Health management for wire insulator integrity

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***Abstract*—A model-based approach for the definition of requirements for detecting progressive failures in wire insulation integrity is presented. The model-based approach combines theoretical models, numerical simulation and experimental data to demonstrate advanced data interpretation from common diagnostic hardware. Our approach is applied to wire chafing problems observed within the aviation industry. This approach is used to demonstrate the detection of changing impedance and erosion of shielding due to common chafing causes in twisted-pair wire geometry prior to any possible shorting or open condition in the conductors. Results are encouraging for finding flaws in shielding prior to any disruptive damage to the inner conductors.**

***Index Terms*—Transmission line theory, fault diagnosis, time domain reflectometry, distributed parameter circuits.**

I. Introduction

The application of non-uniform transmission line theory is presented for developing a model-based health management system for assessing chafing in avionics wire harnesses. The model theory, experimental laboratory work and validating numerical simulations are discussed. Published maintenance statistics from the Federal Aviation Administration (F.A.A.), the U.S. Coast Guard (U.S.C.G.) and the U.S. Naval Air Systems Command (NAVAIR) along with a desire to prevent potentially hazardous and costly problems motivates the need to detect and categorize wire chaffing damage before system failure occurs. The research presented is sponsored by NASA's Aviation Safety Program as part of the Aging Aircraft and Durability Project.

The F.A.A., the U.S.C.G. and NAVAIR have separately analyzed maintenance data to determine the most frequently occurring problems in the Electrical and Wiring Interconnect System (E.W.I.S.) within their respective air fleets. Since the F.A.A. does not operate a large fleet of aircraft, they performed tear-downs of retired aircraft and extensive analyses of the wiring systems were conducted [1]. Both NAVAIR and the Coast Guard have technicians record error codes representative of the problem being worked. Although operating environments and vehicle types differ significantly between the three agencies, nonetheless all three report similar E.W.I.S. failure statistics.

NAVAIR reports [2] that 37% of all reported E.W.I.S. problems are related to wire chafing. Another 18% are classified as unspecified short. The Coast Guard, which operates helicopters over the ocean and therefore has a higher percentage of corrosion issues than any other agency, reports that 20% of the recorded maintenance cases had wires cut or broken, another 19% had the connector damaged or broken, and another 19% were chafed wires [3]. It is important to note that most of these cases resulted in unscheduled maintenance. Secondly, the incidence of wire and connector problems is typically under-reported. This phenomenon of under-reporting is a consequence of wiring not being seen as a system but rather a thing that connects two or more systems together. Therefore when there is a system malfunction, and unless broken wires are visibly obvious, a line replaceable unit (L.R.U.) or other sub-system is the first target in maintenance operations.

The F.A.A. used a coarser categorization of faults during the teardown inspections. This resulted in 55% of the E.W.I.S. cases being labeled breach in insulation and 14% in cut wires. Each agency used their own maintenance reporting codes of varying degrees of fidelity. Efforts are under way by NAVAIR and the Coast Guard to create finer reporting codes and as well as to better train technicians so that higher fidelity in maintenance records can be achieved.

Even though each agency has examined different fleets with different training practices and error reporting codes, it is clear that the majority of E.W.I.S. problems result from chafed or broken wiring and failing connectors.

The principle means for a technician to discover the location of a broken or shorted wire is through the use of Time-domain Reflectometry (T.D.R.) test equipment. T.D.R. works by applying a voltage step at one end of a wire/harness under investigation. The voltage pulse travels down the wire, and if the wire is broken, then a positive voltage step is reflected back to the transmitting test equipment. If a wire is shorted, then a negative voltage step is reflected back to the test equipment. The length of time that it takes the reflected pulse to travel back indicates, relative to the velocity of

Manuscript received April, 2008. This work was supported in part by NASA's Aircraft Aging and Durability Project within the Aviation Safety Program.

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propagation along the wire, the distance of the fault relative to the test equipment.

