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Finding Fault: Locating Hidden Hazards on Aircraft Wiring

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On a cold morning your car won't start. It might be a dead battery, a corroded battery terminal, a broken battery wire or a bad alternator…. Here is a system with only a handful of connections, yet it may take you several tries to debug and diagnose the problem. Magnify that problem by 1000, and you have some idea what faces maintainers of aircraft and other complex densely-wired systems. Aging wiring has been identified as an area of critical national concern, an area that the Center of Excellence for Smart Sensors at the University of Utah under the direction of Dr. Cynthia Furse is working to address with fault finding methods capable of locating intermittent faults to within a few centimeters on live wires in flight.

As today's military and commercial aircraft age past their teen years, the many kilometers of wiring buried deep within their structures begin to crack and fray. Once thought to be rare and benign, such faults are found by the hundreds in a typical aircraft. Unlike obvious cracks in a wing or an engine, damaged wire is extremely difficult to detect, but the resulting arcing and electromagnetic emissions can be just as deadly: faulty wiring has been implicated in the downing of Swissair 111 near Nova Scotia in 1998 and of TWA 800 off New York's Long Island in 1996. Indeed, any densely wired system is vulnerable--the space shuttle, nuclear power plants, subways and railroads, large industrial machinery, homes and business buildings, communication and power distribution networks, and even the family car.

Public scrutiny has prompted strongly worded recommendations from the likes of NASA, the U.S. Federal Aviation Administration, and the National Transportation Safety Board (NTSB). "The safety of the nation's wire systems is an issue of major importance to us all," noted a White House report issued in 2001. Several months earlier, the NTSB concluded its lengthy investigation of TWA 800 with the verdict that a short circuit sparked an explosion in the center wing fuel tank. The condition of the wiring, it noted, was "not atypical for an airplane of its age." Among the NTSB's recommendations was to incorporate into aircraft "new technology, such as arc-fault circuit breakers and automated wire test equipment."

Failing the test of time

Typically, a copper conductor (from 1 to 10 mm in diameter) is covered by a thin outer insulation (from 0.5 to 2 mm thick). Damaged insulation can expose

About the Author

Dr. Cynthia Furse's research is motivated by solving problems that make a difference in the world. Cindy is the Director of the Center of Excellence for Smart Sensors, which applies expertise in electromagnetics and signal processing/ communication to sensing and data communication in complex lossy scattering media such as the human body, geophysical prospecting, ionospheric plasma, and aircraft wiring networks. She is recognized nationally for development of a system for on-board automatic testing of aging aircraft wiring to prevent in-flight fires and loss of control signals.

Cindy's passion is teaching, and she is known for her educational initiatives. This year, she spearheaded curriculum reform to integrate ECE concepts into project-based designs. Cindy has received various teaching awards including the Teacher of the Year from the Utah State University College of Engineering 2000, and USU Faculty of the Year 2002. She is also chair of the IEEE Antennas and Propagation Education Committee.

Cindy received her BSEE ('86), MSEE ('88) and PhDEE ('94) at the University of Utah and was a professor at USU for five years before returning to the U in 2002.

the copper, giving rise to arcs, shorts, and electromagnetic emission and interference. As the wire ages, the insulation may become brittle and crack. Chafes appear as wires vibrate against each other, a tie-down, or any other hard surface. Maintenance can also be hard on wires, as they may be nicked by workers' pliers, or bent beyond their tolerable radius, or sprinkled with metal drill shavings, chemicals or water, or even used as stepladders in hard-to-reach places. Even simple moisture condensation can spell trouble, particularly in conjunction with polyimide insulation, which breaks down when exposed to moisture and heat, not a good scenario for a vehicle that must contain drip loops in the wiring, because it is normally wringing wet after each flight! Moisture creating a short circuit between compromised wires can cause a tiny arc, gradually carbonize the insulation, and finally result in flashover and fire. And it isn't just old planes that have problems. In areas such as the wheel well, nearly 1/3 of all planes will have wiring faults within the first year.

