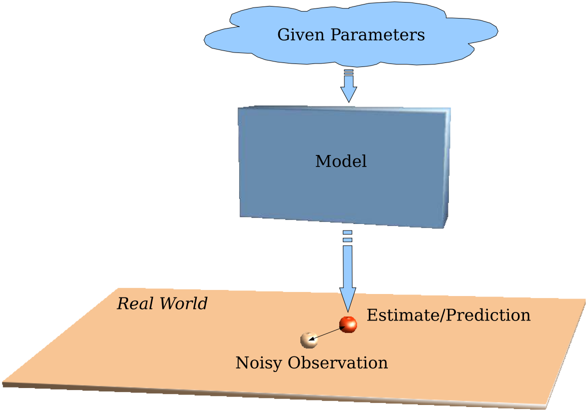
Main idea:

Ping wire with an input pulse and see what comes back.



Forward Model

A way to deduce the observations from given parameters.



Physics Based Modeling

- Given the parameters:
  - input signal
  - cable dimensions and materials
  - fault size and location
- The model estimates the signal reflected by the wire
- Estimates are derived from Maxwell's Equations using:
  - numerical methods and minimal assumptions
  - simplified but effective closed form solutions

Numerical PDE Solver

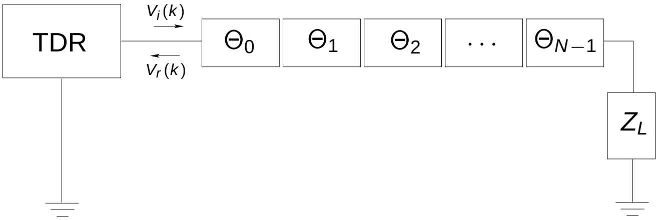
Parameters

$$\nabla \cdot D = \rho \qquad \nabla \times E = j\omega B$$

$$\nabla \cdot B = 0 \qquad \nabla \times H = J - j\omega D$$

TDR Response

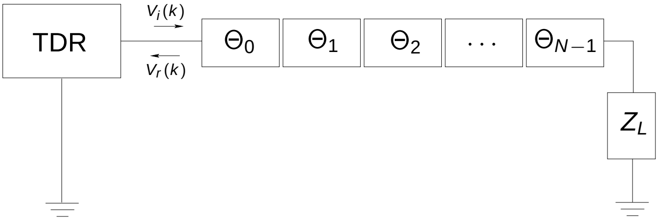
Example: LTI Model



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

- 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 Model



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

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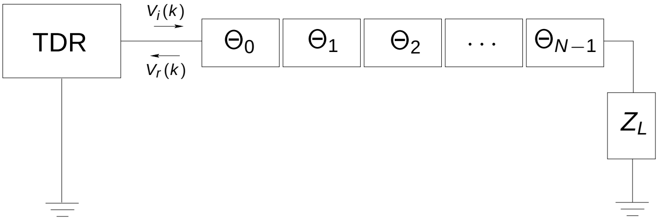
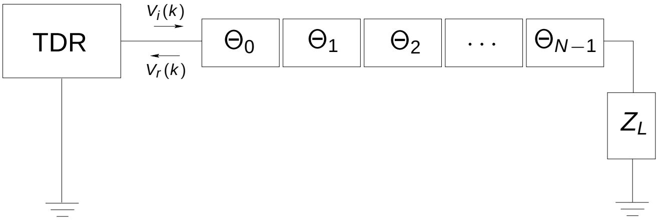
Example: LTI Model



$$V_r(k) = 0V_i(k) + 0V_i(k-1) + \ldots + 0V_i(k-N+1) = 0$$

- 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 Model



$$V_r(k) = 0V_i(k) + 0.1V_i(k-1) + \ldots + 0V_i(k-N+1) = 0.1V_i(k-1)$$

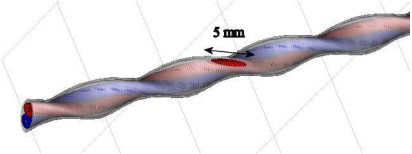
- The reflection coefficients Θ_k and input $V_i(k)$ are given
- Motivated through physics by assuming the line is lossless and linear time invariant (LTI)

Model Verification Approach

- Compare with simulated results obtained by solving Maxwell's equations
  - This is the best of all models we have
  - Further simplifications can not perform better
- Collect data from repeatable laboratory experiments with controlled parameters

Simulation

- Create a computerized 3D model of the wire under test
  - define material types and cable dimensions
  - define fault location and size
- Numerically solve Maxwell's equations to come up with the TDR response
  - comparison with lab results reveals best model performance
- All done using CST Microwave Studio, a commercially available computational electromagnetics (EM) package.

