Aging Wire Fault Diagnosis Using Faster, Higher-Precision Methods

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***Abstract*—This paper presents novel implementation of forward and inverse methods for locating faults in the shields of coaxial cable and other shielded lines. In accomplishing these tasks, direct and probabilistic inversion methods are used to estimate fault and wire parameters. Some numerical finite-difference techniques are capable of modeling the characteristic impedance of a chafe one frequency at a time or without consideration of frequency dependence. Other more computationally expensive software takes frequency into account. By simulating limited number of points, we can use a curve fitting technique to predict the chafe profile and thus save time in the long run. The ABCD forward method also provides a quick and yet realistic solution to the transmission modeling, making modeling a cascaded transmission line system easily done by connecting the modulized blocks. With the success of the forward modeling method, the inversion can be benefited from it. Iterative inversion methods are capable of recovering multiple unknown parameters (lengths and impedances) by approaching the result gradually. Gradient inversion and maximum *a posteriori* (MAP) inversion results for fault location and size were found to be accurate. A simple and yet effective wire fault profile building technique are also presented. Finally, a novel method of external field measurement from small chafe holes is presented. These new methods prove highly useful for simulation and analysis of complex systems. Thus, faults can be accurately identified, located, and diagnosed with high precision, providing real solutions for greater safety and reparability in aerospace wiring systems. Location and diagnosis of faults in aging electrical wiring can enable their timely repair, thus preventing costly and potentially hazardous post-failure repairs.**

I. Introduction and Background

Location and diagnosis of faults in aging electrical wiring can enable their timely repair, thus preventing costly and potentially hazardous post-failure repairs. This project focuses on one of the most challenging problems in electrical fault location—finding small chafes in the shields of shielded wires (coax, twisted shielded pair, etc.). These small faults produce such small reflection signatures that in many cases they are undetectable against the background noise on aircraft. This objective is attained using forward and inverse methods, along with a new external field measurement method.

Hard wire faults (open/short) have been well studied. These faults are easier to find and most of reflectometry measurements have demonstrated to be effective. However, partial faults (chafes) are more difficult to identify since the system usually does not show any noticeable symptom until the fault is too severe. Chafes are the result of improper workmanship, abrasion or vibration against other wire or structural members. Exposing the conductor in the air, the severity of chafes is prone to worsen over time. Like human health, early detection in aircraft wiring fault typically has a much better chance of curing the problem and can possibly prevent catastrophic disasters.

II. Forward Methods

Detailed models of the faults and a method to integrate multiple fault models (including measured data) were developed in a unified forward model that describes effects of the fault and its surrounding system. Models were produced of shielded cables, where the external environment has little or no impact on the cable, and thus potentially enable location of much smaller faults than have previously been detectable. Unique aspects of this model include its modularity (ability to efficiently integrate data from multiple simulations and measurements), detailed fault models (including frequency dependence of the faults), and the ability to model small faults with great precision while still incorporating them into a full system model (which normally has lower precision for more efficient computation).

Various techniques have been used to model chafes on the wire. For simplicity, signal propagating in TEM mode is typically assumed. However, a coaxial cable for example, once the shield is damaged, the signal no longer propagates entirely in TEM mode and the analysis can be much more difficult once the higher order modes are involved. Although higher order modes do not play a significant role if the fault is small and the frequency is low, once the fault is severe or the frequency is high enough, the effect can be noticeable. Analytical electromagnetic modeling does not work effectively on multiple modes/frequencies with arbitrarily geometric variations. Thus, modern techniques use numerical methods such as the finite-difference methods discussed below to synthesize the reflectometry results. A common drawback is the heavy burden of the computational resources. This is especially true when the fault is small, where fine resolution is needed. In such cases, ABCD, S-parameter theory, and Computer Simulation Technology (CST) can prove useful. Each of these methods will be presented in this section.

A. Finite-Difference Method (FDM)

In order to characterize the damaged wire, the fault impedance Z_F must be obtained. The Finite Difference

Method (FDM) can accomplish this task by modeling a cross-section of damaged cable, as shown in Figure 1, and numerically calculating the impedance Z_F. FDM works by "sampling the voltage potential within some finite simulation domain and then approximating the derivative operation with a finite-difference. When applied to a time-independent partial differential equation, the net result is a linear system of equations that may be readily solved via matrix inversion" [1].