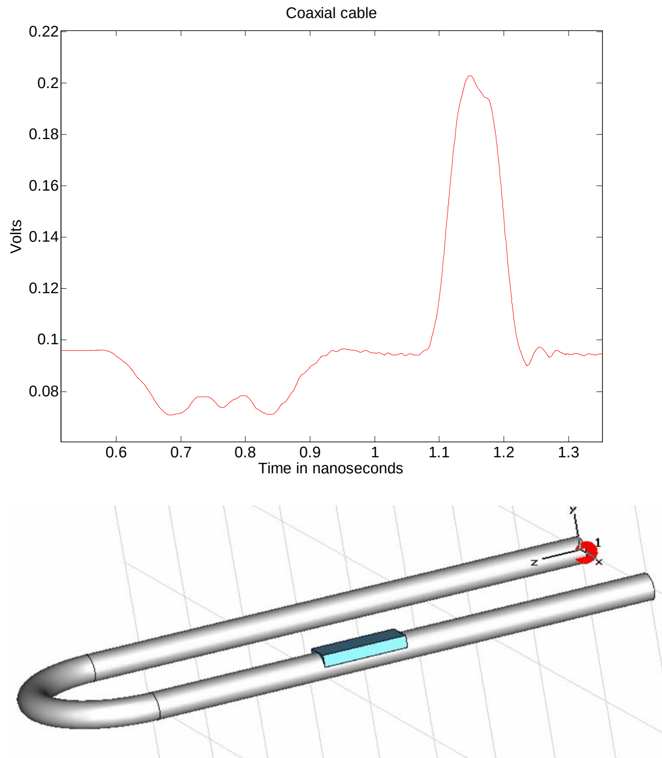

Fig. 1. Bottom: Coaxial cable with a five cm bend radius and a one cm chafe fault located at the rectangle (shield and dielectric between shield an inner conductor removed). Top: T.D.R. signal corresponding to this cable. Large peak is reflection due to chafe.

Although this description is simple, often the plots of the reflections are very messy and difficult to interpret. This has been one of the biggest challenges in getting T.D.R. accepted within the aviation maintenance community. It is much more common to find T.D.R. based maintenance techniques used within the telecommunications industry due to the nature of high-bandwidth wiring found within these systems.

There have been many hardware developments related to T.D.R. for testing avionic E.W.I.S. Currently there are several hand-held T.D.R. test units available over the counter, such as 3M's 900AST which is specifically designed for the aviation industry. Several small businesses have been funded by various government agencies to develop hardware capable of more reliable cable interrogation. Although these companies are progressing nicely towards developing hardware, there is still considerable effort required in developing software to infer fault types and locations. In particular, it is still not possible, even with "bleeding edge" hardware and software, to reliably and accurately assess the state of chafing along a length of wire prior to a short or open condition.

This software gap exists primarily because there has not been sufficient effort devoted to developing proper model-based methods for inferring the impedance (or respective permittivity and permeability) profile continuously along a length of wire. This paper presents our attempts towards model-based wire integrity research from a requirements definition perspective with respect to chafing faults.

This paper is organized as follows: Section II discusses the theory and goals behind our work including an example of why fault detection can be difficult with T.D.R.. This is followed by an explanation of the compact Green's functions used in this paper. Section III discusses the experiments and simulations used to investigate the theory presented. Finally, the results of the experiments and simulations are presented in Section IV.

II. Theory - Non-uniform Transmission Lines

A. *Goals*

The non-uniform transmission line theory presented here is based entirely upon [4]. The goals behind the adopting non-uniform transmission line theory for assessing wire insulator chafing are:

1. Assess the depth(s) and location(s) of any chafing faults continuously along the length of the wire.
2. Assess the integrity of the shielding prior to developing a fault in the inner insulated conductors.
3. Validate performance using known conditions with simulated data and laboratory experiments.

In addition, the requirements for signal measurements on a non-uniform transmission line are:

1. Measurements are only available at the ends of the harness. These measurements will be known as V_t - the transmitted voltage, and V_r - the reflected voltage.
2. V_i - the incident voltage waveform is induced at the end of the cable where the reflections are measured.

B. *Why is TDR interpretation hard?*

Conceptually T.D.R. is simple enough, so why is it difficult, in practice, to assess the state of wiring when given a representative T.D.R. plot? Two common and seemingly simple wire configurations will serve as illustrative examples of the hidden complexity in interpreting T.D.R. plots. First, examine a T.D.R. signal for a coaxial cable with a smooth nominal bend in Figure 1. The magnitude of the reflection due to the bend is 26 mV whereas the magnitude of the reflection due to complete insulation removal (at the rectangle) is 109 mV. Clearly, a fault is distinguishable from a bend in this instance. Next, examine a power cable and its associated T.D.R. in Figure 2. In this figure the magnitude of the reflection due to the bend is 9.6 mV and the magnitude of reflection due to the chafe fault is 6.5 mV. A bend in the wire is a worse "fault" than the chafe. In this example a technician needs to know the exact geometry and routing of a harness before being able to interpret the T.D.R. result, a virtual impossibility in any real-world setting.

