Frequency-Domain Reflectometery for on-Board Testing of Aging Aircraft Wiring

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***Abstract*—Aging aircraft wiring poses a significant safety threat and has been implicated in losses of both military and commercial aircraft. This paper describes the conceptual design and function of a "smart wiring system" based on a low-cost frequency-domain reflectometer (FDR) that can be used to test the integrity of aircraft cables nondestructively on board. This system will enable the pilot or maintainer to test all critical wiring systems prior to flight at the push of a button. The details and test results from the FDR system on realistic aircraft wires are described. The system has a bandwidth of 0.8–1.2 GHz, a range of 4.5 m, and a resolution of 3 cm and can determine the length and terminating impedance of a cable harnesses from measurements at a single end. The system is now being miniaturized to be imbedded in a "connector saver" format for aftermarket installation on common existing platforms.**

***Index Terms*—Aging wire detection, frequency-domain reflectometer (FDR), wire fault detection.**

I. Introduction

As THE military and commercial airliners age past their teen years, miles of wiring buried deep within their structures begin to crack and fray, and these problems can be very difficult to detect. Arcing and electromagnetic emissions from holes in wires can create havoc on an airplane. Cracks and small insulation frays, once thought to be rare and benign, are found by the hundreds in typical aircraft, and are cause for concern in any system with large amounts of wiring—the space shuttle, nuclear power plants, large machinery, trains, and even cars. Recent airline tragedies in which wiring is implicated include SwissAir 111, and TWA 800. The tragedies have pushed the need for wire-diagnosis techniques into the limelight and elicited strong responses from the Federal Aviation Administration (FAA), National Air and Space Administration (NASA), National Transportation Safety Board (NTSB), the Nuclear Regulatory Agency (NRA), and the White House [1]–[3].

While the most common method of finding cable faults is still visual inspection, the technology has been developed rapidly to help maintainers for finding and diagnosing a faulty wiring. One of the methods of testing cables is to measure the resistance from end-to-end of the cables. A low resistance means the cable is "good," and a high resistance means that it is broken. Several automatic methods of these measurements are available, and are routinely used. The only complication to this method is the complexity of the cable system itself. These methods determine which cable has the fault, but cannot locate the fault within the cable.

In an expansion of this technique, low-voltage (28 V or less) resistance tests [2] utilize a floating comparator to analyze the currents on the cables as the input current is stepped through several different levels. In a healthy cable, Ohm's law would predict that the resistance should stay the same for all current levels. If a nonlinear response of resistance is observed, this can be used to identify and locate cold solder joints, bad crimps, carbonization of the cable or connectors, and foreign matter on or near the cables. This method can be used on a fueled airplane (unlike high voltage tests). This method is probably not suitable for miniaturization or for pinpointing where on the cable the fault has occurred.

Another method, the dielectric-withstand-voltage (DWV) test, places a very high voltage (500 V or more) between adjacent, supposedly unconnected wires, and the leakage currents from one wire to another are measured to detect a degraded insulation, other small or large faults and frays [2]. Again, this method is not suitable for miniaturization or pinpointing the fault.

Reflectometry methods (which will be described in more detail in Section III) send a low-voltage high-frequency signal down the wire and detect reflections from anomalies along the length of the wire. These methods are presently available for detecting open and short circuits, and techniques for detecting frays, cold solder joints, and other small anomalies are emerging. All of these methods require that at least one end of the cable be disconnected from the plane and connected onto the test fixture. Typical test fixtures may be hand-held, brief-case sized, or large (size of a washing machine). This connection and reconnection increases the risk of maintenance-induced damage (particularly on old, brittle cables) and is generally done at the depot level of maintenance every few months or years.

In addition to methods for finding a fault on a wire prior to its causing an electrical incident, techniques are also being developed to detect the incident itself and disengage the wire. Arc-fault circuit breakers can reduce the risk of fire by tripping when an intermittent short circuit is detected. Ordinary cir-

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cuit breakers are heat-sensitive bimetal elements that trip only when an excessively large current is passed through the circuit long enough to heat the element. This I^2T power may be on the order of 1000% of the rated current for 0.35 to 0.8 s. By comparison, a single arc-fault event may last only 1.25 ms, and a series of events may last 20-30 ms. [2]–[4]. Although not enough to trip the circuit breaker, these arc faults can cause catastrophic local damage to the wire, and fires can occur with the breaker remaining intact. Arc-fault circuit breakers contain sophisticated electronics to sample the current on the wire at submillisecond intervals. Both time- and frequency-domain filtering are used to extract the arcing fault signature characteristic from the current waveform. This signature can be integrated over time to discriminate between a normal current and a sputtering arc-fault current. Advanced pattern-matching algorithms can discriminate between "ordinary" transients, such as motors being turned on and off and the "random" current surges that occur with arcing. Arc-fault breakers are required in new home wiring, and are being miniaturized for use on aircraft. These breakers are normally used in tandem with a traditional heat-sensitive breaker or include a heat-sensitive element in addition to the pattern-matching electronics. One of the significant challenges of the arc-fault circuit breaker system is to find the location of the fault to repair it once it has been detected. Without a quick and effective system for locating the fault, there is a great concern that the "human factor" will come into play and that someone will reset the circuit breaker, thinking that the fault they cannot see does not exist, and it must be a "bad circuit breaker". Therefore, the existing or emerging techniques for locating cable faults must be coupled with the arc-fault circuit breaker for maximum safety effectiveness.