The hazard of these pervasive "wet arcs" has prompted the development of arc fault circuit breakers. Ordinary circuit breakers are heat-sensitive bimetal elements that trip only when a large current passes through the circuit long enough to heat the element. This power may be on the order of 1000 percent of the rated current for 0.35 to 0.8 seconds. By comparison, a single arc fault may last only 1.25 ms, and a series of events may last 20–30 ms. Too fleeting to trip the circuit breaker, these arc faults can nonetheless cause catastrophic local damage to the wire. Fires have been known to break out with the breaker still 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 arc-fault signature from the current waveform. This signature may be integrated over time to discriminate, by means of pattern-matching algorithms, between a normal current and a sputtering arc-fault current. And so ordinary transients, due to, say, a motor being turned on and off, can be distinguished from the random current surges that occur with arcing.

Arc-fault breakers are already required in new home wiring in the United States and are now being miniaturized for use on aircraft. One of the most significant problems that is limiting the adoption and implementation of arc-fault breakers is lack of a method for locating the tiny damage left on the wire after the breaker has tripped. The figure below shows the damage left after a traditional thermal circuit breaker has tripped, damage that is clearly visible or that could be found with today's test methods, and damage that could have started a fire if flammables had been near the fault when it occurred. The figure on the right shows the damage left after the arc fault circuit breaker has tripped, damage that is so small that the wire is still fully functional, has an impedance discontinuity of less than an ohm, and damage that would be extremely difficult or impossible to locate.

Emerging technology from the Center of Excellence for Smart Sensors at the University of Utah that can locate these faults has been identified as a critical enabling technology for the deployment of arc fault circuit breakers.

Today's Fault Location Methods

Wire troubleshooting is still very much a hands-on art that has changed little over the last 40 years. Among the techniques in current use are visual inspection, impedance testing, and reflectometry.

Visual inspection is still the most common way to check for wiring failures. It entails accessing the cables

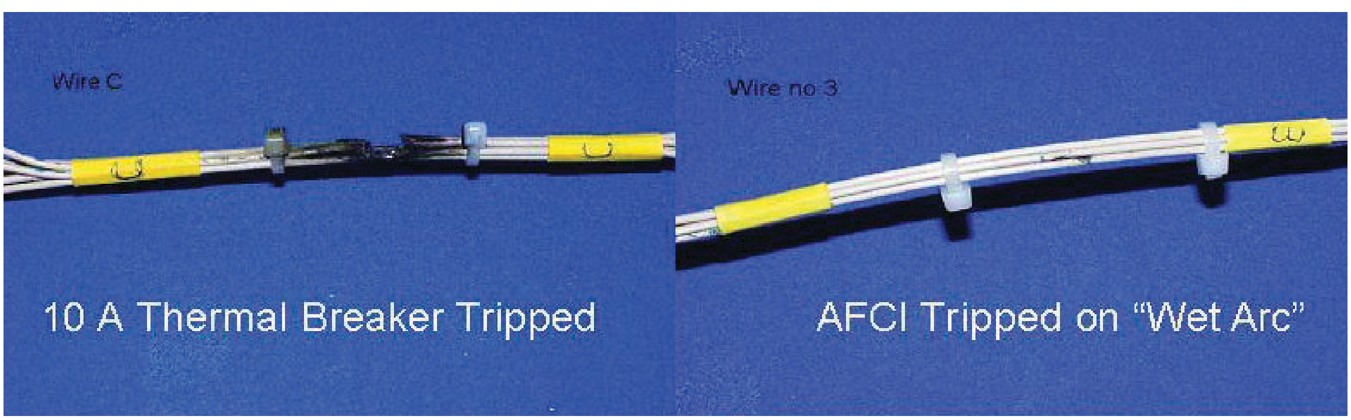

Figure 1: Samples of polyimide wire that have been tested for wet arcs. Two radial cracks were made 1/4" apart, and several drips of saline solution were dripped over these cracks when the system was energized with three-phase 400 Hz 115V power. The wire on the left shows damage typical of today's thermal breakers, and the wire on the right has damage typical of protection by an arc fault circuit breaker.

and then carefully checking the insulation for holes and cracks, often no larger than the head of a pin. Whole sections of wiring never get inspected: chafed insulation can be hidden under clamps or around corners, or within multiwire bundles, each consisting of 75 or more wires. And many wire bundles are built right into the walls of the aircraft.