The primary difference between the two T.D.R. examples is the presence of shielding surrounding the coaxial cable. Shielding on the wire(s) has a positive impact on the ability to detect faults, providing higher amplitude reflections than the unshielded equivalents and affording a greater likelihood of detection. In addition, it is highly desirable in practice to detect chafing when it occurs only within the shielding *before any damage has occurred to the insulation of the inner conductors.* This approach thus minimizes the chance of a short or open condition developing prior to detection and subsequent replacement of the damaged wire harness.

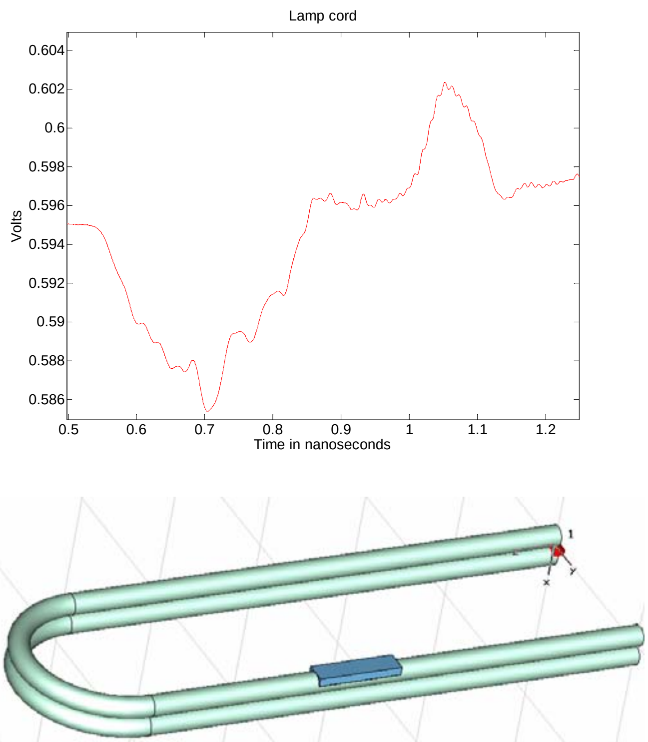

Fig. 2. Bottom: Geometric model of power cable with 1 cm complete chafe fault after 5 cm bend radius. Top: T.D.R. for this cable.

C. *Compact Green's functions*

The non-uniform transmission line theory presented in [4] begins, as is standard in general transmission line theory, by splitting the traveling voltage waves into forward and backward moving components:

$$V(x,t) = V^{+}(x,t) + V^{-}(x,t) \tag{1}$$

Then making the assumption that the transmission line is time-invariant, causal, and linear we can express the split voltages as follows:

$$V^{+}(x, t+\tau(0,x)) = a^{+}(x)V^{t}(t) + G^{c+}(x,t) * V^{t}(t) \tag{2}$$

$$V^{-}(x, t+\tau(0,x)) = a^{-}(x)V^{t}(t-2\tau(x,l)) + G^{c-}(x,t) * V^{t}(t) \tag{3}$$

where,

$$\tau(x_1, x_2) = \int_{x_1}^{x_2} \frac{dx'}{c(x')}$$

represents the time it would take the wave to travel from location x_1 to location x_2 with non-uniform propagation velocity given by $c(x)$ see [4].

The functions $G^{c\pm}(x,t)$ are known as the compact Greens functions for the non-uniform transmission line. From equations (2) and (3) we notice that, along with the direct attenuation terms $a^{\pm}(x)$, the compact Greens functions relate the observed transmitted voltage to the forward and backwards moving voltage waves $V^{\pm}(x,t)$ any where on the line. In particular, the incident and reflected voltage waves are represented as follows:

$$V^{i}(t) = a^{+}(0)V^{t}(t) + G^{c+}(0,t) * V^{t}(t) \tag{4}$$

$$V^{r}(t) = a^{-}(0)V^{t}(t-2\tau(0,l)) + G^{c-}(0,t) * V^{t}(t) \tag{5}$$

There always exists a mapping between the standard distributed transmission line parameters (impedance Z(x), propagation velocity c(x), resistance R(x) and shunt conductance G(x)) and the model parameters: the right and left compact Green's functions $G^{c\pm}(x,t)$ and the direct attenuation functions $a^{\pm}(x)$.

$$\{Z(x), c(x), R(x), G(x)\} \Leftrightarrow \{G^{c+}(x,t), G^{c-}(x,t), a^{+}(x), a^{-}(x)\} \tag{6}$$

However, in practice one applies a known incident voltage stimulus, and then measures the reflected and transmitted voltages. An *inverse mapping* is needed to relate the applied incident voltage and measured outputs to the model parameters. This mapping is expressed as:

$$\{G^{c+}(x,t), G^{c-}(x,t), a^{+}(x), a^{-}(x), c(x)\} \Leftrightarrow \{V^{i}(t), V^{r}(t), V^{t}(t)\} \tag{7}$$

The process of performing the *inverse mapping* is known by many names including parameter retrieval, model inversion and parameter inference.
More generally, the inverse mapping also involves many unmentioned random variables that need to be retrieved simultaneously along with the desired model parameters. In addition, because many of the variables are considered random quantities (such as variation in insulation thickness, wiggles in geometry) this is a stochastic inversion problem and so we advocate using a Bayesian model inversion technique.