This paper describes an emerging "smart wiring system" technology for on-board detection and location of faults in cables prior to electrical incidents or after an arc-fault circuit breaker has tripped. Rather than having to connect and disconnect the cables every time a test is desired, the electronics will be placed within the wire system itself and left in situ. They can be activated at the touch of a button (such as before or after each flight). In future generations of the system, the electronics may even be able to detect faults in real time during flight, thereby finding the "intermittent" faults that plague maintainers and enabling real-time reconfiguring of the wiring system to bypass damaged wires. Section II describes how the electronics will be integrated into existing aircraft wiring structures. Section III explains the different type of reflectometry methods that could be used in either an on-board or off-board test system. Section IV describes the details of the electronics and analysis required for phase detection FDR (PDFDR) that is the basis of this on-board test system. Section V describes the performance of the system for a variety of wiring types, and Section VI summarizes the first generation system and the work that is under development for further generations of on-board test equipment.

II. "Smart Wiring System"

The "smart wiring system" provides on-board testing of anomalies in aircraft wiring using small, inexpensive PDFDR

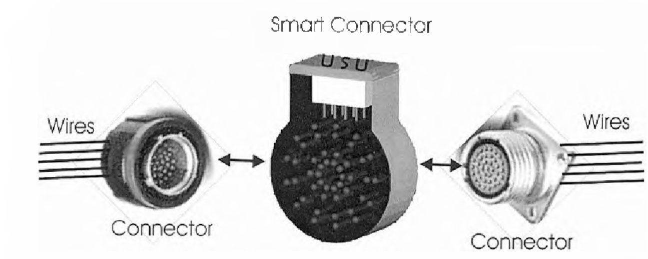

Fig. 1. Smart connector with connector-saver configuration.

that are integrated directly into the electronics of the aircraft system. For ease of installation in existing aircraft without, the electronics will be completely self-contained (including test sensor(s), microprocessor for control and analysis, battery/power supply, wireless data communication system, etc.) in a connector-saver configuration shown in Fig. 1. This "smart connector" will be installed at various junctions between wires and can test all wires that are electrically connected to this location. Typical aircraft wiring configurations can contain upto the order of 1500 connectors, more than 50 different wiring types and gauges, and over 20 different types of connectors, many of which are keyed for a specific location. Fortunately, in many of these configurations each smart connector can access significant portions of a network. The smart connector, can "see" through low-impedance terminations (connectors, junction boxes, etc.), but cannot "see" beyond the first high impedance termination (avionics, open switches, etc.). At present, each individual subsystem that is to be fitted with smart connectors must be analyzed to determine the optimal location of the test connectors. The desired range and resolution can be adapted for each subsystem, and the form of the smart connector must be adapated to fit the connectors in that subsystem. The first conceptual design for a 72-pin bayonet-type connector is shown in Fig. 1. Other shapes of connectors would also require additional space allocated for the test electronics. Each connector (72-pin variety) would weigh approximately 1 oz. Thus, it is likely that smart connector savers would be used only on flight-critical circuits or those that are particularly maintenance intensive.

The reason these devices are called "smart" is that they autonomously test the cable harnesses and associated loads to which they are attached, interpret the data, collect it via a wireless communication network, and extract the information critical to the maintainer – which wire is damaged, where it is damaged, and the type of the damage. The present generation, described in this paper, is meant to detect open and short circuits on wires that are not live (un-powered aircraft on the ground). Next generations under development may also detect frayed insulation and other small anomalies and may be used on live wires [5], [6].

III. Reflectometry Methods for Testing Cables

The main sensor in the "smart wiring system" is a PDFDR. Reflectometry systems connect to one end of a wire under test (with the other end either disconnected or connected to its normal load), and place a low power, high-frequency voltage signal directly on the wire itself. This signal reflects from discontinuities along the wire and from the end of the wire. The reflectometer detects and analyzes this reflected signal to determine the length of the wire and its load. When wires are combined into complex harnesses, the signatures of the multiple reflections from all of the junctions within these harnesses can get visually complicated and have led to the reputation that it "takes a Ph.D. to analyze them." In spite of this complexity, significant advances have been made in the past few years that enable automatic detection of faults. Reflectometry systems can be divided into two broad classes—time-domain reflectometry (TDR) and FDR.

TDR [8]–[12] launches a short rectangular step of voltage down the cable (shaped pulses can also be used). The wave travels to the far end of the cable, where it is reflected back, and circuitry at the source end of the cable is used to receive this reflected voltage. The incident and reflected voltages are both seen on the cable simultaneously, although their time domain signatures are generally separated in time because of the travel time delay down the cable. The cable impedance, termination, and length give a unique temporal signature that can be used to determine the status of the cable. Large changes in the wire (open or short circuits) cause large reflections that are easy to measure, and small changes in the wire (junctions, frays, etc.) cause smaller reflections that are more difficult to detect. TDR electronics include a fast-rise time pulse generator and fast voltage sampler, as well as a microprocessor or computer to analyze the results. Rise times on the order of ten or hundreds of picoseconds are typical, and samplers of similar order are available, but costly.

