Diagnostics and Prognostics of Wiring Integrity via Joint Time-Frequency Domain Reflectometry

Jingjiang Wang, Philip Crapse, John Abrams, Yong-June Shin and Roger Dougal
Department of Electrical Engineering, University of South Carolina
301 South Main Street, Columbia, SC 29208, USA

Trang Mai, Lan Tran and Joseph Molnar
Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375, USA

Abstract
The integrity of the wiring in the electric power system of an aircraft is vital to its safe operation. To ensure the wiring integrity, it must be tested to determine if any incipient defects exist. For this purpose, joint time-frequency domain reflectometry (JTFDR) has proven to be effective on shielded, coaxial cable. This paper demonstrates the ability of JTFDR to also effectively detect and locate incipient defects on the more challenging unshielded twisted-pair cables. Though these cables have greater attenuation and are more susceptible to interference, the versatility and configurability of JTFDR allow it to be successful for detection and location of the defects. This paper also addresses age capability of JTFDR for cable prognostics. Using a heat chamber to simulate accelerated thermal aging, coaxial cables are exposed to extreme heat monitored over time. The time-frequency cross-correlation function employed by JTFDR provides indices that are monitored and analyzed to determine if a cable has been aged permanently by the exposure or if it is still operable. Monitoring these JTFDR indices may also be used to predict both hard faults before they occur and the remaining life of the cable.

1. Introduction
The safe operation of an aircraft depends largely on the integrity of the wiring in its electric power system [1]. The typical electric power system in an aircraft contains miles of wiring [2], some of which is difficult to access and most of which is exposed to constant vibration, routine maintenance operations, heat, and other age-related disturbances [3]. Especially in aging aircraft, these disturbances lead to potentially disastrous insulation deterioration [1]-[2]. Damaged wiring has been blamed for past electrical fires and fuel tank explosions [5] and even for the deadly crashes of Swissair flight 111 in 1998 and TWA flight 800 in 1996 [1]. Making matters worse is that these defects are often small and difficult to detect [1]-[4] and the current state-of-the-art technology is insufficient. However, recent developments in wiring integrity seek an innovative prognostics technique that can assess the health condition of the wires in order to scientifically predict insulation failure by evaluating the remaining operational life.

The current state-of-the-art technology for wiring diagnostics can be largely categorized as time-domain analysis or frequency-domain analysis. Time-domain analysis typically employs time-domain reflectometry (TDR); frequency-domain analysis commonly involves either frequency-domain reflectometry (FDR) or standing-wave reflectometry (SWR). These reflectometry techniques are based on the analysis of a reference signal and any signal(s) reflected by imperfections on the wire being tested. A variety of techniques are used to perform wiring diagnostics in aging aircraft, but reflectometry methods have proven to be extremely effective in
locating hard faults. However, these classic techniques are limited by the fact that they analyze the reference and reflected signals in either the time domain or the frequency domain only. For accurate and sensitive incipient fault detection, joint time-frequency domain reflectometry (JTFDR) has proven to be effective [6].

JTFDR captures the advantages of both TDR and FDR while avoiding some of their limitations by using advanced digital signal processing techniques. This innovative technique utilizes a reference signal that is localized in both the time and frequency domains. This reference signal is composed of a Gaussian envelope applied to a linear chirp signal. A distinct advantage of this reference signal is its configurability; the user can properly select the parameters of the reference signal, including frequency bandwidth, center frequency, and time duration, by considering the frequency characteristics of the wire under test. After obtaining the time-frequency distributions of the reference and reflected signals, JTFDR computes the time-frequency cross-correlation of the two distributions and uses the peaks of the correlation to detect the defects and determine their locations. JTFDR has proven to accurately and sensitively detect both hard and soft defects on coaxial cables. Unlike coaxial cables, twisted-pair cables are unshielded and are more susceptible to interference; thus it is technically challenging to detect and locate the defects with reflectometry techniques. This paper will explore the efficacy of applying JTFDR to unshielded twisted-pair cables. By introducing and filtering additive noise, JTFDR can successfully detect and locate defects in unshielded twisted-pair cables.

Many schemes have been proposed for the diagnosis of a wiring defect, but few, if any, can predict one. To achieve scientific prognosis of an aging cable, we need to monitor a cable for signs of insulation degradation, but this is not possible with classic diagnostic techniques. However, the unique features of the time-frequency cross-correlation employed by JTFDR allow it to sensitively monitor all minor imperfections. Changes or growth in the time-frequency cross-correlation indicate that the faulty condition of a wire or cable is worsening. In addition, the time-localization of the reference signal used by JTFDR enables us to accurately locate the faulty section of a wire. For this research, accelerated thermal aging was applied to a cable in order to simulate the effects of aging on a wire and then monitor the features of JTFDR to assess the technique’s capability as a wiring prognostics tool. The process and results of these tests are reported here.