III. Experimental Approach

A. Chafing Apparatus

In order to understand how to approach artificially inducing chafe spots in wiring within the laboratory environment, it is necessary to identify the sources of chafing on-board an aircraft. Chafing typically occurs because proper maintenance practices were not followed. Although the manners of chafing are numerous, a few typical cases are listed in the following categories:

- wire insulation rubs against metal such as edges on a rack, screw points or hydraulic lines
- wire insulation rubs against another harness, which might have rough over-braid
- wire/insulation is pinched for example in a hatch or bound too tightly by a clamp
- wire insulation is impacted by or rubs sharp plastic edges, as might be found on cut-off plastic tie-wraps.

The Society of Automotive Engineers (S.A.E.) is responsible for maintaining and developing standards for electrical systems used in avionics. Standardized methods for wire testing are included in this [5]. There are a couple of well established standards for testing the abrasion resistance of wire but unfortunately these are not representative of real-world chafing conditions. A new standard for wire-on-wire abrasion is currently under development (primarily within the Air Force) designed to standardize the effects of over-braid abrasion on insulated wire. Most of the standards work on abrasion is focused upon measuring the number of “rubbing” cycles necessary to expose a conductor. In the study described here, we are interested in how the T.D.R. signal changes as a function of the depth of chafing into the shielding. Because of this distinction, an alternative chafing setup was designed and used within our laboratory as shown in Figure 3.

Our chafing mechanism employs a 600 grit diamond impregnated steel rod as shown in Figure 3. The wire under test is held within a plastic fixture on a pivot mount with weights so that a constant force is exerted by the wire onto the abrasive rod. The rod is moved forward and back at 10 Hz. with a stroke length of 1 cm. A D.C. voltage of 5 volts is sent through the abrasive rod and the continuity to the shielding is continuously checked.

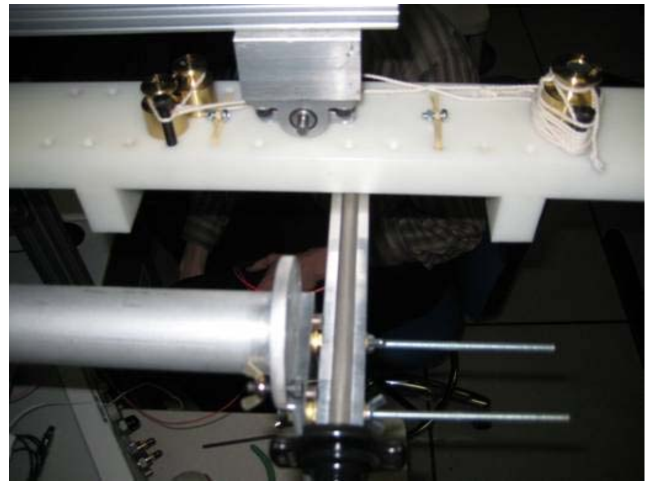

Fig. 3. Chafing apparatus consisting of a 600 grit diamond impregnated steel rod attached to a vibrating arm. Wire under test (not visible) is mounted beneath the white plastic with brass weights on top and a pivot in the center.

B. Laboratory Experiments

The wire under test is shielded twisted pair from A.E. Petsche Co. (BMS13-48, Type 24, Class 2, 2 conductor shielded). This type of wire is typical in hydraulic sensing applications. The exterior insulation on the wire has a permittivity around 2 which is really not that different from the permittivity of air (1.0). Because of this, we are not interested in trying to measure scrapes of the exterior insulation but rather we are interested when chafing starts to create holes in the shielding.

The process that we followed was to first prepare the wires by chafing them just to the point when a 5v DC can be detected conducting to the shield. This level of chafing is sometimes barely perceptible by eye, as shown in Figure 5.