FDR [also called swept-frequency reflectometry (SFR)] sends a set of stepped-frequency sine waves down the wire. These waves travel to the end of the cable and are reflected back to the source. Electronics at the source end are used to sense either these reflected waves or the standing wave produced by the combination of the incident and reflected waves. There are three types of FDR that are commonly used in radar applications and can also be adapted for measurement of wires and cables. These are frequency-modulated continuous-wave (FMCW) systems, standing-wave reflectometry (SWR) systems, and PDFDR systems. Note that the literature is inconsistent on the names given to these methods, so when comparing methods it is essential to know the basic workings of the device.

FMCW systems use a set of high-frequency sine waves with frequencies that are ramped up in time, usually linearly [13]. The reflected wave is separated from the incident wave, usually by a directional coupler. By measuring the difference between the frequency of the reflected wave and the new (ramped up) frequency of the incident wave, the elapsed time and hence the length of the cable can be determined. The electronics for this system include a voltage-controlled oscillator (VCO) or other sine wave generator, a method or ramping up the control voltage to ramp up the frequency, and a sensor that can detect the frequency of both incident and reflected sine waves or the difference between them. This frequency detector must function at the high frequency that is sent down the cable (typically in the hundreds of megahertz to few gigaherz range).

SWR systems [14], [15] also send a high-frequency sine wave down the cable. The incident wave is reflected, and the superposition of the two waves produces a standing wave on the cable. The incident wave is not separated from the reflected wave in this method. The magnitude of the standing wave depends on the location and type of the load on the end of the cable and the frequency of the incident wave. Multiple measurements are required in order to determine the length and load on the cable. These measurements could be made at different locations, such as in the old "slotted line" measurements [16], but physically moving the detector is not practical for wire testing. Alternatively, measurements could be made at different frequencies, which is practical and useable for wire testing. When the frequency is swept, two basic types of measurements could be used. One method is to measure the magnitude of the standing wave at the source for every frequency in the step [13], and map out the standing wave and hence the length and load. This method can be sensitive to noise and frequency-dependent loads or losses on the line. Electronics for measuring the magnitude can be envelope detectors, received-signal-strength-indicator (RSSI) chips, or other methods commonly used for measuring the power levels of high-frequency waves. A measurement that is less sensitive to these problems is to step the frequency and determine the frequencies where either the nulls or peaks of the standing wave are observed at the source [14]. Electronics for measuring the nulls of the standing wave can be either a zero-crossing or slope indicator or other frequency-detection methods that are typically used in FM radio reception. If the frequencies are chosen conveniently within the range of typical consumer electronics applications, SWR electronics can be reasonably cost effective.

The PDFDR system [17]–[19] also sends a set of stepped frequency sine waves down the wire, where they are reflected from anomalies on the cable. Unlike SWR but similar to FMCW, the PDFDR isolates the reflected wave from the incident wave. While the FMCW method measures the frequency difference between the two waves, the PDFDR method measures the phase difference (which is proportional to time delay, the value measured by the TDR system). This phase difference can be detected using a frequency multiplier (mixer), which multiplies the two signals together. The output of the mixer includes two frequencies—the sum of the incident and reflected frequencies, and the difference of these two frequencies. Since the incident and reflected frequencies are the same, their sum will be the second harmonic (a high-frequency signal that is automatically filtered out by a low-frequency analog-to-digital (A/D) converter) and a dc signal (which is measured by the PDFDR system). As the frequency is stepped, the dc voltage at the output of the mixer has a sinusoidal (or sum of sine waves) signature that can be used to determine the length and load of the cable or anomalies along its length. Electronics for this system include a VCO and the phase detector (mixer). This is a simple, small, and expensive reflectometry system, and was therefore chosen for the "smart wiring system".

Confusion is common in the names of FDR methods, so for the purposes of clarity in this paper they will be referred to as "FMCW," "SWR," and "PDFDR" methods. Be aware that other authors may use different names for the various FDR systems, or may refer to one or another of these systems simply as an "FDR" system.

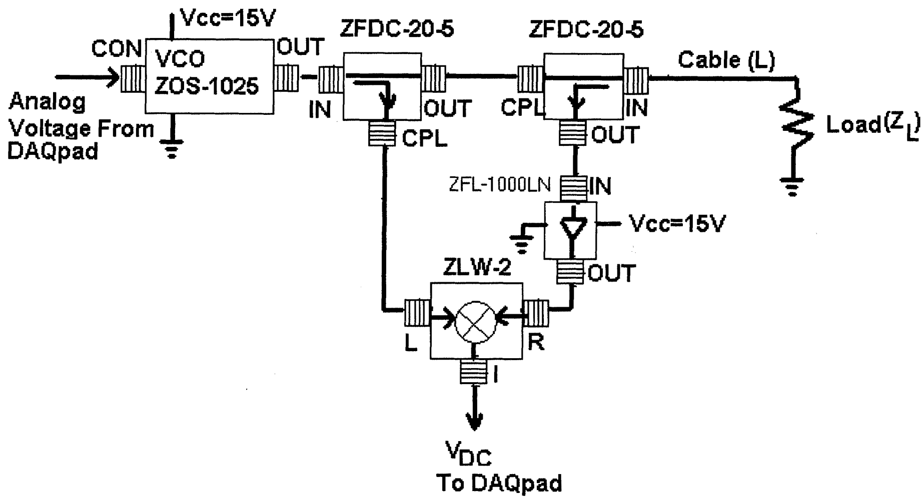

Fig. 2. PDFDR circuit.