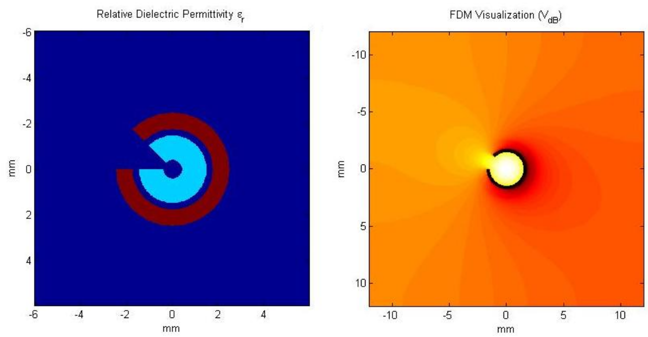

Fig. 1. *left:* Simulated damaged dielectric, where red represents the outer jacket and cyan represents the inner wire dielectric. *right:* Leaking fields from damaged shield, where white center wire is fixed at 1 V and black outer shield is grounded.

To determine the characteristic impedance of a chafe, a technique proposed in [2] is to utilize the two-dimensional finite difference method to estimate the effective capacitance of the cutaway section. The effective characteristic impedance can be derived as

$$Z_{\text{eff}} = \frac{1}{v_p C_{\text{eff}}} \tag{1}$$

where v_p is the velocity of propagation,

$$v_p = \frac{1}{\sqrt{\mu_0 \epsilon}} \tag{2}$$

The reader is referred to [1] for a more complete description of FDM and [3] for an overview of how characteristic impedance is simulated using finite difference methods.

B. Finite-Difference Time-Domain (FDTD) Method

Finite-Difference Time-Domain (FDTD) is a computational electrodynamics modeling technique that solves Maxwell's equations [4]. Because it is a time domain method, solutions can cover a wide frequency range with a single simulation run [5].

One advantage of the FDTD method is that it can be used for simulation of faults containing graded (gradual) impedance changes along the line. Because many faults contain graded changes in real life, these simulations provide a more realistic method of determining the types of reflections and signal changes that can be expected from such faults. A discretized approach to adjusting the RLGC parameters can be implemented in a cell-by-cell manner, where the resulting characteristic impedance gradually changes across the length of the fault.

C. ABCD Method

The ABCD method simulates the TDR response of cascaded transmission lines, as shown in the simple TDR setup displayed in Figure 2. A TDR tester (Z_S) is connected to the transmission line as a signal source while a load (Z_L) is at the end of wire.

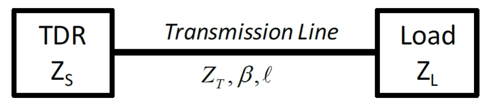

Fig. 2. A simple TDR setup.

The time domain response of TDR is then simply the inverse Fourier transform,

$$\text{TDR} = F^{-1}\left\{S(\omega)H_{\text{TDR}}(\omega)\right\} \tag{3}$$

where $S(\omega)$ is the source signal in frequency domain and H_{TDR} is the transfer function of the TDR. Figure 3 shows a multi-section setup with a reactive load of 1 nH and 47 pF in series and the result is shown in Figure 4.

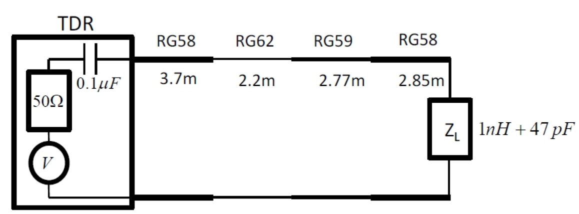

Fig. 3. A multi-section setup with a capacitive load.

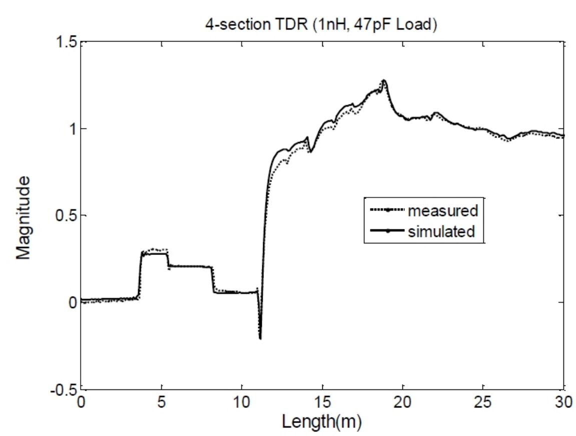

Fig. 4. Multi-section setup with a reactive load.

