Mixed-Signal Reflectometer for Location of Faults on Aging Wiring

Peijung Tsai, *Student Member*, Chet Lo, *Member*, You Chung Chung, *Senior Member*, and Cynthia Furse, *Senior Member*

***Abstract*—Location of faults on aging cables is of great interest to maintainers of aircraft, cars, power distribution systems, communication systems, etc. One class of methods for locating faults is frequency domain reflectometry (FDR), using sine waves as the forcing function. A new frequency domain method called mixed-signal reflectometry (MSR) is described in this paper and compared to data from phase detection FDR (PDFDR) methods. The MSR is less expensive and smaller than the PDFDR and has very similar performance. A prototype system using the 100–200-MHz bandwith with 256 40-kHz steps is shown to have a resolution of about 10 cm, very similar to a PDFDR in the same frequency band.**

***Index Terms*—Nondestructive evaluation, reflectometry, wire fault location.**

I. INTRODUCTION

AGING aircraft wiring has been identified as an area of critical national concern [1]. Since the wiring for most planes was intended to last the lifetime of the plane, it was not designed to be replaced or even to be easily inspected, which makes maintaining wiring a daunting and expensive task. Safety is, of course, a concern after the crashes of TWA 800 and Swissair 111, in which arced wiring was implicated [2].

Several methods are available for locating faults on wiring. End-to-end connectivity and/or resistance checking and visual inspection are the most common methods in practice today [1]. While these methods are certainly useful for detecting faults, actually locating where on the wire they occur can be very difficult. Several methods have recently emerged or are emerging to help locate faults on wires. Virtually all of these methods simply rely on measuring the distance to the end of the wire and/or the impedance or load at the end. If this has changed over time or is not what it is "expected" to be, then a fault is assumed to be present at the "end" of the wire. These methods can locate only "hard" faults (open or short circuits), not frays, chafes, bends, etc., since these small anomalies are too small to measure with any of the methods described below.

Capacitance sensing (for open circuits) and inductance sensing (for short circuits) is perhaps the simplest of the test methods [3]. The capacitance or inductance per unit length is known, from which the length of the wire can be found. This method has advantages over the reflectometry methods described below in that it is more accurate for very short (less than 1 ft) lengths of wire than reflectometry methods. It can also be used for long lengths of wire with good accuracy. It cannot, however, be used on any type of branched network, and the inductance sensing for short circuited wires tends to be very sensitive (and, therefore, prone to errors) for some types of unshielded wires.

Reflectometry, which sends a high-frequency signal down the wire and measures the reflected return, is commonly used for locating faults on wiring. Time domain refelctometry (TDR) uses a voltage step or pulse as the test signal [4]–[6]. The location is determined by the time delay between the step and its reflected echo. TDR, the "granddaddy" of reflectometry methods for wire testing, is accurate for locating faults, but it is expensive and requires professional experience to interpret the results. It also is not easily built in a small, low-power system.

Sequence and spread spectrum reflectometry (S/SSTDR) use a digital pseudonoise (PN) pulse train or sine-modulated PN code to locate faults on wires [7], [8]. These sensors are capable of locating faults on wires that are live, since the test function can be detected even when it is well below the noise margin of the signal already on the wire. This gives S/SSTDR a significant edge over all other reflectometry systems, because they can locate intermittent wiring faults potentially in flight. There are a number of applications where this level of complexity and capability may not be needed, however, and this is the application space that simpler methods such as frequency domain reflectometry address.

A frequency domain reflectometer (FDR) [9] is accurate for finding the distance to hard faults (open/short) and less expensive than TDR or S/SSTDR. It is more expensive than capacitance sensing but is capable of locating faults on branched networks, whereas capacitance sensing is not. FDR sends out a sinusoidal wave or set of sine waves and analyzes the phase and/or magnitude of the reflected wave. There are several members of the frequency domain reflectometry family. Phase detection FDR (PDFDR) [9] (which measures the phase difference between the waves) requires a voltage controlled oscillator, two directional couplers, and a mixer to measure the phase shift between the incident and reflected wave and, hence, the length of the line and location of fault. Standing wave reflectometry (SWR) [10], which measures the magnitude of the standing

---

Manuscript received December 23, 2003; revised December 1, 2004. The associate editor coordinating the review of this paper and approving it for publication was Dr. Eugenii Katz.