TDR and FDR methods are strongly related. In theory, TDR provides information on the reflected wave on the cable over "infinite" bandwidth. In practice, this "infinite" bandwidth is very large, but limited by the rise time of the pulse and the speed of the sampling circuitry. In theory, FDR methods provide *identical* information over a selected subset of frequencies (usually a much smaller bandwidth than TDR). In practice, of course, differences in the sensitivities and accuracy of the electronics can cause variation in how the different systems perform. Still, it is useful to know that data received using a TDR can be replicated using an FDR method, and vice versa.

IV. Principle of Operation of the PDFDR

A. System Operation

As described in the previous sections, FDR has been used extensively in radar systems for measuring distance. For this application of aging wiring, it will be adapted to find the length and termination impedance of a cable. A PDFDR block diagram is shown in Fig. 2. A VCO provides a sinusoidal signal that is stepped over a given bandwidth (for example, 0.8–1.2 GHz). An analog dc voltage from the personal computer (PC) or microprocessor unit (mpu) controls the frequency of the VCO. The VCO signal is split in the power divider. A 20-dB coupler is used to divide the power, so that -20 dB of the incident power is sent to the mixer, and the remainder is sent to the cable. The incident signal travels down the cable and reflects back from the load at the end. The superposition (sum) of the reflected and the incident waves forms a standing wave on the cable.

The reflected wave is isolated from the incident wave by the second directional coupler and is sent to the mixer. The mixer "multiplies" the frequency on the radar frequency (RF) port by the frequency on the intermediate frequency (IF) port. The output has three frequency components—the RF frequency, an upper sideband frequency at RF + IF, and a lower sideband at RF – IF. When RF and IF are at the same frequencies as they are in PDFDR, this lower sideband is at zero frequency (dc). This dc voltage at the mixer output is the signal that we will detect and use to determine the length and load of the line. An A/D input to the computer acts as a low-pass filter and removes the higher frequency components, because it does not have sampling speeds to accommodate them.

The mixer is a square law device, that outputs power (in our case we are interested in the dc power) directly proportional to the squared magnitude of the sums of voltages on the RF and IF ports. The incident voltage on the RF port is given by $Ae^{-\mathrm{jkL}}$, and the reflected voltage on the IF port is given by $Be^{+\mathrm{jkL}}$. A is the amplitude of the incident wave after being split and sent to the RF port of the mixer. $e^{-\mathrm{jkL}}$ is complex notation for a wave traveling in the positive direction (toward the cable load). B is the magnitude of the reflected wave when it reaches the IF port of the mixer. Using a 20-dB directional coupler virtually all of the reflected signal is sent to the mixer. The reflected voltage B is $A\Gamma$, where Γ is the reflection coefficient of the load. Γ is $+1$ for an open circuit, -1 for a short circuit, and is complex for capacitive and inductive loads. The square law output of the balanced mixer (dc voltage) is therefore given in (1). Assuming that the load is either open, short, or resistive, Γ will be strictly real (no capacitive or inductive component)

$$V_{\mathrm{dc}} = \left|Ae^{-\mathrm{jkL}} + Be^{\mathrm{jkL}}\right|^2 = A + A\Gamma^2 + 2A\Gamma\cos(2kL) \quad (1)$$

where $k = 2\pi f/v_p$, f is the frequency that is output by the VCO, and v_p is the velocity of propagation on the cable, typically 0.6 to 0.8 times the speed of light in vacuum.

Equation (1) is for the theoretical PDFDR response of a system with a single reflection, but our system has some components that change this response. First, the offset term $(A + A\Gamma^2)$ vanishes, because a balanced mixer is used. Second, the mixer we are using is an inverting mixer, so the dc output voltage is the negative of that given above. The 20-dB directional coupler also induces a dc voltage that depends on the power levels arriving at the coupler. Considering all of these changes, the resultant dc voltage at the output of the mixer is

$$V_{\mathrm{dc}} = C_1 + AC_2\Gamma\cos(2kL) \quad (2)$$

where C_1 and C_2 are constants that dependent on the circuitry. We do not need to know their exact values, as we will be ignoring C_1 [the dc term in the fast Fourier transform (FFT) sequence] and normalizing out AC_2. An additional consideration for all practical circuit designs is that the magnitudes of the two inputs to the mixer may not be (in general, are not) equal. This does not change the form of the dc voltage function, however, so is not of consideration here. A final consideration is for cable harnesses with multiple reflections (such as a "Y"-shaped junction). For this case, multiple reflections will occur, and a sine wave representing the distance to each reflection will be added to (2). This changes the problem in nontrivial ways. Methods have been developed to analyze this data for a few connections, which is normally sufficient before the cable is terminated in an avionics box. [19]

B. Analysis of the PDFDR Response

The response of the PDFDR system is found from the dc voltage at the output of the mixer as the transmitted signal is stepped over a range of frequencies from f_1 to f_2 (bandwidth $f_{\mathrm{BW}} = f_2 - f_1$) in steps of Δf. This response is the sinusoidal waveform $(\cos(2kL))$ where $k = 2\pi f/v_p$. The number of cycles in this waveform is proportional to the distance (L) being measured. The FFT of this waveform will give a Dirac delta function (single spike) at a location we will call Peak.