D. S-Parameter Theory

S-parameter theory can also be used to simulate faulty wires [6]. In order to simulate the response of the wire system (the forward model), a system of S-parameter equations was derived for the damaged wire case. This case included one chafed section of length z_2, located at a distance z_1 along a wire of total length z_T.

Time-dependent voltage $v_M(t)$ is obtained by using the inverse Fourier transform. The following equations outline the steps taken to obtain $v_M(t)$, the simulated time-domain reflectometry (TDR) response:

$$V_S(\omega) \Leftrightarrow v_S(t) \tag{4}$$

$$V_M(\omega) = H(\omega) \cdot V_S(\omega) \tag{5}$$

$$v_M(t) \Leftrightarrow V_M(\omega) \tag{6}$$

The transfer function $H(\omega)$ is derived from S-parameter theory. The forward voltage $V_M(\omega)$ can then be obtained by multiplying the frequency response $V_S(\omega)$ of the input (source) signal with the transfer function $H(\omega)$ of the system.

E. Computer Simulation Technology (CST)

CST Microwave Studio offers a powerful 3D Quasi-TEM mode, in which the result takes both TEM and higher order modes into account. Additionally, one can import virtually any shape of the model from CAD software. However, like most iteration-based algorithm (i.e. FDTD, FEM), CST is painfully slow at high resolution or where the point of interest is small while the wire is long. Relying entirely on CST/FDTD to generate a wide range profile is not feasible.

Efficiency and precision are critical for inverse solution; however, they are often mutually exclusive. Instead of running the numerical modeling at every single possibility, we can utilize the polynomial curve fitting algorithm to minimize the points required.

1) Analysis: Once the shield is cut more than 60° as shown in Figure 5, at frequency of 5 GHz, the field lines start to bend and the characteristic impedance calculation is no longer as simple.

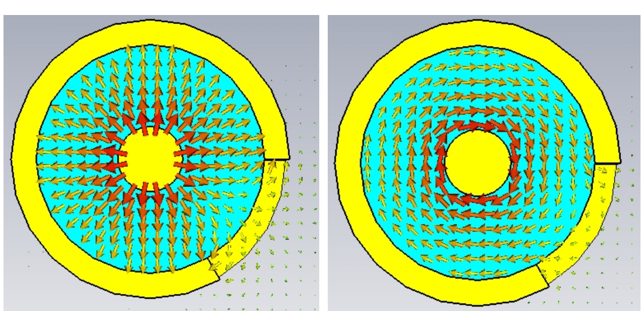

Fig. 5. Electric field (left) and magnetic field (right) in coaxial cable with 60° cutaway.

CST's Quasi-TEM mode simulation combines the effect of both TEM and higher order modes. Instead of using multi-stage processes (FDM to calculate effective capacitance and derive the characteristic impedance), we can obtain the characteristic impedance of the fault directly. As shown in Figure 6, 13 points from 0 to 359 degrees were obtained using CST. By utilizing polynomial curve fitting algorithm, we can easily plot the profile that represents the properties of the faulty shield. This profile represents the prediction of the fault severity of the chafed RG58 coaxial cable. A 9th order polynomial expression derived by Matlab Curve Fitting Toolbox is revealed as:

$$Z(\theta) = p_0 + p_1\theta^1 + ... + p_8\theta^8 + p_9\theta^9 = \sum_{n=0}^{9} p_n\theta^n \tag{7}$$

where θ is the cutaway angle in degrees and p_0–p_9 are constant coefficients.

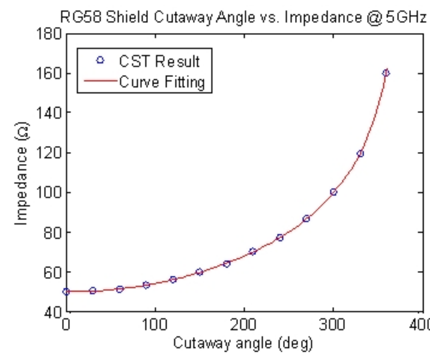

Fig. 6. RG58 2D profile at 5 GHz.