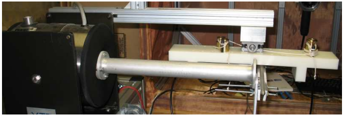


Experimental Data Collection

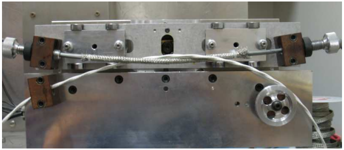
- Focus on twisted shielded pair wire type
- Measure TDR response of undamaged cable
- Use an abrasive apparatus to chafe a small section of the wire for a set period of time (or number of cycles)
- Measure TDR response of the chafed wire

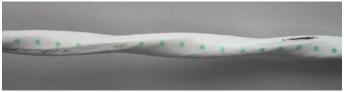
Figure: chafe to short, 4k, and 8k cycles beyond short

Abrasion Chafing



Wire on Wire Chafing

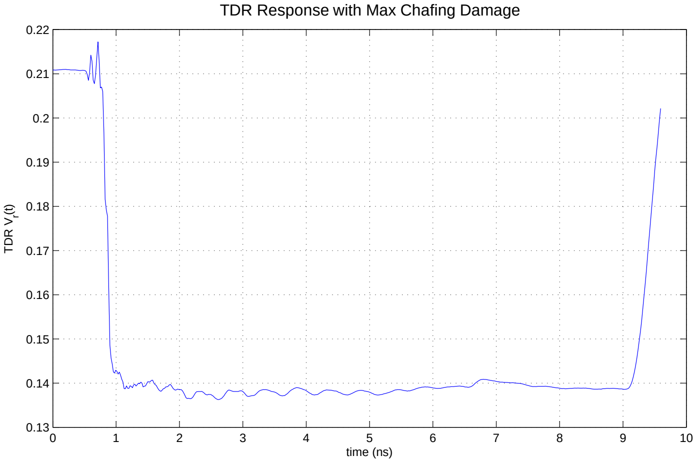




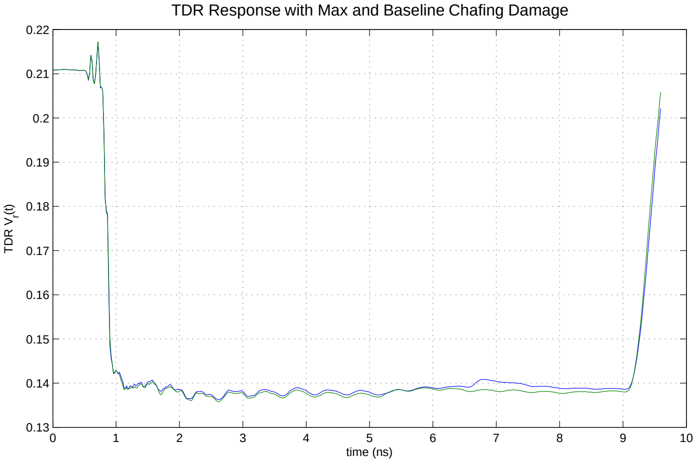
All data sets are publicly available at:

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

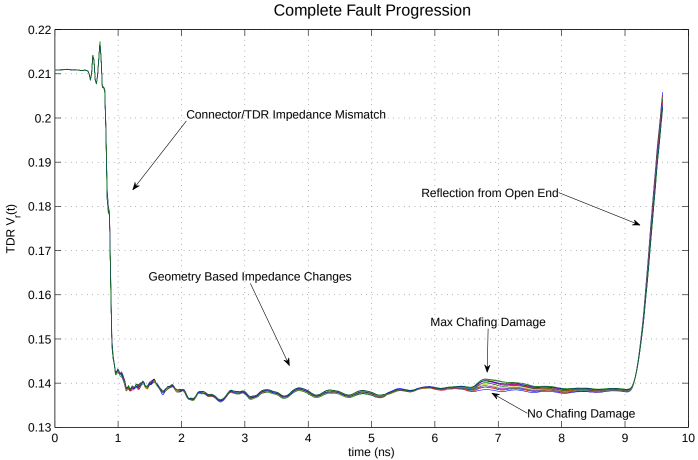
Experimental Fault Progression



Experimental Fault Progression

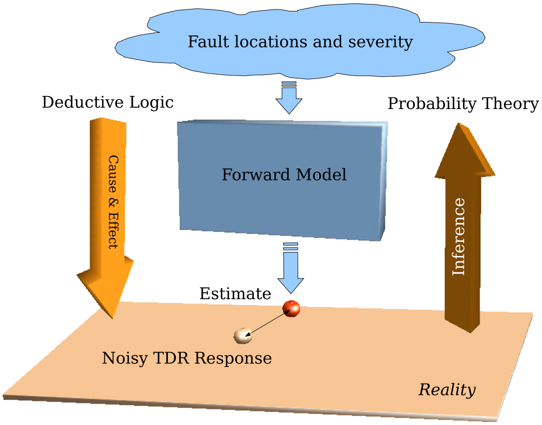


Experimental Fault Progression

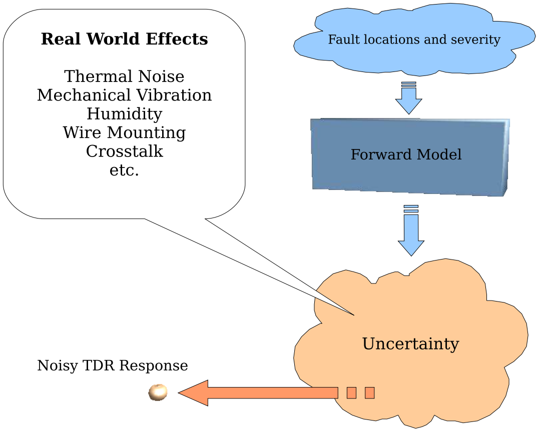


The Real Problem

Given the reflected TDR signal, estimate fault locations and severities.



Sources of Uncertainty



Optimal Fault Detection

- Let,
  - Θ represent fault locations and severities
  - y represent our observed TDR response measurement
  - $F(\Theta)$ represent the deductive forward model
- We want to find Θ that solves:

$$\begin{array}{ll} \text{maximize} & \textbf{Prob}(\Theta | F, y) \\ \text{subject to} & \text{constraints} \end{array} \tag{1}$$

- Provides the most likely fault locations given the observed signal and accepted model
- More importantly, $\textbf{Prob}(\Theta | F, y)$ characterizes estimation certainty

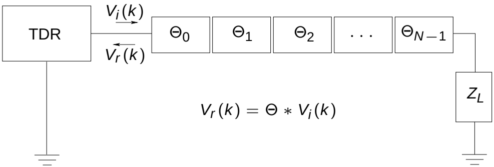
Just one problem left ...

- How do we get $\textbf{Prob}(\Theta|F,y)$?
- Use Bayes Rule:

$$\underbrace{\textbf{Prob}(\Theta|F,y)}_{\text{posterior}} \propto \underbrace{\textbf{Prob}(y|F,\Theta)}_{\text{likelihood}} \underbrace{\textbf{Prob}(\Theta|F)}_{\text{prior}} \tag{2}$$

- Terms on the right are found as follows:
  - $\textbf{Prob}(y|F,\Theta)$ follows from deductive logic (since Θ is given) and specification of the measurement noise process
  - $\textbf{Prob}(\Theta|F)$ represents our prior knowledge of Θ

Example Using the LTI Model



- $\Theta \in \mathbf{R}^N$ 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

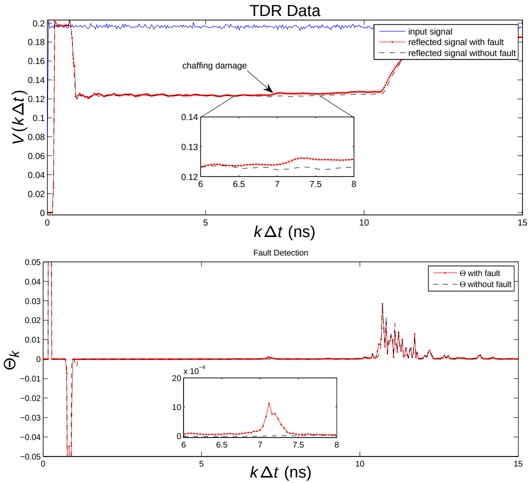
- Likelihood: $\textbf{Prob}(y|F,\Theta) \propto e^{-\frac{1}{2\sigma^2}\|F(\Theta)-y\|^2}$
- Prior: $\textbf{Prob}(\Theta|F) \propto e^{-\lambda \sum_{k=0}^{N-1} |\Theta_k|}$
  - A heuristic for prior information that Θ is sparse
- Solve: maximize $\textbf{Prob}(\Theta|F,y) \propto \textbf{Prob}(y|F,\Theta)\,\textbf{Prob}(\Theta|F)$,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

$$\text{minimize} \;\; \frac{1}{2\sigma^2}\|F(\Theta)-y\|^2 + \lambda \sum_{k=0}^{N-1} |\Theta_k| \tag{3}$$

  - Since $F(\Theta) = H\Theta$ is a linear function, (3) is a convex optimization problem
  - Can be solved globally and efficiently for large N
  - None of this is obvious and depends on missing details

Example estimation result

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



Accomplishments

- Developed a simulation and experiment based fault library
- Set foundation for modeling and optimal fault detection

Future Goals

- Understand electromagnetic effects of wiring damage
- Provide testing and requirements guidance
- Quantitatively assess real-world effects

Characterize our ability to find and diagnose chafing faults.

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