The distance L is found from the location of this Peak by

$$L = \left(\frac{\text{Peak} - 1}{N_{\mathrm{FFT}} - 1}\right)\left(\frac{N_F - 1}{f_1 - f_2}\right) v_p \tag{3}$$

where

- Peak location of the Dirac delta peak in the FFT (an integer value);
- v_p velocity of propagation in the cable (m/s);
- f_1 start frequency of the FDR (Hz);
- f_2 stop frequency of the FDR (Hz)'
- N_F number of frequencies in the PDFDR $= (\mathrm{f_2 - f_1})/\Delta\mathrm{f}$;
- Δf frequency step size for PDFDR (Hz);
- N_{FFT} number of points in the FFT (an integer value, generally 2048).

C. Range of the System

The range of the system $L_{\max}$ is limited by the Nyquist Criterion [21], a basic premise of communication theory that requires that a sinusoidal signal must be sampled twice per period in order to take an accurate FFT. The range is reached when only two frequency samples are taken per cycle of the dc voltage waveform. Since the signal must travel both down the cable and back, the maximum cable length that can be measured is half the allowable range. This maximum length is therefore

$$L_{\max} = \frac{v_p}{4\Delta f}. \tag{4}$$

A frequency resolution of $\Delta f = 10$ MHz used in the PDFDR prototype will give a range of 4.5 m for cables with a velocity of propagation approximately 2/3 the speed of light. The maximum resolution available from the VCO that was used in this prototype is $650 \sim 1020$ MHz, which gives a maximum length of 138 m. If cables longer than this length are measured, the length will "wrap around". For instance, if $L_{\max} = 4.5$ m, and you measure a cable 5-m long, the calculated length will be 0.5 m.

D. Resolution of the System

The resolution (accuracy) of the measurement is limited by the resolution of the FFT that is used to find the number of cycles in the dc voltage waveform. The number of points in the FFT N_{FFT} is given by communication theory as $N_{\mathrm{FFT}} = 1/(\Delta f)(\Delta 2kL)$, so the resolution is $\Delta L = v_p/(2N_{\mathrm{FFT}}\Delta f)$. The number of points in the FFT, N_{FFT}, can be increased or decreased as desired to increase the resolution. This is done by "zero-padding", adding zeros after the original sampled data. Additional measured samples are not needed, so the only limit to the number of samples that can be added is computational resources for computing the FFT. For this system with $\Delta f = 10$ MHz and $N_{\mathrm{FFT}} = 1024$, a resolution (expected error) of 3 cm is achieved. The observed experimental error for coaxial cable is below 0.5 cm, which is below this limit.

E. Minimum Cable Length

The shortest length of cable that can be measured occurs when there is only one maxima in the set of dc data. For the FDR system running from 0.8–1.25 GHz (450-MHz bandwidth) in 10-MHz increments, this is about 22.33 cm. Spectral estimation methods [22] and others [23], [24] that are used for nonuniform sampled signals can be used to reduce this minimum cable length, so this should not be assumed to be a theoretical limit.

An additional limitation must be noted for non 5-Ω cables. Because of the nonsinusoidal waveforms that these cables produce (discussed later), a dc offset and other low frequency terms are produced are produced in the dc voltage waveform. These were eliminated in the present software by filtering them out (ignoring them). This effectively removes the ability to "read" short cables, and the new minimum distance is 26 cm. More advanced software could be developed to remove this problem through either baselining or deconvolving the window function caused by zero padding, and this is recommended for future versions of the PDFDR prototype.

F. Types of Faults Detected

All reflectometry methods rely on a strong reflection from the fault on the cable in order to locate it. Open and Short circuits provide the largest reflection coefficient, so not surprisingly they are the easiest to detect. Fortunately for detection and location, many other faults of interest appear as very near open- or short- circuits at the high frequencies commonly used in reflectometry methods. Wires that have been arced, even if the circuit breaker has blown before they become an open circuit to dc measurement, show up as near-open circuits. Moisture (particularly salt water) in a connector, or between frayed wires, often appears as a near-short circuit. Damaged insulation, however, which many aircraft maintainers would like to be able to detect, causes such minor reflections that it is virtually indistinguishable by FDR methods.

TABLE I
COMPONENTS USED FOR PROTOTYPE PDFDR CIRCUITS

Connectorized	Surface-Mount [25]	
ZOS-1025	JTSO-1000W	VCO (650 to 1020 MHz)
ZFdc-20-5	LRdc-20-2J	Power Splitter (20 dB directional)
ZFL-1000LN	not used	Low Noise Amplifier (20 dB) (optional)
ZLW-2	ADE-5	Balanced Mixer

TABLE II
TYPES OF CABLES TESTED

	type of cable	velocity of propagation / c	characteristic impedance
Non-aircraft Wire	coaxial (RG58 and 8)	0.77	50 ohm
	twin lead (video)	0.78	300 ohm
Aircraft Wire	twisted shielded pair	0.61	45~80 ohm