Since characteristic impedances are frequency dependent, we can generate a few more sets of data at different frequencies of interest and use the similar polynomial surface fitting algorithm in order to obtain the 3D frequency-dependent characteristic impedance profile of the faulty coax, as shown in Figure 7. Similarly, a characteristic impedance function of cutaway angle and frequency can be obtained. Once this fault profile is defined, it can be reused again and again without further time-consuming simulations or calculations. Additionally, the field technician can estimate the severity of the fault based on the fault profile (or chart) of each type of cable.

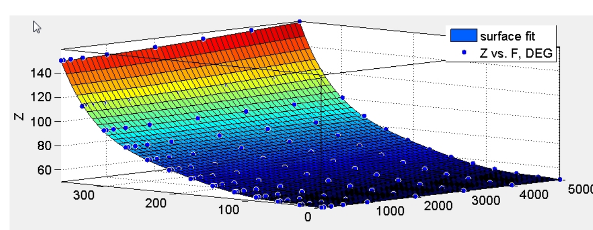

Fig. 7. RG58 3D profile from 1 MHz – 5 GHz.

2) Results: With the collaboration of the ABCD method, the modeling of chafed wires can be made efficiently without any numerical approach. Once the profile is defined, the modeling and prediction of the chafe can be done within no time. Finally, efficient and fast forward modeling is one of the key elements for the success of inversion technique. With this profile building technique, numerical iterations can be reduced or possibly eliminated, where most of the inversion effort is spent.

III. Inverse Methods

Inverse solutions were developed that determine the location and nature of the fault, using the forward solutions developed, perhaps in multiple simulations, to compare to the measured data in some way. The inverse methods explored here include Bayesian statistical analysis, gradient and iterative methods, and the beginnings of a novel exterior-field measurement approach. The important focus of these inversion schemes is inversion of very small faults in a complex environment.

A. Maximum A Posteriori (MAP) Estimation

In Bayesian statistics, a maximum *a posteriori* probability (MAP) estimate can be used to deduce original wire and fault parameters from reflectometry measurements [6]. In this way, faults can be detected, located, and diagnosed with much greater accuracy than in previous methods. This is primarily because not only the existence and location of the fault can be detected, but also the nature of the fault and wire parameters, such as fault size, dielectric permittivity of the insulation, conductivity of the wire, and other factors. For instance, permittivity may not be known in realistic test configurations. This leads to uncertainty in velocity of propagation, wire length, and thus in fault location. Probabilistic methods can determine the permittivity and/or other wire parameters while also finding the fault type and location.

Using the S-parameter forward model, an inversion scheme using Bayesian probability can detect the location and parameters of an unknown wiring chafe using reflectometry or S-parameter data. Model parameters m can include wire properties such as dielectric constants, and fault parameters such as location z_1, width w, and length z_2.

In this way, prior probability $P(m)$ can be estimated for each variable in the variable set m, either as a Gaussian distribution with mean μ and standard deviation σ_M, or as a uniform distribution of equal probability. In this case, the location (z_1) and size of the fault (w, z_2) can be treated as uniform probability distribution functions (pdfs) in order to treat all locations and sizes as equally possible. This is because location and fault size are unknown, whereas other wire parameters such as permittivity or conductivity are generally known or presumed because more information regarding wire parameters is available, and thus Gaussian distributions centered at presumed valued can be used in prior probability.

The maximum likelihood method can be used to obtain the solution set m_0 which maximizes the conditional probability $P(m|d)$.

$$P(m|d) = \frac{P(d|m)P(m)}{P(d)} \quad (8)$$

$$m = \{z_1, z_2, z_T, w, \epsilon_r, ...\} \quad (9)$$

$$m_0 \Rightarrow \text{maximize}\, P(m|d) \quad (10)$$

Measurements have been taken using several different wire types, including RG58 cable. The accuracy of the MAP algorithm can then be analyzed to determine the limits of fault size and its detectability. Preliminary tests have verified that the code could at least locate very large faults. Similarly, smaller faults can be produced on other cable types, measured, and analyzed using the algorithm.

B. Gradient Methods

Gradient inversion methods—such as steepest descent, conjugate gradient, or the Newton method—can be used in order to minimize misfit error and calculate an optimal solution [7]. In exploring these methods, the Newton method can be evaluated, where the expression for $A(m)$ can be defined using S-parameter theory as in (6), where data $d = A(m) = d(z)$.