2. Experimental Setup

The experimental setup for the testing described above is pictured in Figs. 1(a) and 1(b). Fig. 1(a) shows the experimental JTFDR wiring test bed, which is composed of a signal generator (Tektronix Arbitrary Waveform Generator 610), a data acquisition device (Agilent Infinium 54754A), and a control PC. The computer controls the arbitrary waveform generator (AWG) to produce the Gaussian envelope chirp signal, which propagates into the target cable via the circulator. This reference signal is reflected at the fault location and back to the circulator. The circulator redirects the reflected signal to the digital oscilloscope. The computer program controls and synchronizes the AWG and oscilloscope, calculates the time-frequency distribution of the reference and reflected signals, and executes the time-frequency cross-correlation algorithm to detect, locate, and assess defects on a cable. Fig. 1(b) shows the heat chamber used for accelerated thermal aging for prognostics (a process discussed in more detail in Section 4).
3. Incipient Defects Detection and Location on Twisted Unshielded Cables

Unshielded twisted-pair (UTP) cables are among the most problematic cables for detecting and locating defects with reflectometry techniques. They have uncontrolled impedance and are more susceptible to interference. Therefore, after previously proving the effectiveness of JTFDR on coaxial cables, we have deemed it necessary to test the technique on UTP cables to verify the versatility and robustness of JTFDR.

The UTP cable used in this experiment is the MIL-C-27500 22-MW-5S provided by the Naval Research Laboratory. The sample is 15 m long and has an incipient defect located at 5 m. The cable can be easily bent and entangled, which will create small knots along the cable. These bends and knots can cause undesired reflections unrelated to actual defects, thus concealing the real incipient defects. Because the UTP cables have much higher attenuation than coaxial cables, the chosen center frequency of the JTFDR incident signal cannot be too high or the reflection will be too weak. However, the fact that a lower center frequency will generate lower resolution in the location measurement also needs to be considered. For those reasons, the incident signal for this experiment is chosen to have a 100 MHz center frequency and a 50 MHz bandwidth. A defect corresponding to the removal of 0.25 in. of outer insulation is also created on the UTP cable at 5 m.

For a comparison of the reflectometry techniques, TDR is first applied to the cable to see if it can locate the defect. Then, JTFDR will be applied to the same UTP cable. The results of these tests are given in Figs. 2(a-e) below. Fig. 2(e) reveals that TDR is of little use on the UTP cable; although the beginning and end of the cable are readily observable, it is difficult to distinguish the reflections of the incipient defect from other false reflections. Figure 2(a) shows the waveforms of the incident and reflected waveforms in the time domain using JTFDR; once again, it is difficult to observe the reflections from the defect in the time domain. However, the plot of the corresponding joint time-frequency cross-correlation function of the waveforms [Fig. 2(b)] shows an obvious peak which corresponds to the defect. Still, because of the knots in the UTP cable, the figure displays many other false reflections, which create bumps along the curve that make it difficult to detect any true defects. The resulting overlapped peaks cause inaccurate defect location calculations. According to calculations from Fig. 2(b), the defect is located around 6.5 m, far from the actual location of the incipient defect at 5 m.
To avoid the situation described above and to increase the robustness of JTFDR, two techniques are implemented into the post-processing algorithms:

1) Additive noise: Because the false reflections from the bends and knots are comparatively smaller than reflections from real incipient defects, random white noise can be added to the reflected waveforms to cover the fake and weak reflections and thus cause the reflections from incipient defects to stand out. Fig. 2(c) shows the joint time-frequency cross-correlation plot after adding noise. This figure is an improvement on Fig. 2(b) as the effects of most of the fake reflections are removed, but the curve corresponding to the known incipient defect is still unsymmetrical and ineffective for calculating location. Using Fig. 2(c), the defect is calculated to be at 5.7 m, which is better than the calculation obtained before adding the noise yet still unsatisfactory.

2) Notch filter: To improve on the results in Fig. 2(c), the center frequency being used in the JTFDR reference signal (100 MHz) is filtered out of the additive noise. Fig. 3 shows the magnitude plot of the designed notch filter in frequency domain.

Figure 2. (a) Incident and reflected waveforms of JTFDR in time domain; (b) corresponding time-frequency correlation without noise added; (c) corresponding time-frequency correlation with noise but without filter; (d) corresponding time-frequency correlation with noise and filter; and (e) classical TDR results.