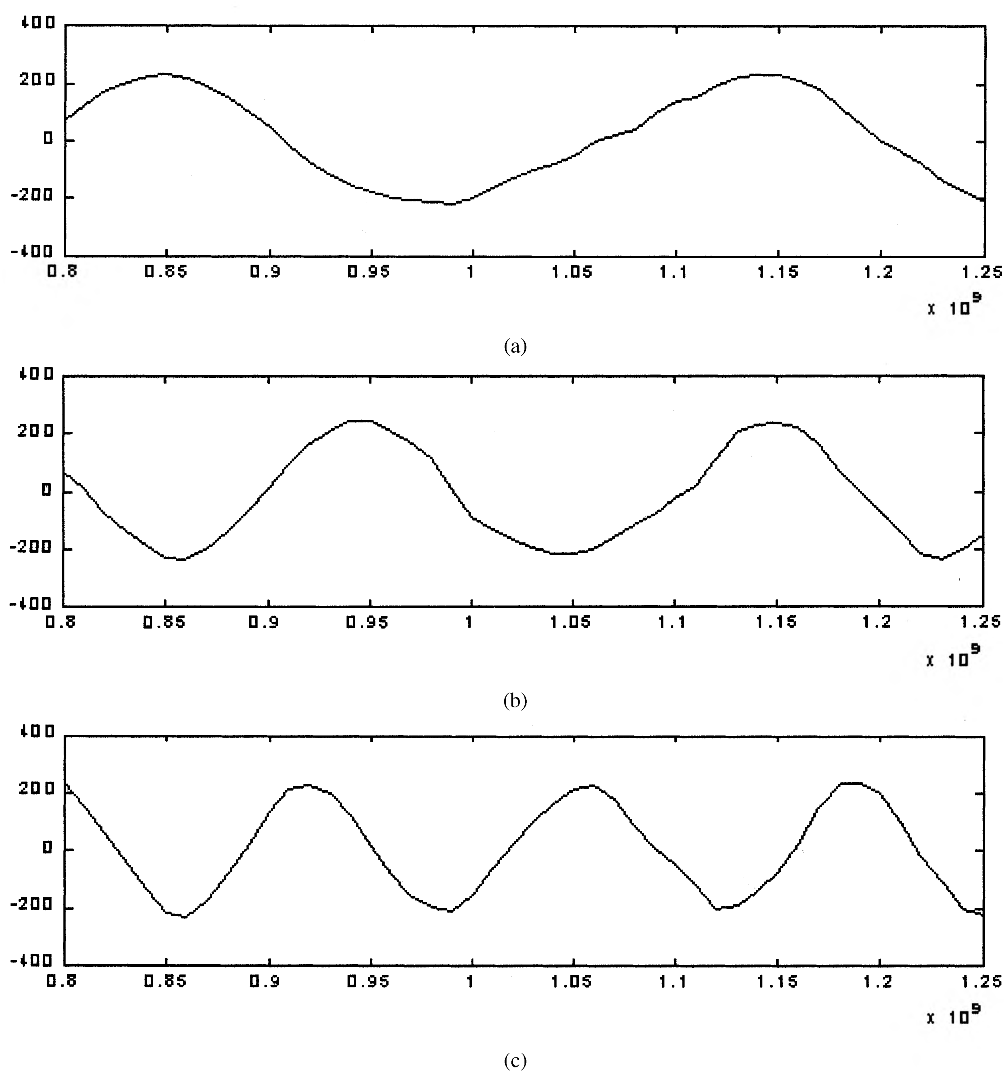

Fig. 3. Measured results for dc voltage at the mixer output as a function of frequency, for RG-58 coaxial cable. (a) 40-cm cable. (b) 75.69-cm cable. (c) 122.3-cm cable.