P. Tsai and C. Lo are with the Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT 84112 USA (e-mail: ptsai2002@yahoo.com; clo@ece.utah.edu).

Y. C. Chung is with the Information and Communication Enginnering Department, Daegu University, Kyungsan, Kyungbuk 712-714, Korea (e-mail: youchung@daegu.ac.kr).

C. Furse is with the Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT 84112 USA, and also with VP Technology, LiveWire Test Labs., Inc., Salt Lake City, UT 84117 USA (e-mail: cfurse@ece.utah.edu).

Digital Object Identifier 10.1109/JSEN.2005.858894

wave produced by the superposition of the incident and reflected waves, requires a high-frequency system for measuring magnitude. Frequency-modulated continuous wave (FMCW) systems use a set of high-frequency sine waves with frequencies that are ramped up in time, usually linearly. 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. This method has not been used for wire testing, to our knowledge.

This paper describes a new member of the frequency domain reflectometry family, mixed-signal reflectometry (MSR). Unlike PDFDR, the two signals do not need to be separated by expensive, large directional couplers. Unlike SWR, it does not require a high-frequency voltage measurement device. MSR uses the sum of two sine waves, one incident and the other reflected, squares the sum, and analyzes the DC voltage extracted from the square of the sum.

II. MIXED-SIGNAL REFLECTOMETRY

An MSR contains a voltage-controlled oscillator (VCO) and a mixer, as shown in Figs. 1 and 2 (an attenuator, with attenuation factor A, may be added to prevent overloading the mixer; however, it is not required theoretically). The VCO sends out a sinusoidal wave into the wire under test. When the sinusoidal wave reaches the end of the wire, it reflects back and is superimposed on the incident wave. If the transmitted sinusoidal wave is $\sin(\omega t)$, then the reflection at the point of transmission is $\alpha(\tau)\Gamma\sin[\omega(t+\tau)]$. Where ω is the VCO frequency, $\alpha(\tau)$ is the attenuation due to the length of returning path, Γ is the reflection coefficient at the point of impedance discontinuity, and τ is the time it takes for the signal to go round trip. This combination of the incident and reflected waves then goes through the attenuator which reduces the amplitude of the signal to prevent overloading the mixer. The attenuated signal is now $A[\sin(\omega t)+\alpha(\tau)\Gamma\sin(\omega(t+\tau))]$ and feeds into both the LO and RF inputs of the mixer simultaneously. The output of the mixer is the square of the sum of the incident and reflected signals

$$\begin{aligned}&\{A[\sin(\omega t)+\alpha(\tau)\Gamma\sin(\omega(t+\tau))]\}^2\\&\quad=A^2\left\{\left[\frac{1}{2}(1+\alpha^2(\tau)\Gamma^2)+\alpha(\tau)\Gamma\cos(\omega\tau)\right]\right.\\&\qquad-\frac{1}{2}[\cos(2\omega t)+\alpha^2(\tau)\Gamma^2\cos(2\omega(t+\tau))\\&\qquad\left.+\,2\alpha(\tau)\Gamma\cos(2\omega t+\omega\tau)]\vphantom{\frac{1}{2}}\right\}.\end{aligned}$$

This contains the second harmonic (2ω) of the sine wave and a DC value $A^2[(1/2)(1+\alpha^2(\tau)\Gamma^2)+\alpha(\tau)\Gamma\cos(\omega\tau)]$. The mixer output goes into an analog to digital converter, which automatically filters out the high-frequency component (typical low-frequency A/D converters do not respond quickly enough to read high frequencies and effectively average them out) and records the DC value and sends it to a computer. The computer controls the VCO and increments the frequency. The measurements are repeated until 256 DC values have been collected. The recorded DC values as a function of VCO frequency are then a sinusoidal wave whose angular speed is linearly proportional to the time delay τ and, in turn, the wire length. After removing the mean value $(A^2/2)(1+\alpha^2(\tau)\Gamma^2)$, the DC value will become $A^2\alpha(\tau)\Gamma\cos(\omega\tau)$ [please note that, for a given wire, τ is a constant, and so is $\alpha(\tau)$], and the Fourier transform of the DC value will show a peak at the corresponding delay. For different impedance discontinuity, Γ has different values. The peak has a magnitude dependent on the value of Γ, as shown in Fig. 4. Also from Fig. 4, it is shown that the peak magnitude decays exponentially, a function $\alpha(\tau)$, as the distance from the impedance discontinuity increases. So, $\alpha(\tau)$ gives a good indication about the maximum length of a wire that MSR can measure. Small frays, bends, etc., may also be thought to produce additional reflections that could interfere with the MSR measurement, but their impedance discontinuities are so small (generally less than 0.1% reflection) that these reflections are negligible [12].