Another approach involves measuring the cable's resistance and/or capacitance. A low resistance means the cable is "good," and a high resistance means that it is broken. Capacitance is proportional to cable length. While these methods can locate a hard fault on a single (unbranched) cable, they cannot locate small faults or faults on branched networks. To find small faults such as those left after an arc fault, a very high voltage (500 V or more) can be placed between adjacent, supposedly unconnected wires. Current leakage from one wire to another can indicate degraded or damaged insulation, although it cannot locate it. To actually locate a small fault, inert gas (such as helium) can be injected near the wire, decreasing the breakdown voltage and causing a tiny arc where the wire insulation is compromised, thus locating small faults with moderate voltage levels. This method is limited by physical access to all parts of the wire under test.

Time domain reflectometry (TDR) is customarily used to trace wiring problems. A short, typically rectangular pulse is sent down the cable, and the cable impedance, termination, and length give a unique temporal signature to the reflected signal. A trained technician then interprets the signature to determine the health of the cable. Such signal interpretation is particularly necessary for aircraft systems, where wires branch into complicated network structures and connect to active avionics. The running joke about TDR is that it requires a Ph.D. to use. There are other flavors of Reflectometry, too. Standing-wave (SWR) and frequency-domain reflectometry (FDR) involve sending a set of stepped sine waves down the wire and measuring the magnitude and / or phase of the reflected wave.

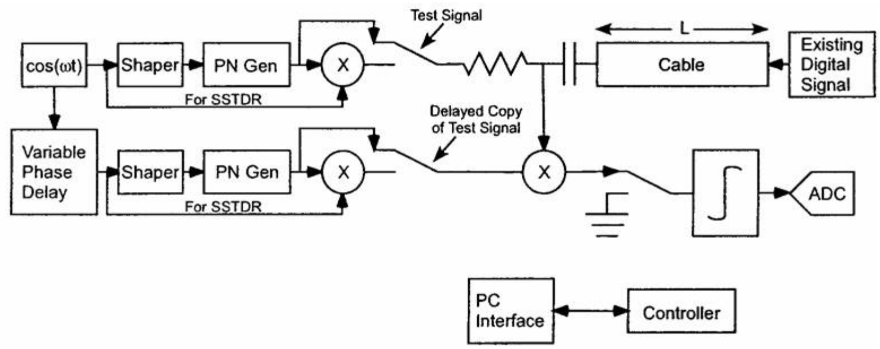

Figure 2: Spread Spectrum Test System

Spread Spectrum Reflectometry

Today's reflectometry methods are not able to locate the tiny faults left after an arc fault event, because their impedance discontinuity is too small to create a measurable reflection. On the other hand, if the fault could be found during the few milliseconds the arc occurs, it would be an actual short circuit, which returns plenty of reflected power! This is the concept that led to the development of Spread Spectrum Reflectometry in our lab.

Spread Spectrum signals have been used in communication and radar for over 50 years. Direct Sequence Spread Spectrum (DSSS) communication uses a high speed pseudo noise (PN) code multiplexed with existing digital data to spread the spectrum, increase the number of simultaneous users on the line, and reduce the effects of noise and jamming. This same ability to reduce interference with other "users" and to resist "jamming" provides the ability to test live wires in flight without either interfering with the avionics signals or being corrupted by them.

The basic spread spectrum system is shown in Figure 2. In order to guarantee no interference with the avionics, the PN code is very small (25-70 dB down) compared to the data signal. In fact, it is below the noise margin) of the data. The PN code is added to the data/noise signal, and the combined signal is transmitted down the wire, where it reflects from the end of the wire. The combined incident/reflected signal is correlated with the PN code. This correlation is high if the two codes are synchronized, and low if they are not. Thus the system is capable of running live, with the test signal completely buried within the system noise. It can locate intermittent faults a few milliseconds long to within a few centimeters over tens to hundreds of meters of wire.