All results are reported in number of chafing cycles beyond this initial shield exposure point, where one chafing cycle is defined as a forward and backward stroke of the abrasive rod along a wire. The number of cycles investigated ranged in discrete increments: 0, 2,000 (2K), 4K, 6K, 8K and 10K cycles. The extent of the chafe on the wire was manually measured by hand and thus added some variability to the process as well. The most reliable method involved measuring the width of the wire at the point of chafing, since the point of chafing was on one edge.

In the second set of experiments (multi-sample case), different wires were chafed for a different number of cycles so that it would be more difficult to simply baseline out the geometric distortions of a single wire. Two sets of 8 wires each were chafed. Of the 8 wires, two were chafed for 4K cycles with T.D.R measurements taken at 0K, 2K and 4K. Two more wires were chafed for 6K (with measurements at 0K, 2K, 4K, and 6K). This process was continued for two more wires to 8K and two more to 10K cycles.

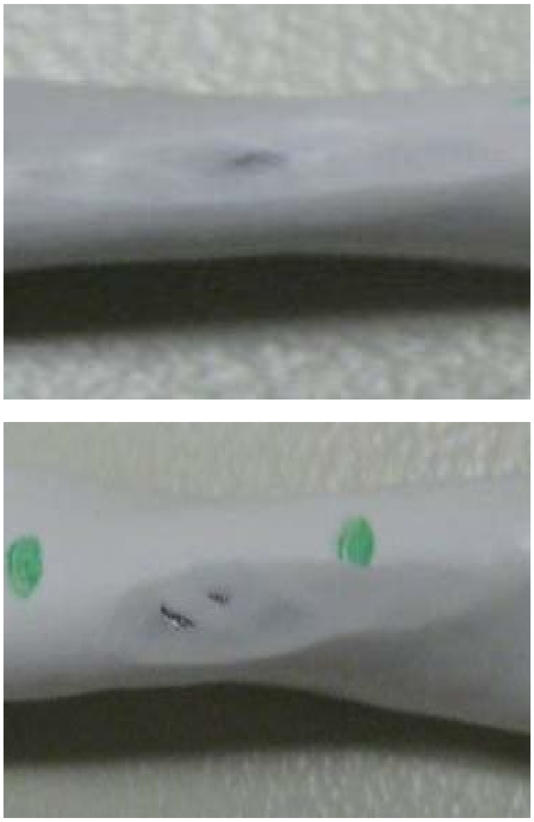

Fig. 4. Three chafes on shielded twisted pair. Chafing was performed until shielding became conductive to the chafing steel rod.

C. *Simulations for validation*

In efforts to both validate as well as to generate noise free data, we have employed a commercial microwave simulator: CST's Microwave Studio. This software performs high fidelity simulation of Maxwell's equations using the Finite Difference Time-Domain (F.D.T.D.) method. The simulator allows for detailed 3-D geometric modeling enabling very specific removal of shapes of shielding. It also enables arbitrary wave-shapes to be induced and the corresponding reflections and transmissions to be measured.

A representation of the geometry of the shielded twisted pair is depicted in Figure 5. The simulations consisted of inducing a voltage waveform step function with a 50 nsec rise time, similar to commercial T.D.R. devices, onto one end of the wire and then recording the transmitted and reflected waveforms at the respective wire ends. Holes ranging from 0.75 mm to 6mm in length were created in the shielding for individual simulations to emulate the growth of experimentally created shield flaws. The shielding holes were ellipsoidal and oriented along the length of the wire. The shielding was modeled as a continuous sheet whereas the shield of the actual wire consisted of a woven mesh.

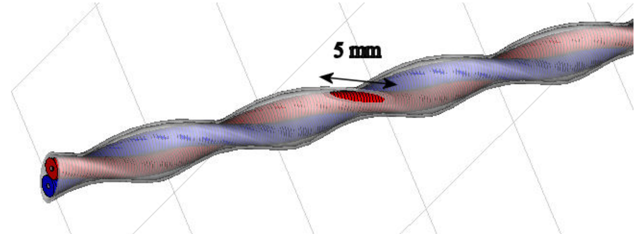

Fig. 5. Geometric model of a shielded twisted pair with a single ellipsoidal hole shown in the shielding.

We have implemented a version of the compact Green's function parameter retrieval code in the Mathwork's Matlab© language. The simulation results of this mathematical model are compared to the output of the F.D.T.D. simulator with high degree of success. The Matlab code was tested for its ability to retrieve (estimate) two of the four parameters while holding the other two fixed. In our case, we are interested in retrieving the velocity of propagation ($c(x)$) and the impedance ($Z(x)$) while assuming values for the serial resistance ($R(x)$) and the shunt conductance ($G(x)$).