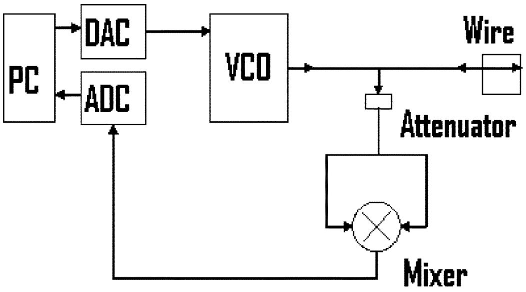


Fig. 1. MSR system diagram.

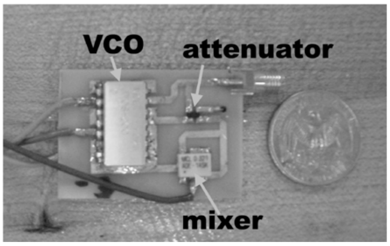


Fig. 2. Prototype MSR circuit. The electronics for this prototype are from MiniCircuits, Inc [11]. The VCO part number is JTOS200, the attenuator is LAT15, and the mixer is ADE-1ASK.

Notably, if there are sources of additional reflections on the wires, such as from a branched network, additional frequencies will also be observed, corresponding to the distance to each reflection point and the magnitude of the reflection coefficient seen at that point. The combined signal is a linear combination of the sinusoidal waves with corresponding frequencies and phase shifts. The output from the mixer after removing the mean becomes $A^2\sum_i\alpha(\tau_i)\Gamma_i\cos(\omega\tau_i)$. The Fourier transform of the DC value will show a sequence of peaks corresponding to the combination of delays as shown in Fig. 3. The analysis of these responses can become very complex for branched wire networks where many, possibly overlapping, reflections can be observed. Methods to resolve the network topology have been addressed separately [13] and are beyond the scope of this paper.

III. MEASUREMENT RESULTS

The MSR gives results that are very similar to a PDFDR [9]. Fig. 3 shows the DC voltage of the PDFDR and the MSR for three wires of lengths 94.4, 457.2, and 711.2 cm. The wire is

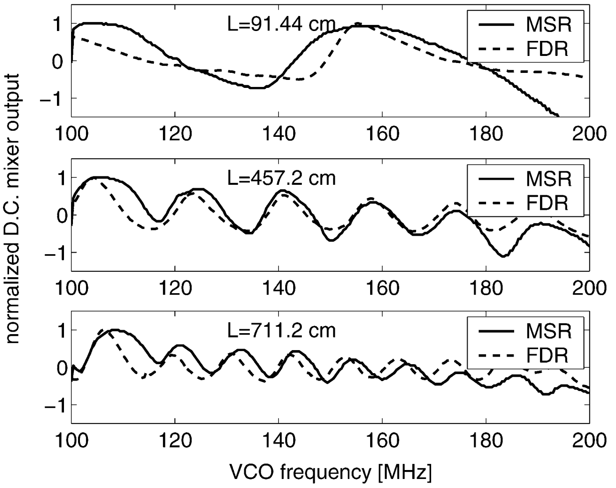


Fig. 3. MSR and PDFDR DC mixer output comparison for wires of length 91.44, 457.2, and 711.2 cm from top to bottom, respectively. All data is normalized to a maximum of 1.0.