The misfit functional between predicted data $A(m)$ and observed data d_{obs} is then defined as

$$\phi(m) = \|r\|^2 = \|A(m) - d_{obs}\|^2 \quad (11)$$

The Newton method involves linearization of the nonlinear operator A by some vicinity of point m:

$$A(m + \Delta m) \approx A(m) + F\Delta m \quad (12)$$

where F is the Frechet derivative at the point m, and Δm is a variation of the model parameters. Here, the Frechet derivative consists of the partial derivative:

$$F = \left[\frac{\partial d}{\partial m}\right] \quad (13)$$

In matrix notation, the updating process occurs as:

$$r_n = A(m_n) - d \quad (14)$$

$$\Delta m_n = -(F_{m_n}^T F_{m_n})^{-1} F_{m_n}^T r_n \quad (15)$$

$$m_{n+1} = m_n + \Delta m_n \quad (16)$$

The function was programmed in an iterative process, where the value for Δm was continuously updated until a certain convergence criterion was met, which was defined as in terms of percent error (PE).

$$PE = \frac{\|r\|}{\|d\|} \times 100\% \quad (17)$$

In this application, measured fault signature size is often relatively very small, as shown in Figure 8. Because of the tiny size of the measured fault signatures, ranging from 1 to 15 mV for a 1 V input signal in this case, it is necessary to use extremely high levels of accuracy, otherwise the signature can become lost in the noise or nuances of the system measurements. In this case, the level of accuracy used as the convergence criterion was a low $PE = 0.01\%$. This level of accuracy produced results inasmuch as the noise level did not exceed the size of the chafe signature. Noise levels up to 0.1 mV were found to be acceptable with accuracy levels up to $PE = 0.1\%$.

When the noise level is too high, as shown in Figure 8, the tiny signature becomes buried and much more difficult, if not impossible, to detect.

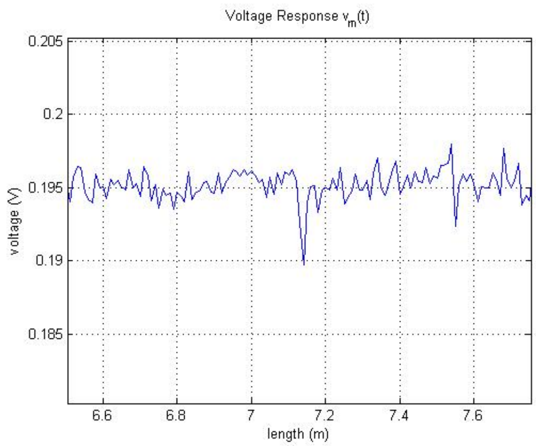

Fig. 8. Chafe signature lost in noisy data.

It may be noted here that such low-noise measurements are now increasingly possible because of the development of high-precision instrumentation and the use of *shielded* coax, the shield of which greatly reduces noise and interference levels.

C. Iterative Inversion Method

Trying to solve the inverse problems analytically is typically not an option. However, with the advances in computing technology, extensive studies have been done using numerical approaches.

One of the key successes in the transmission line inverse problems is the forward solver, in which the efficiency (speed) and the fidelity often determine the outcome of the inverse solution. For application of the iterative inverse method, we have chosen the frequency-domain ABCD method [3] as our forward solver due to its simplicity and the features that fit well with numerous cascaded transmission line sections. The inversion and reconstruction algorithm block diagram used in this paper is shown in Figure 9.

1) Applying Steepest Descent Optimization: Although a decent result can be achieved in only few tens of iterations with an educated guess, had the initial estimation far off the objective, the converging performance could be degraded accordingly. Additionally, the $L - Z$ profile was oscillating especially toward the end of wire. This was due to the limitation of the 1Ω resolution we set in the beginning of the process. The impedances in the prior sections were not matched properly, therefore, cause the multiple reflections at the later sections. We can of course increase the Z resolution,

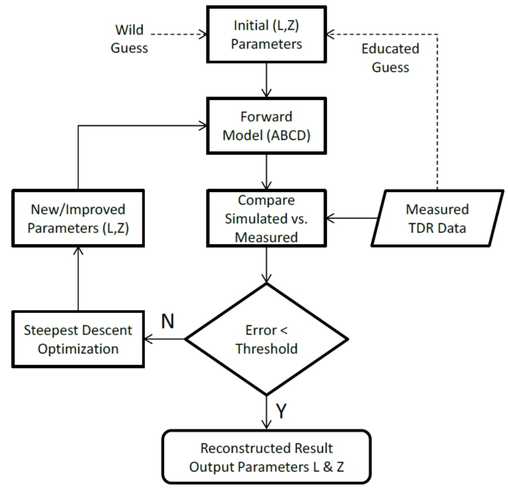

Fig. 9. Inversion and reconstruction algorithm block diagram.

however, at the cost of computational efficiency. In addition to the fluctuation, the convergence of the previous method is quite low. That is, we can only approach our objective linearly by 1Ω per iteration. If the initial estimation was off by large, it would take long time to converge. Furthermore, we may never reach to the real profile since we are limited by the preset resolution of 1ω.