IV. Results

Representative examples of applying our chafing mechanism are shown in Figure 6 for 4K, 8K and 10K cycles of chafing beyond shield exposure where the ruler's tick marks indicate mm. In general, at 4K cycles the shielding is damaged but no noticeable holes have formed. This type of damage may or may not be evident on a T.D.R. trace. At 6K cycles of chafing the shielding has small holes but the insulation of the inner conductors has not yet been revealed. At 8K cycles of chafing the shielding has worn away sufficiently to expose the inner core conductor insulation which is blue. Please note that there is also blue dye on the surface of the exterior white insulation which was used to help identify the chafing region. At 10K cycles a large hole in the shielding is evident and the inner conductor insulation has begun to be scratched but is still completely intact.

Although encouraging, the results of this for a single wire sample are insufficient to draw a conclusion when considering how much T.D.R. signals may vary from wiring sample to wiring sample. To address this, we present the results from chafing multiple wires.

Figure 7 shows the TDR reflections for a single wire sample after having been chafed for 0, 2K, 4K, 6K, 8K and 10K cycles. The difference in reflection between the 0 and 2K cases is negligible.

Figure 8 depicts the absolute difference in reflections measured for multiple wires with the baseline measurements of each wire subtracted. In this figure, it is clearly distinguishable that even small holes (6K cycles) in the shielding are revealed in the reflections. This indicates that it should be possible to assess chafing into the shielding long before any damage is done to the inner conductors.

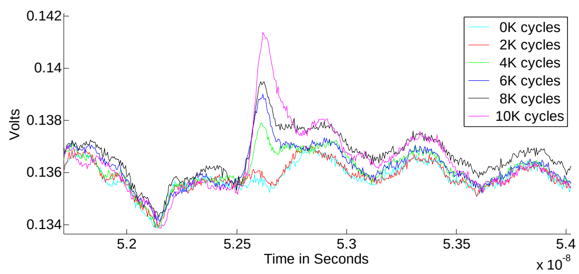

Fig. 7. TDR reflections due to chafing after 0K (cyan), 2K (red), 6K (blue), 8K (black) and 10K (magenta) of chafing cycles.

This profile was chosen in order to induce a non-trivial inhomogeneous permittivity but at the same time have a simulation that was verifiable. The results from applying both the FDTD software as well as the Matlab code are depicted in Figure 10. The outputs of both the simulator and compact Green's function codes are nearly identical. More important than this result is to determine the ability to retrieve the transmission line parameters using the Matlab code which is our eventual goal. As a very early and preliminary result to this retrieval process we present Figure 11.

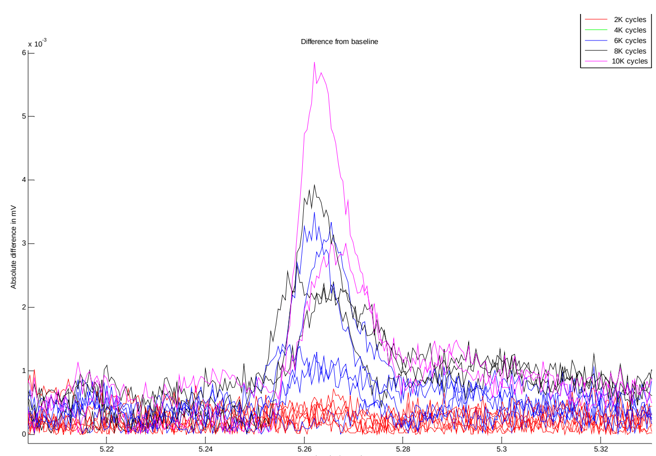

Fig. 8. Differences in reflections from baseline due to chafing after 6K (blue), 8K (black) and 10K (magenta) of chafing cycles.