Figure 3. Bode plot of designed notch filter.
The above plot indicates that the 100 MHz component of the signal input to the notch filter is filtered out. The noise added to the waveforms will be filtered first by this notch filter so that the noise no longer has the center frequency component of the incident waveform. The resulting noise after the notch filter better conceals the false reflections because the main frequency component of the reflections has already been filtered out. Figure 2(d) shows the joint time-frequency cross-correlation plot corresponding to the reflected waveforms after adding the filtered noise. Although the peak value of the curve corresponding to the incipient defect decreased to 0.5, the shape is much more symmetrical than in the two previous cases. With these improvements, the incipient fault location is calculated with acceptable accuracy at 5.1 m.

The test results above show that by adding pre-filtered white noise to the waveforms, JTFDR can accurately detect and locate incipient defects on unshielded twisted-pair cables, a feat that TDR cannot accomplish.

4. Accelerated Thermal Aging Testing for Prognostics

Aging can cause the degradation of electric cables and the failure of their critical functions. For effective prognostics, this process must be carefully monitored. The various techniques used to monitor the condition of cables can be categorized as mechanical, chemical, or electrical, depending on the different properties the technique monitors. However, thus far all available techniques are destructive, need to be performed in a laboratory setting, or cannot provide information about the remaining useful life of the cables. For this reason, JTFDR should be able to monitor a cable’s condition and predict the remaining useful life of installed electric cables. The following tests will show the great promise of JTFDR as a prognostic technique for installed cable systems.

For the accelerated aging test reported here, M17/95-RG180 cable samples were selected. These cables have a low-density dielectric Polytetrafluoroethylene (PTFE) and a Fluorinated Ethylene Propylene (FEP) jacket. The length of each sample is 10 m, and the hot spot is located from 5 m to 6 m; thus, the length of each hot spot is 1 m. The incident waveform sent down the cable has a time duration of 5 ns, a center frequency of 400 MHz, and a 100 MHz bandwidth which is selected based on the wave propagation property (e.g. attenuation) of the cable under test.

The procedure for the accelerated thermal aging test consists of three steps. Before the cable is put into the heat chamber, which is preheated to a specific temperature, the waveforms are acquired and processed to obtain the time-frequency cross-correlation baseline for future comparison. The intended hot spot of the sample is then put into the chamber for a certain number of hours, depending on how much the cable is to be aged. To monitor the aging process, the waveforms are acquired and processed after each hour to obtain an updated time-frequency cross-correlation plot. To achieve authentic and scientific results, this procedure is performed three times after each hour. After the accelerated thermal aging process, the cable is removed from the chamber and allowed to cool to room temperature.

To illustrate some of the technical limitations of classical TDR and to show how they are resolved by JTFDR, Fig. 4 offers a comparison of a set of experimental results. One meter of a 10 m coaxial cable was exposed in a thermal aging heat chamber for 15 hours and was then tested using TDR [Fig. 4(c)] and JTFDR [Figs. 4(a)-(b)]. As shown in Fig. 4(c), although TDR certainly reveals the beginning and end of the cable, this method makes it nearly impossible to detect and locate the hot spot in the coaxial cable.
The problems of TDR can be resolved using JT FDR. Figs. 4(a)-(b) show the experimental JT FDR results using the proper reference signal design and the time-frequency cross-correlation function under the same experimental conditions used to produce the TDR results in Fig. 4(c). The top portion of the figure shows the time-domain incident and reflected signals from the end of the 10 m cable. Fig. 4(b) illustrates how the time-frequency cross-correlation function of the reference and reflected signals can detect, locate, and assess the defects in the cable. For detection, the time-frequency cross–correlation function quantifies the existence of the signal component associated with the reference signal in terms of time and frequency signatures. This function is normalized between 0 and 1 so that the detection of the defects can be quantified within bounded values; i.e., the function indicates the probability of reflection from potential defects. Again, the reflection from the hot spot is not easily observed in the time domain only. However, the time-frequency cross-correlation function at the bottom of Fig. 4(b) clearly shows the detection and location of the hotspot. In addition, because this function provides time resolution and reveals the local time center, it can be used to accurately locate the defect in the cable.

![Figure 4. (a-b) Comparisons of JTFDR, and (c) classical TDR.](image)

The example in Fig. 4 illustrates how JTFDR is better able to detect age-related degradations than TDR. To demonstrate the capability of JTFDR to monitor the severity of a defect over time, Fig. 5 shows the result of an aging test at 250°C (50°C higher than the maximum operating temperature of the cable under test). Fig. 5 presents the time-frequency cross-correlation function before the aging, after 5 hours, and after 15 hours of thermal aging. The time-frequency cross-correlation functions at the origin and at the open-end of the cable show a peak value of 1. These values at the beginning and end of the cable do not change with thermal aging; however, the time-frequency cross-correlation exhibits reflections from the hot spot located at 5 to 6 m away from the beginning of the cable. Notably, the time-frequency cross-correlation peak value increases from around 0.1 before testing up to 0.5 after 15 hours.