A classical, but effective steepest/gradient descent optimization method [8] can fit quite nicely in this inversion algorithm. For a defined and real function F, in the neighborhood of a point x in the direction of the negative gradient of $x - \nabla F(x)$, we can find an ideal γ, where the step size γ is a real number that determines the speed of convergence. If is too small (underestimated), this method converges slowly. On the other hand, if γ is too large (overestimated), the convergence may oscillate or may not converge at all. Therefore, choosing a proper γ is critical for optimization. For TDR inversion, our changing variable is the characteristic. Therefore, the steepest descent function can be re-written as:

$$Z_{n+1} = Z_n - \gamma_n \nabla \Gamma(Z_n) \tag{18}$$

Applying the steepest descent method with the step size equals to 110, the converging efficiency has improved significantly. After only 10 iterations, the $L - Z$ profile has achieved a result that is better than the previous method with 50 iterations.

2) Iterative Inversion on Chafes: Chafes on transmission lines are more difficult to identify, producing very small reflection coefficients that might be buried in measurement noise, and their short lengths also make the detection challenging. A very high frequency TDR is usually required to identify frays. Thus, we have to increase the resolution in our algorithm as well. Figure 11 shows a partial fault of 5 cm long, 120° cut on the shield of a 3.59 m RG58 coaxial cable.

Again, we start with an initial guess of uniform characteristic impedance of 60Ω. After 10 iterations, the fault of 5 cm is identified at 1.9 m on the coaxial cable. The $L - Z$ profile reveals that the characteristic impedance of the fray is

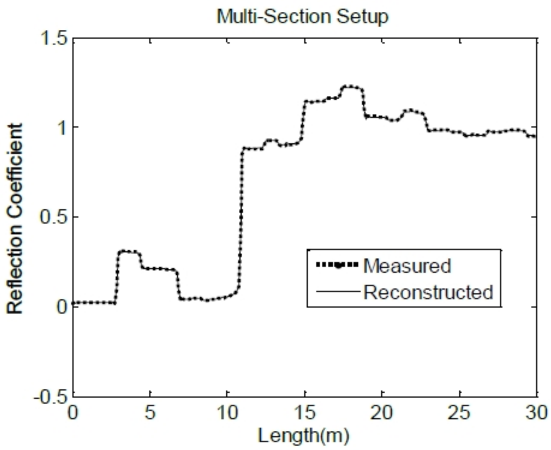

Fig. 10. The measured vs. reconstructed result after 5 iterations using steepest descent with converging constant = 110.

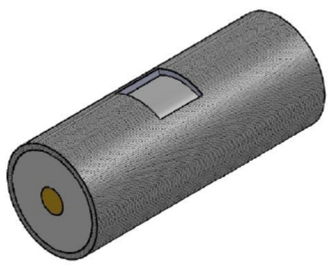

Fig. 11. A 5 cm, 120° shield cutaway on a 3.59 m long RG58 coaxial cable.

roughly 60Ω. This inversion method shows the characteristic impedance, however, not the physical size or the nature of the fault. Figure 12 shows the comparison between the measured vs. reconstructed result. The results are closely matched even with the small reflection coefficient in a noisy measured data.

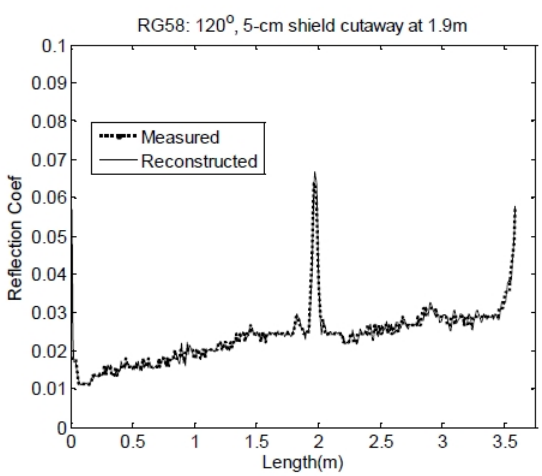

Fig. 12. The measured vs. reconstructed result on the RG58 fray.