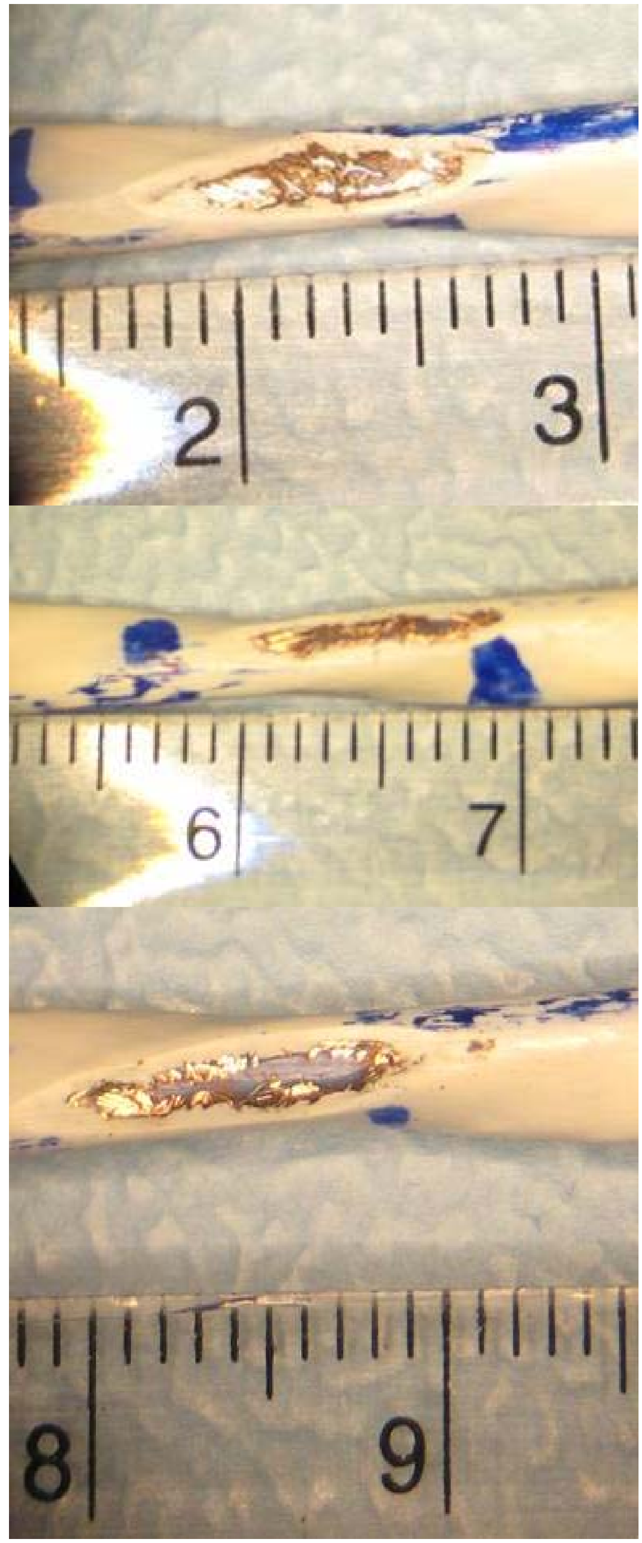

Fig. 6. Examples of shield chafing. Top picture results from chafing 4,000 cycles beyond initial shield exposure, middle is 8K cycles and bottom is 10K cycles. Ruler ticks indicate millimeters.

The compact Green's function matlab code was tested against the commercial FDTD simulator by simulating a wire which had a trapezoidal permittivity profile as shown in Figure 9.

Figure 11 demonstrates that it is possible (currently in some limited cases) to map from the incident, transmitted and retrieved voltages to the velocity of propagation (c(x)) and the impedance and its derivative (Z(x) and $Z_x(x)$).

The results of Figures 7 and 8 are indeed encouraging for finding flaws in shielding prior to any disruptive damage to the inner conductors. In order to ensure that these results are not more representative of experimental artifacts, validating simulations were performed using Microwave Studio. The results of these simulations are presented in Figure 12.

Figure 12 represents reflections from T.D.R. step input when a hole is opening in the shielding due to a fault that increases in length and depth but is not allowed to remove any dielectric from the inner conductors. This plot shows that we are indeed within the same range of the magnitude of a reflection between simulation and reality. The biggest difference has to do with the laboratory data more greatly showing the effects of the twists in the twisted pair wire.

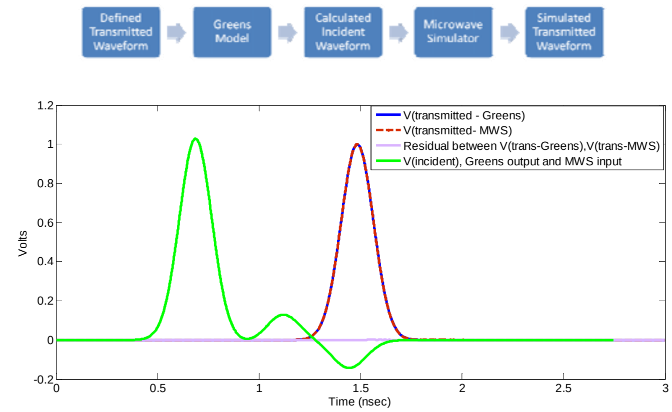

Fig. 10. Verification process followed and the resultant output from both the commercial FDTD simulations as well as from the compact Green's function Matlab code.