Our research in conjunction with our industrial partners is working towards integrating this technology directly into the arc fault circuit breakers, into the connectors between the wires, and eventually into the wires themselves.

Team engineering

But a method that can run on live wires, that can locate millisecond faults, that doesn't interfere with the existing aircraft signals … this is just the tip of the engineering iceberg. Aircraft power wires (*power systems*) have multiple branches (*network theory*) that create multiple reflections (*multipath communication theory*). Correlation (signal processing) can be done using

A rat's nest of wiring in the belly of an aircraft at the FAA Test Site, Albuquerque

analog (*circuit hardware and prototyping*) or digital methods (*mixed signal chip design*), and peak detection (*detection and optimization*) depends on the nature of the fault (*electromagnetics measurement and simulation*). The system needs to be tiny (*packaging*), corrosion resistant (*chemical engineering*), meet military and FAA specifications (*mechanical engineering*), and fit in aircraft form factors (*aerospace engineering*). The 1500 connectors and breakers in the plane all need to communicate (*wireless networking*) with the maintainer, transferring the practical hands-on knowledge of "the old guard" to a 20-year-old aircraft mechanic (*knowledge management*) through the ultimate graphical user interface (*computer science*) integrated with the individual aircraft's database (*database management*) in a convenient handheld package (*windows CE programming*). And it needs to be designed for manufacturing, reliability, flight hardening, etc. etc. etc. (*commercialization, marketing, financing, business*). This project is preparing over 25 of our graduate and undergraduate students, and also three high school students, for the complexity of real-world engineering. Frankly, it is also teaching professors Furse, Farhang, Harrison, Chung, Chen, and Lo about complex and multilayer system design, too. Integration with our industrial partners is critical to the success of our project, and it is also critical to the success of the true education of our research team.

Not to panic

If you happen to be flying this week, do not panic. Few wiring problems end in disaster. There is cause for concern, though, as the air fleet continues to age, and our reliance on air transport grows. While an aircraft's other major systems undergo preflight testing and regular inspection and maintenance, its central nervous system–wiring–has been long neglected. Sorely needed are new maintenance methods that account for the aging of wires, as is done for aging structural and computer systems.

Diagnosis is good. Prognosis is better. And prevention is better still. This last may require a new way of thinking for electrical engineers, who tend to be more at home with obsolescence than geriatrics. For aging aircraft wiring, the dream of smart systems that can detect and locate the intermittent faults before they cause disasters like TWA 800 and Swissair 111 is on the horizon. The Center of Excellence for Smart Sensors at the University of Utah is proud to be making a difference in how the most basic neuron in our electrical nervous system, the wire, is understood and maintained. Soon, this tiny neuron will have a mind all its own, whether it is in an aging airplane, train, ship, skyscraper, nuclear power plant, communication network, or even in your family car.

Further Reading:

Website: *www.ece.utah.edu/~cfurse*

C.Furse, P.Smith, M. Safavi, "Feasibility of Spread Spectrum Reflectometry for Location of Arcs on Live Wires," accepted to IEEE Journal of Sensors

Cynthia Furse, You Chung Chung, Rakesh Dangol, Marc Nielsen, Glen Mabey, Raymond Woodward, "Frequency Domain Reflectometery for On Board Testing of Aging Aircraft Wiring," IEEE Trans. Electromagnetic Compatibility, May 2003

Excerpts from this article taken from: C.Furse, R. Haupt, "Down to the Wire: The Hidden Hazard of Aging Aircraft Wiring," IEEE Spectrum, Feb. 2001, pp.35-39

Produced for the alumni and friends of the College of Engineering, University of Utah, 201 Kennecott Bldg., Salt Lake City, Utah 84112. For further information or to request additional copies, call Marilyn Davies, Director of External Relations, (801) 581-7194 or visit our web site at www.coe.utah.edu.