D. External Field Method

Finally, a novel approach is explored where the fields are measured external to the cable. If the shield is intact, these should be uncorrelated to those on the inside of the cable, however if the shield is damaged sufficiently for fields to escape, these external fields will be correlated with the internal fields. Measuring the fields on the external surface of the cable shield appears to be a promising method of locating small faults on the cable. This method reduces the huge dynamic range that was previously required to sense both large reflections from normal connections within the system and minute reflections from the damaged shield. This method may prove to be even more effective than internal measurements for these small faults in cable shielding.

E. External Field Theory and Simulation

Determining the fields on the outside of the cable due to a fault in the shield will involve a process of simulation and lab measurements. The type of wiring we are going to focus on in this section is the standard coax cable, although the concepts can be extended to twisted shielded pair (TSP) and other shielded cable types. The question we are most interested in is what fields propagate from the inside to the outside of the cable when there is a hole in the shield

Bethe developed rigorous mathematical expressions to describe fields leaking through a small hole between two cavities [9]. Bethe's theory was applied to waveguides and validated by additional studies [10]-[11]. Two waveguides were placed parallel to each other with a small hole connecting the two. Fields were shown to leak into the adjoining waveguide through the small hole. Applying the theory to coax cables, if a signal is traveling down the cable and there is a small hole in the shield, then some fields could be leaking out and may be detectable on the outside of the shield.

Visually these simulations indicated signals on the outside of the cable that are propagating towards both ends of the cable. These signals could potentially be picked up by a probe on the outside of the wire. Their mere presence indicates a hole. The phase shift between the incident signal on the wire and that received from outside through the hole may be able to tell us the location of the hole. The magnitude and/or frequency spectra of these signals may be able to tell us the size and nature of the hole.

These rudimentary simulations provide motivation to continue research and modeling of small faults to aid in the study of the external fields. Improvements to the model to more accurately reflect shield damage, size, signal excitation, and expressions to describe these external fields will be further studied.

1) Coil Receiver Technique: With a simple model of an RG58 coax cable established we turn our attention to detecting the external fields. One approach utilizes a coil (toroid) sensor. The coax cable goes through the center of the coil, and measurement devices connected to the coil receive signals. The following subsections present a simulation and initial lab results from such a setup.

2) Simulation: A simplistic CST model was simulated using a basic coil. Building upon the RG58 coax model already developed, a ferrite coil was added as illustrated in Figure 13. This model was simulated with the same parameters defined earlier in the paper.

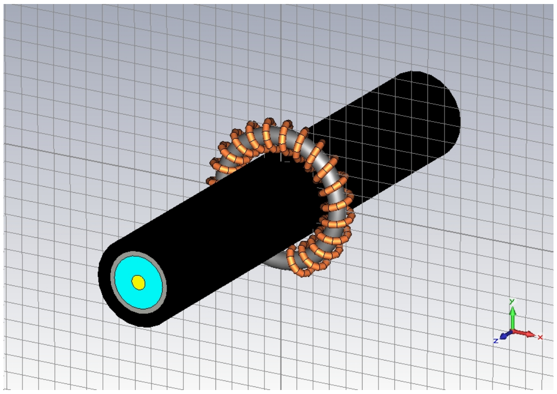

Fig. 13. RG58 coax modeled in CST with coil sensor.

Although this CST model is fairly basic, the result helps motivate the additional research and study needed to better understand the fields leaking outside the cable and the potential use of a coil sensor. The downside of this CST simulation is the incredibly small response of the signal, with peak-to-peak magnitude no greater than 1 μV/m. It will be very difficult to measure and capture these signals. As the coil moves away from being centered over the hole the signals are even smaller and more difficult to detect. Still, our simple measurement system has been able to detect the faults.

3) Experimental Measurements: The previous section provides motivation that measurable fields exist on the outside of the cable. A few questions quickly arise; how far do the fields extend, how large are the fields, and perhaps most importantly can the fields be detected in practice? We know that small faults are difficult to detect with common TDR measurements, because the reflected signal becomes lost in the noise. One advantage to the detection of holes in the shield is that these types of faults are *not* intermittent. That means we can look for them in relative leisure when the aircraft is on the ground, in a quiet environment with no other signals (other than environmental noise) on the cables being tested.