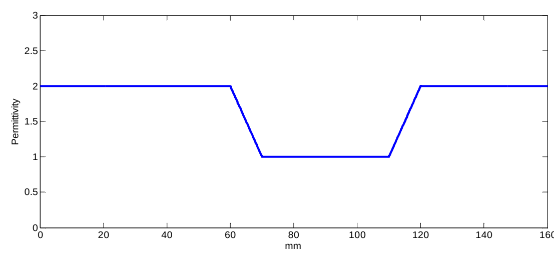

Fig. 9. Permittivity profile used in simulation.

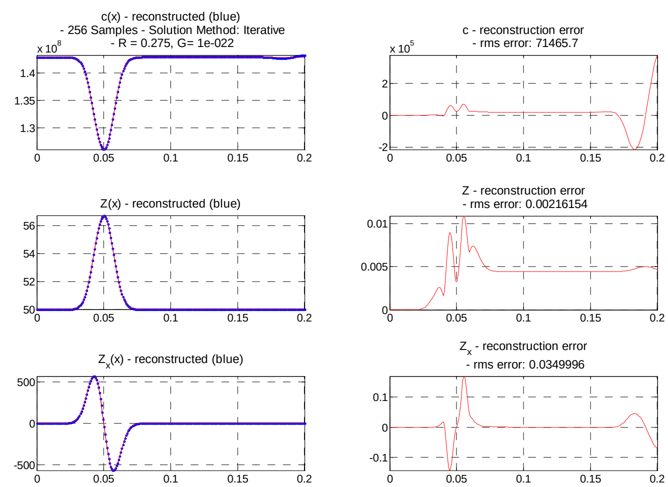

Fig. 11. Retrieved parameters and associated errors using the compact Green's functions.

V. Conclusion

This paper presented a model-based approach for defining requirements using Time Domain Reflectometry (T.D.R.) data for the detection of wiring insulation failure. The model-based approach is used to enhance the understanding of T.D.R signals by mapping them to the physical characteristics of a transmission line continually along the wire, and re-interpreting them as spatial profiles of specific physical quantities such as impedance or permittivity and permeability. The changes in the physical characteristics of the transmission line models are indicative of a developing flaw condition.

We have demonstrated the validity of the model-based approach by combining the theoretical models of transmission lines and their respective methods for reconstructing the spatial profile of the wire characteristics, a generalized numerical simulator to solve Maxwell's equations using a geometric model of the wires, and laboratory data that mimics typical fault conditions found in practice. Cross comparison of two or more of these methods under varying fault conditions has demonstrated the consistency of our results, and strengthens the case for a more advanced interpretation of T.D.R. signals as a means for fault detection.

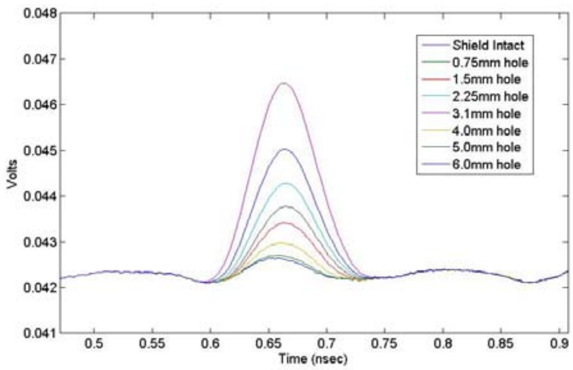

Fig. 12. Simulation results for reflections from T.D.R. when hole in shielding is increasing (thus depth of fault increases).

The concept of operations depends upon having the on-board capability to inject interrogation signals into harnesses and to record the resulting transmitted and reflected voltage waveforms. This could be done for example every time a plane is transferring passengers to a jet way. The on-board data could then be wirelessly transmitted to a ground station. The necessary model parameters could be inferred from this data after each flight. For example, an estimate of the continuous profile of impedance along targeted wires. This process would then start to accumulate model parameters over multiple weeks.

Another algorithm could then be employed to monitor the changes that occur over periods of weeks, months or years. These changes are used as inputs to predict the remaining useful life relative to rates of estimated chafing.

Our current efforts are devoted to the construction of a library of fault "signatures" that represent typical faults found in aging wiring. It is our intention to make these sets available on the web to encourage further algorithmic research into diagnostics and prognostics for wire health management.

ACKNOWLEDGMENT

The authors would like to thank the following individuals for fruitful conversations that either helped to inspire or continue progress on this work: Terry Thomas at Boeing Electronic Systems, Daniel Perey, Elliott Cramer and Rick Young at NASA LaRC and Scott Christian at United Airlines.

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