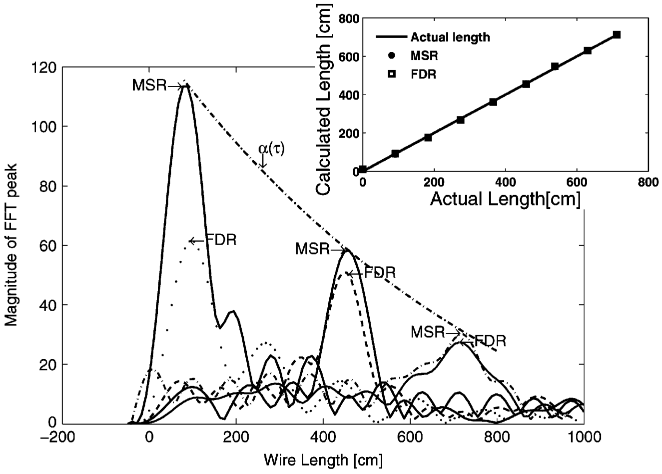


Fig. 4. Fourier transforms of the MSR and FDR responses for wire lengths of 91.44, 457.2, and 711.2 cm.

twisted shielded pair aircraft wiring, with a velocity of propagation of 0.61 times the speed of light. The MSR and PDFDR give very similar data for long wires. For short wires, the MSR gives less distortion in the signal than the PDFDR.

MSR (and all other reflectometry methods) have an impedance discontinuity where the board attaches to the wire, which produces a reflection corresponding to near zero length. This introduces a low-frequency sinusoidal signal superimposed with the higher frequency signal from the end of the wire. If the wire being tested is long, the reflected energy is relatively small due to attenuation in the wire, and the amplitude is relatively small compared with the amplitude from the reflection at the connection to the board. Thus, the low-frequency (zero length) peak may dominate, giving an incorrect length measurement. This problem can be reduced by using signal processing to remove the low-frequency noise from the data.

Fig. 4 shows the 2048-point Fourier transform of the MSR response of the different wire lengths from Fig. 3 after removing the low-frequency signal. As expected, the location of the FFT peak is linearly proportional to wire length, and the amplitude of the FFT is an exponential curve $\alpha(\tau)$, the attenuation due to small loss on the wires.

The location of the peaks from Fig. 4 show the calculated length of the wire compared to the actual length for the MSR and PDFDR. The maximum error for these methods is about 10 cm for this example. Note that the error is relatively constant over the lengths tested (0 to 800 cm). This is typical of all but the most lossy wires (such as "filter wire" that is designed with internal loss to attenuate high-frequency signals). Even though the peaks in Fig. 4 are smaller for longer wires because of attenuation and dispersion, they are still sufficiently large that the measurements are accurate. The error is mostly associated with the ability to identify the exact location of the peak from the Fourier transform (Fig. 4) data. This is independent of wire length. Additional sources of error, such as not knowing the wire type and its resultant velocity of propagation or linear fit (as in Fig. 4), would create an additional source of error that would be proportional to wire length, typically on the order of 10% error. In our measurements, we have assumed that wire type is known.

IV. SUMMARY

The performance of a MSR was compared to a PDFDR. The MSR can be built for less cost than the PDFDR, without sacrificing performance. The MSR has less distortion in the observable sinusoid and, therefore, less error when translating into the Fourier transform and wire length. For longer wires, the MSR has more error from the low-frequency response at the connection to the board, probably due to the lower magnitude of the signal sent down the wire.

REFERENCES

[1] Wiring Integrity Research (WIRE) Pilot Study, NASA, A0SP-001-XB1, Washington, DC (2000).

[2] C. Furse and R. Haupt, "Down to the wire: The hidden hazard of aging aircraft wiring," *IEEE Spectrum*, no. 2, pp. 35–39, Feb. 2001.

[3] N. N. Amarnath, "Capacitance and Inductance Sensors for the Location of Faults in Wires," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Utah, Salt Lake City, 2004.

[4] G. J. Conroy, "Cable fault locating by electronic means," in *Proc. Mines Technology Transfer Semin, Mine Power Distribution*, Mar. 1995, pp. 104–114.

[5] N. G. Paulter, "Long-term repeatability of a TDR-based printed wiring board dielectric constant measurement system," *IEEE Trans. Instrum. Meas.*, vol. 47, no. 6, pp. 1469–1473, Dec. 1998.

[6] N. A. Mackay and S. R. Penstone, "High-sensitivity narrow-band time-domain reflectometer," *IEEE Trans. Instrum. Meas.*, vol. 23, no. 2, pp. 155–158, Jun. 1974.

[7] C. Furse, P. Smith, M. Safavi, and C. Lo, "Feasibility of spread spectrum reflectometry for location of arcs on live wires," *IEEE Sensors J.*, vol. 5, no. 6, pp. 1445–1450, Dec. 2005.