In order to explore the capability of JTFDR to assess the status of the cables in the accelerated thermal aging test, we considered the following cases:

- Test #1 is the accelerated thermal aging process at 250°C.
- Test #2 is the same as test #1, but at 150°C (50°C lower than the maximum operating temperature).
- Test #3 is also the same test as #1, but with an external defect (0.25 inches of external jacket removed) in the middle of the hot spot to see how the defect affects the aging process.
In each accelerated thermal aging test, a 1 m portion of the cable is exposed to the heat for 14 hours. After the thermal aging, the cable is allowed to cool to room temperature (20°C) for 2 hours. The thermal aging process is monitored by two indices available from the time-frequency cross-correlation function. One index is the local peak value of the correlation curve, which indicates the severity of the aging process at the hot spot. The other index is the area of the time-frequency cross-correlation function, which indicates reflections throughout the cable under test. For convenience, the area is normalized by the area of the full reflection so that 100 correspond to the open end of the cable. The results from the three accelerated thermal aging test described above are provided in Figs. 6(a-f) in terms of the local peak and area of the time-frequency cross-correlation function. On the left side of Fig. 6 is the monitored local peak value [Fig. 6(a-c)] and on the right side of Fig. 6 is the normalized area under the time-frequency cross-correlation function [Fig. 6(d-e)]. The first row of axes [Figs. 6(a, d)] corresponds to test #1. Likewise, the second row [Figs. 6(b, e)] corresponds to test #2 and the third row [Figs. 6(c, f)] corresponds to test #3.

The first row of Fig. 6 corresponding to the local peak and area of the 250°C aging test indicates that the values of both indices have a similar tendency; they greatly increase in the first hour, then increase slowly during the rest of the aging test. During cool-down, both indices quickly decrease to a value between the baseline value (before aging) and the value at the end of the aging. This indicates that the cable cannot go back to its original status after cooling down, meaning the cable is aged permanently and the decreased portion after cooling is corresponding to the temporary effects of the heat in the chamber.

The second row of Fig. 6 displays the peak and area of the 150°C aging test. Once again, the values of both indices have a similar tendency, but they are not the same as test #1. In this case, the indices increase only slightly because the temperature is lower than the maximum working temperature of the cable. They then decrease quickly to the original value (around 0.1) during the cooling process, showing that the cable can go back to its original state, and proving that it has not aged permanently. As in test #1, the decrease after cooling is corresponding to the temporary effects of the heat in the chamber.
The third column of Fig. 6 corresponds to the peak and area of the 250°C aging test with a slight defect on the hot spot. The values of both indices again behave similarly; in the first hour, they increase to a high value close to that of the full reflection, as if from an open or short circuit, and then stay around that value for the rest of the aging test. During cool-down, the values of the indices quickly decrease to values a little lower than the values at the end of the aging but still much higher than the original. As in test #1, this proves that the cable cannot return to its original status, and it is aged permanently. In this case, the cable is aged much more seriously than in the 250°C aging test without a defect. This aging test shows that a defect, such as the loss of the outer insulation, amplifies the aging effect. Although this paper addresses accelerated thermal aging testing with coaxial cable, future research will investigate the effectiveness of JTFDR on other types of cable as well.

5. Conclusion

Previously, JTFDR has proven to be accurate and sensitive for fault detection on shielded, coaxial cables. Unshielded cables, however, are more challenging due to their typically high signal-to-noise ratio. Yet, by properly superimposing filtered noise onto its reference signal, JTFDR successfully detects and locates an incipient defect on an unshielded, twisted-pair cable. The time- and frequency-selective design of reference signal design in JTFDR enables us to detect and locate the defects on unshielded, twisted-pair cable.

This research has also demonstrated that JTFDR can successfully monitor the aging process of a cable under duress. The area and the peak of the time-frequency cross-correlation function provide information about the state of a wire under test, and this information can be monitored.
over time. Properly monitoring changes in the time-frequency cross-correlation and related indices reveals, over time, if the condition of a wire at a particular location is worsening. With this capability, JTFDR can predict a hard defect before it reaches its most dangerous state. JTFDR has proven to be robust, accurate, and sensitive for locating hard and incipient defects in both shielded and unshielded wires. This technique also successfully monitors a cable to reduce the possibility of a defect evolving into a dangerous break.

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References