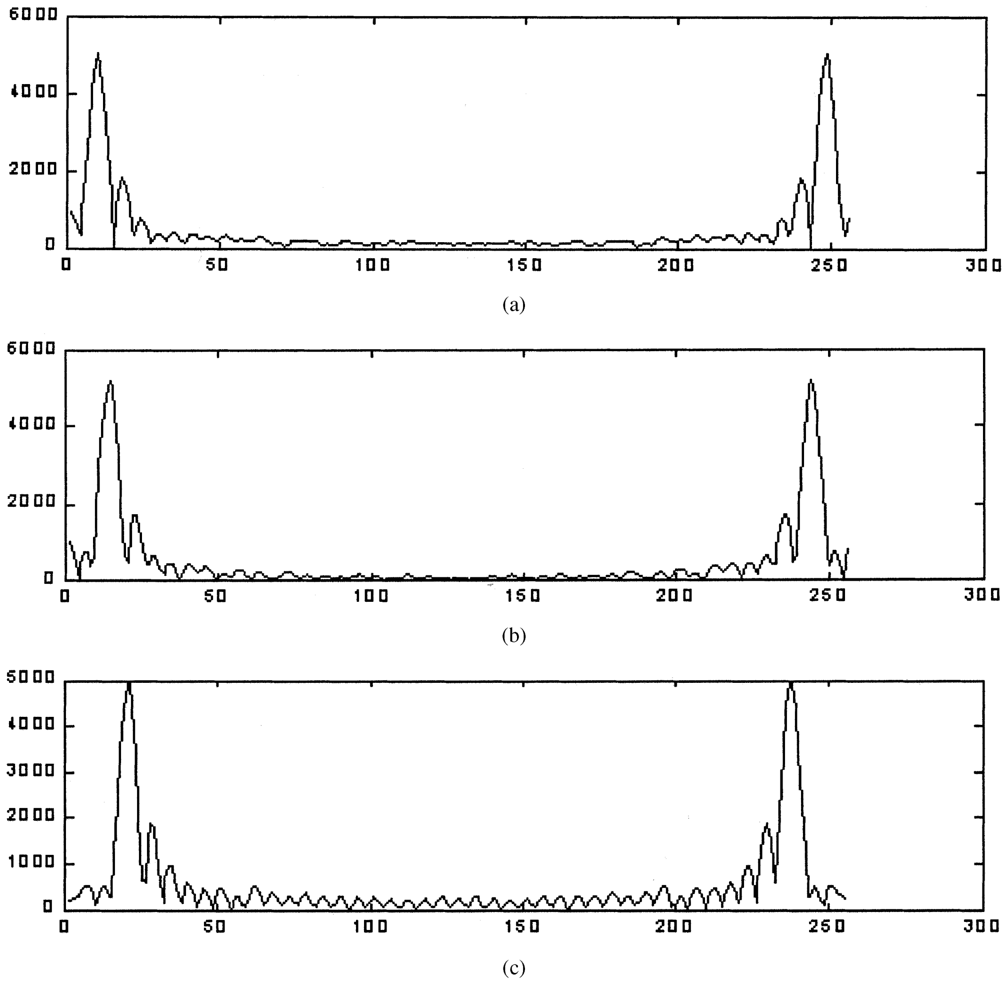

Fig. 4. FFT (based on a 2048-point FFT) as a function of cable length for the cables in Fig. 2. (a) 40-cm cable. (b) 75.69-cm cable. (c) 122.3-cm cable.

G. PDFDR Prototype Hardware

Two versions of the PDFDR prototype have been developed and tested, and their component identification is given in Table I.

The system has been controlled either with a personal computer via a data acquisition system (IBM DAQpad 1200 [26], [27]) or through a microprocessor unit or signal processing chip with built in A/D and digital-to-analog (D/A) converters. The processor sends an analog dc voltage to the VCO. Since the frequency response of the VCO is somewhat nonlinear, a lookup table is used to choose an exact input voltage to produce the desired frequency steps. After a few microseconds delay to allow the VCO to stabilize, the reflected signal to return to the source, and the mixer to stabilize, the computer reads the analog dc voltage from the mixer output. It repeats these steps for each stepped frequency until all voltages have been sampled. It then takes the FFT of the dc samples from the mixer, searches for the maximum peak in the transform, and computes the length using (2).

When the electronics for the FDR are integrated into a multichip module, the entire module can be approximately $1 \times 1 \times 0.25$" in size. The microprocessor can be equally small. The FDR electronics can be mass-produced in this form for under \$20 each. Typical microprocessors that can control and analyze the FDR are also under \$20. It is estimated that the entire connector saver unit could be mass produced for around \$200. The size and weight of the electronics are small compared to the connector saver, which because of its mechanical design is necessarily larger and heavier.

V. Test Results

Several types of cables have been tested, as shown in Table II. The impedances and velocities of propagation were determined using a TDR and/or manufacturers' specifications.

The first set of tests verify that the system works as expected for 50-Ω shielded cables. An RG-58 coaxial cable (50 Ω) was connected as the device under test (DUT) and terminated with either an open or a short (from Hewlett Packard 3.5-mm calibration standards). Fig. 3 shows the measured dc voltages at the mixer output for three different lengths of cable (40, 75.69, 122.3 cm), which are sinusoidal with number of cycles increasing proportional to the length. These results agree extremely well with what was expected and with predictions (using the HP/EEsof Advanced Design System software, but not shown in this paper for brevity) [13], [15]. Fig. 4 shows the FFTs of these waveforms, from which the maximum peak (at a location proportional to the length of the cable) is detected. The location of the maximum peak is used with (3) to find

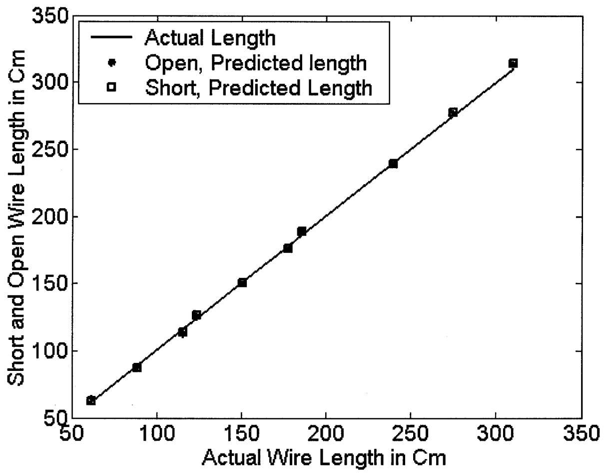

Fig. 5. Coaxial cable test results.

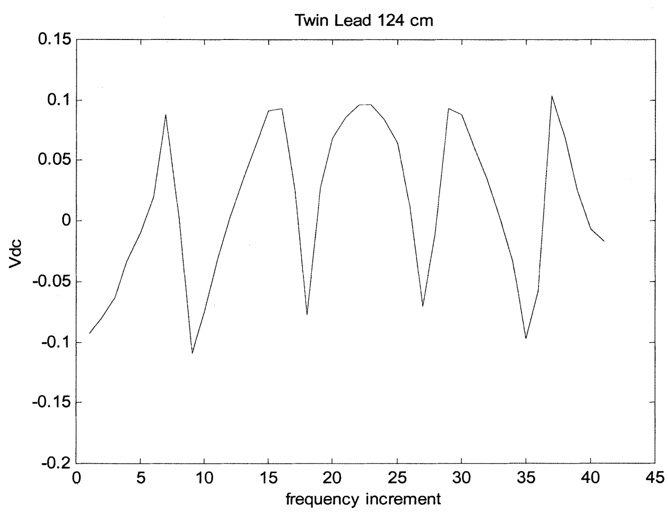

Fig. 6. Measured results for dc voltage at the mixer output showing nonsinusoidal behavior for 124 cm of twin lead cable.