[8] P. Smith, C. Furse, and J. Gunther, "Fault location on aircraft wiring using spread spectrum time domain reflectometry," *IEEE Sensors J.*, vol. 5, no. 6, pp. 1469–1478, Dec. 2005.

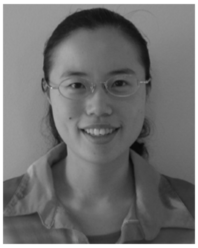
[9] C. Furse *et al.*, "Frequency-domain reflectometry for on-board testing of aging aaircraft wiring," *IEEE Trans. Electromagn. Compat.*, vol. 45, no. 2, pp. 306–315, May 2003.

[10] P. J. Medelius and H. J. Simson, "Non-Intrusive Impedance-Based Cable Tester," U.S. Patent 5 977 773, Nov. 1999.

[11] RF/IF Designer's Guide [Online]. Available: http://www.minicircuits.com

[12] A. Jani, "Location of Small Frays Using TDR," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Utah, Salt Lake City, 2003.

[13] K. Nagoti, "Mapping of the Network Topology From Reflectometry Data," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Utah, Salt Lake City, 2004.



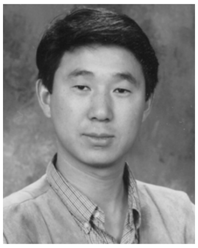
Peijung Tsai (S'02) was born in Taiwan, R.O.C., in 1979. She is currently pursuing the B.S./M.S. degrees at the Electrical and Computer Engineering Department, University of Utah, Salt Lake City.

Her current research focus is on applying multiband frequency domain reflectometry to detect aging wires faults.

Chet Lo (M'01) received the B.A. degree in physics/mathematics, the M.S. degrees in mathematic and electrical engineering, and the Ph.D. degree in electrical engineering from Utah State University (USU), Logan, in 1993, 1997, 1998, and 2001 respectively.

He is a Research Assistant Professor with the Center of Excellence for Smart Sensors, University of Utah, Salt Lake City. His current research interests include wire health monitoring, reflectrometry theory, and adaptive signal processing for branched wiring system identification.

Dr. Lo was awarded the Best International T.A. of the Year and was the winner of the Best Research Paper Competition on Scholar Day at USU.



You Chung Chung (SM'03) received the B.S. degree in electrical engineering from INHA University, Inchon, Korea, in 1990, and the M.S.E.E. and Ph.D. degrees from the University of Nevada, Reno (UNR), in 1994 and 1999, respectively.

He is an Assistant Professor with the Information and Communication Engineering Department, Daegu University, Kyungbuk, Korea. He was a Research Assistant Professor with the Electrical and Computer Engineering Department, University of Utah, Salt Lake City, and Utah State University, Logan. His research interests include computational electromagnetics, optimized antennas and array design, conformal and fractal antennas, smart wireless sensors, aging aircraft wire-detection sensors, optimization techniques, EM design automation tool development, RFID, and genetic algorithms.

Dr. Chung he received an Outstanding Teaching Assistant Award from UNR in 1996. He also received an Outstanding Graduate Student Award in 1999. The National Science Foundation sponsored his 1999 IEEE AP paper presentation. In 2000, he received the third student paper award from the URSI International Student Paper Competition.

Cynthia Furse (SM'99) received the Ph.D. degree in 1994.

She is the Director of the Center of Excellence for Smart Sensors, University of Utah, Salt Lake City, where she is also an Associate Professor in the Electrical and Computer Engineering Department. The Center focuses on embedded sensors in complex environments, particularly sensors for anomalies in the human body and aging aircraft wiring. She has directed the Utah "Smart Wiring" program, sponsored by NAVAIR and USAF, since 1997. She teaches electromagnetics, wireless communication, computational electromagnetics, microwave engineering, and antenna design.

Dr. Furse was the 2000 Professor of the Year at the College of Engineering, Utah State University, Logan, the 2002 Faculty Employee of the Year, a National Science Foundation Computational and Information Sciences and Engineering Graduate Fellow, IEEE Microwave Theory and Techniques Graduate Fellow, and Presidents Scholar at the University of Utah. She is the Chair of the IEEE Antennas and Propagation Society Education Committee and an Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.