The experiment was executed in two steps. During the first step measurements were taken with no damage to the shield. The response from the ferrite coil alone is show in Figure 14. Data collected from the network analyzer was in the frequency domain. A basic inverse Fourier transform was used to convert it to the time domain.

The second part of the test is to damage the shield (using an xacto knife in this case) and retake the measurement. A 1 cm chafe was made on the shield 10 ft from port 1. Measurements in the frequency domain were Fourier transformed to give the time domain response shown in Figure 14. The graph shows a distinct spike caused by the signal leaking out of the cable and being received by the toroid. The spike is not centered around

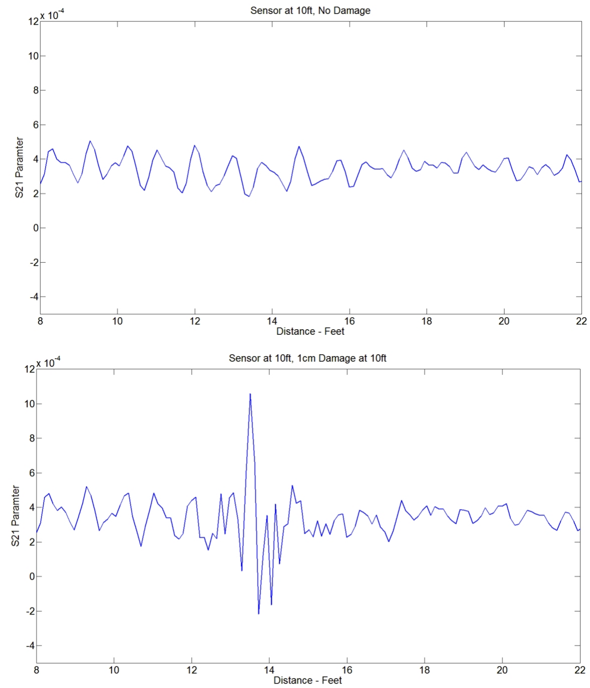

Fig. 14. Measurement before shield damage (top). Measurement after shield damage (bottom). The fault appears at 14 ft because the signal starts at port 1 and travels 10 ft down the cable and leaks out the chafed shield. The coil sensor pickups the sensor and travels 4 ft back to port 2 on the network analyzer. The cable connected to the sensor is much smaller in length than the RG58 coax cable.

10 ft, however, because the signal leaves port 1, travels 10 feet down the cable, out of the hole, is picked up by the sensor, and travels a few feet back through port 2. We are still working out the details of the various velocities of propagation (inside and outside of the cable are different), and the nature of the external signal, to be able to use the measured signature to determine the location of the fault.

IV. Conclusion

This paper presents novel implementation of forward and inverse methods for locating faults in the shields of coaxial cable and other shielded lines. In accomplishing these tasks, direct and probabilistic inversion methods are used to estimate fault and wire parameters.

ABCD method provides a quick and yet realistic solution to the transmission modeling. This method simplifies the transmission line by representing each line section with a single ABCD matrix. Thus, modeling a cascaded transmission line system is easily done by connecting the modulized blocks.

With the success of the forward modeling method, the inversion can be benefited from it. The efficient ABCD method makes the iterative inversion more capable of identifying the nature of the fault.

A simple and yet effective wire fault profile building technique was also presented. Although only RG58 was demonstrated, this method can be applied to any geometric shaped faults. Numerically modeling of multi-mode chafed transmission lines is a slow process. The proposed method provides a quick solution for building chafe or fault profile that can be included in a forward and inverse library.

Initial coax simulations and lab measurements were also presented regarding measurement of external fields from small chafe holes. Computer simulations provided motivation that external fields could be sensed by a rudimentary coil sensor. Lab experiments provided initial data that these external signals are detectable.

These new methods prove highly useful for simulation and analysis of complex systems. Results can be obtained by using detailed models of the faults and a method to integrate multiple fault models (which can include measured data) in a unified forward model that describes effects of the fault and its surrounding system. Models of shielded cables can be used, where the external environment has little or no impact on the cable, and thus potentially enable location of much smaller faults than have previously been detectable. Thus, faults can be accurately identified, located, and diagnosed with high precision, providing real solutions for greater safety and reparability in aerospace wiring systems. Location and diagnosis of faults in aging electrical wiring can enable their timely repair, thus preventing costly and potentially hazardous post-failure repairs.

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