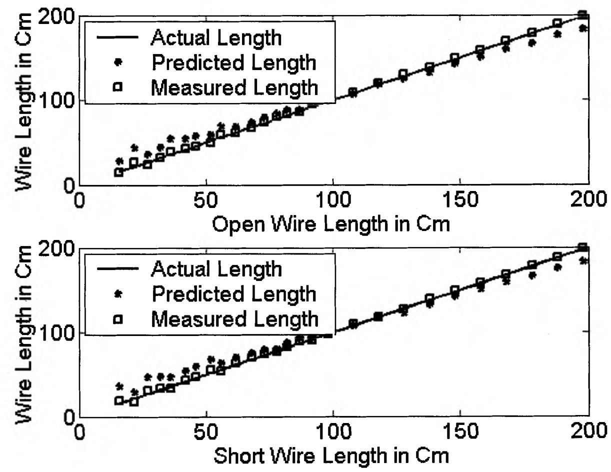

Fig. 7. Twin lead results with open and short.

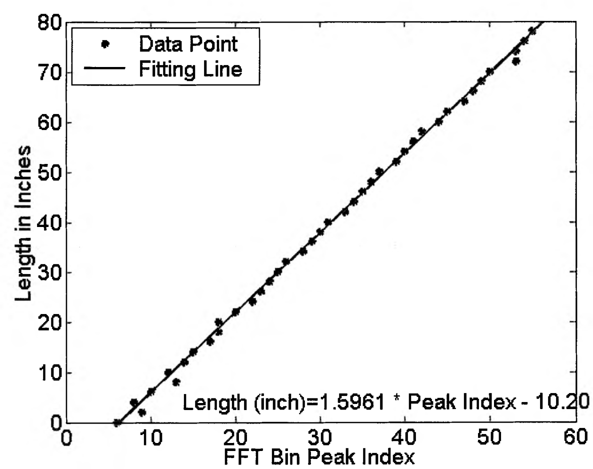

Fig. 8. Peak index of FFT versus length of twisted triple shielded pair cable (M22750–24SE2S23) in F18 with a FDR1000 (430 ~ 1040 MHz).

the predicted length of the cable, which is shown in Fig. 5 compared to the actual lengths of the cables. Predicted lengths are found to be within an accuracy of 0.5 cm. The termination (short or open) was correctly predicted for all of these tests.

The next set of tests demonstrates the system performance for non 50-Ω cable. Twin lead video cable (nominally 300 Ω) was connected as the DUT. Although twin lead cable is not used in aircraft, it demonstrates the reflectometry response that is expected from single-conductor aircraft wires that are tested in pairs. A baby N connector (BNC)-to-banana adapter (which adds an additional impedance mismatch to the circuit) was used to connect the two wires from the twin lead to the 3.5-mm coaxial connector of the FDR. This meant that one lead of the twin lead was connected to the ground (the outer conductor of the 3.5-mm coaxial connector), and the other was connected to the inner conductor. Since the twin lead is symmetrical, it does not matter which lead is connected to which conductor. The end was either left open (baring the wires) or shorted with an alligator clip.

The voltage waveform is no longer a pure sinusoidal, because the twin lead is 300 Ω rather than 50 Ω, and the additional mismatch at the banana connector complicates the waveform, as shown in Fig. 6. When the FFT is taken, a larger peak at the front (zero length) is seen because of this mismatching. In spite of this, however, the peak in the FFT that corresponds to the reflection from the end of the cable gives predicted lengths that are still very good as can be seen in Fig. 7. Maximum error is less than 4 cm. It is worth noting that the nonsinusoidal behavior agrees with predictions using HP/EEsof ADS [13], [14] and is dominated by the mismatch of the cable rather than the banana connector.

This final set of tests show what happens on shielded twisted cable, which is common in aircraft applications. Actual aircraft cable provided by NAVAIR was tested. This cable is shielded twisted cable, where both the shield and inner conductors are made from multistrand wire. This cable shows significant anomalies on the TDR. The apparent impedance of this cable varies from 45 to 80 Ω along the length of the cable, because the twisting varies within the shield, and the conductors are not in constant proximity. This wire was connected to the FDR using the SMA to pins, connecting onto the two inner conductors. The index of the responding peaks of FFT due to the length of the wire has been plotted with the actual length of the wire on y axis. Results for the shielded aircraft wire are shown in Fig. 8. These signatures indicate that the length of the wire has a linear relationship with the peak index of FFT. The resolution is 1.596-in long. The linear equation of the length is (FFT peak index $\times$ 1.5961 in $-$ 10.2 in), as shown in Fig. 8. A more advanced analysis method is currently being developed.

VI. Conclusion

A "smart wiring system" is being developed for on-board testing of aging aircraft wiring. The PDFDR used for the main sensing element in this system has been developed using a frequency range of 0.8–1.2 GHz, this system provides an accuracy of 3 cm and a range of 4.5 m. The range and resolution can be adapted as needed for specific wiring harnesses by changing the frequency bandwidth and number of steps used in the frequency sweep. The PDFDR system has been tested for several types of cables including coaxial, twin lead, and shielded twisted cable of an aircraft wire.

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