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Aircraft Electrical Wiring Monitoring System

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1. Context

The cumulated lengths of electrical cables continuously increases in aircrafts and trucks: now up to 10 kilometers in a modern truck, 40 km in a helicopter or in a fighter aircraft and 500 km in a modern civil transport aircraft such as A380. Electrical wiring is a critical part in the nominal operation of a system. The importance of the wired network has thus grown to the same level as the systems it is connected to [1]. Regarding the increasing complexity of the electric system (increase in the number of electric loads, in the supply voltages), the regulation authorities (FAA, Federal Aviation Administration and EASA, European Aviation Safety Agency) now require to consider aircrafts' electrical wiring as a system on its own, named EWIS (Electrical Wiring Interconnection System).

On-board electronic equipment and systems are now equipped with integrated functions allowing a fast and targeted diagnosis called BITE (Built-In Test), however this is not the case today for the electrical harnesses. The sensitivity to defects evolves because of the design complexity and integration of new technologies: various problems can emerge at system level due to electric cables. The diagnosis of the electrical wiring is then essential to detect and locate these defects, and to improve safety and reduce maintenance costs. This paper presents recent results in wire diagnosis for transportation.

One can question about the necessity of such a Research and Technology work undertaken to improve cabling defect diagnosis, since the reliability of the cables installed in modern vehicles is specified to be compliant with its life time. This statement does not take into account neither the possible human errors during manufacturing, installation of the electrical harness and maintenance operations, nor the stringent operational environment in terms of shocks, vibration and humidity aggressing the wiring infrastructure, composed of cables, connectors and interconnection units.

Several kinds of cable defects must be considered (Figure 1). Depending on them, different techniques must be deployed. Through Ground Maintenance, only established true defects can be located, after being preliminarily detected by classical continuity tests, for example.

Transient defects are an important issue because they only appear during usage. Most of the time they can't be reproduced afterwards; which often leads to electronic pieces of equipment removal with "No Fault Found" after test. The only solution to detect and to locate them is an embedded harness maintenance system. Such a system must be designed for scanning in real time the relevant cables, without affecting their operational mode of operation, in order to detect a defect and then to focus on the suspicious cable to locate it precisely. One must keep in mind that on-board cable monitoring must discriminate true defects from normal discontinuities due to powered off equipment or electrical power distribution reconfiguration such as load sheds.

Cable degradation diagnosis is the most challenging topic because it can reduce the "Aircraft On Ground" (AOG) time or improve the Truck Uptime (availability for the driver), thanks to a maintenance operation before a true defect occurrence. Methods to provide a prognostic are out of the scope of this paper.

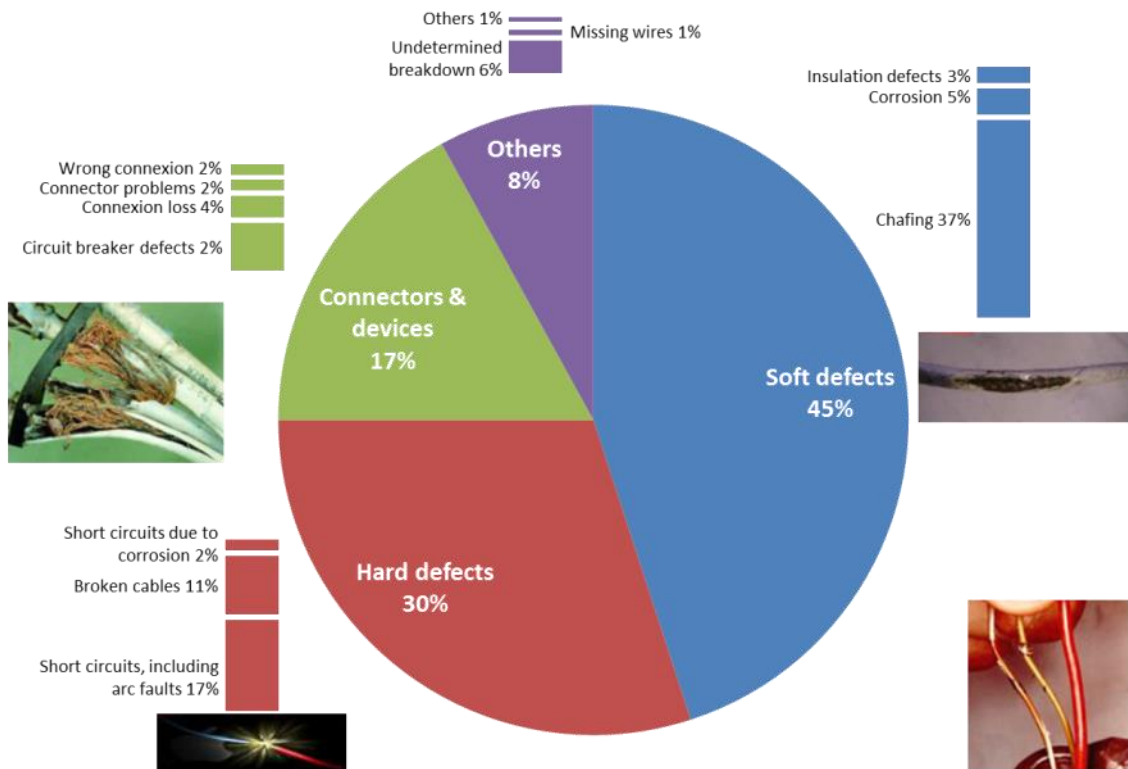


Figure 1 : Classification of wire defects found in aircrafts (NASA)

2. Wire diagnosis reflectometry-based methods

Apart from transports, reliable wired networks are of utmost importance in several domains, such as energy production, large infrastructures, buildings, telecommunication, etc. There are often quite long lengths of wires of various types (Figure 2) and several systems and sometimes even people directly depend on their good health. From a quality of service point of view, it is very important to be able to check the proper state of these cables or to repair any defect as quick as possible. The stakes are huge: the overall cost of an AOG was estimated by airlines up to USD 150000 per hour.

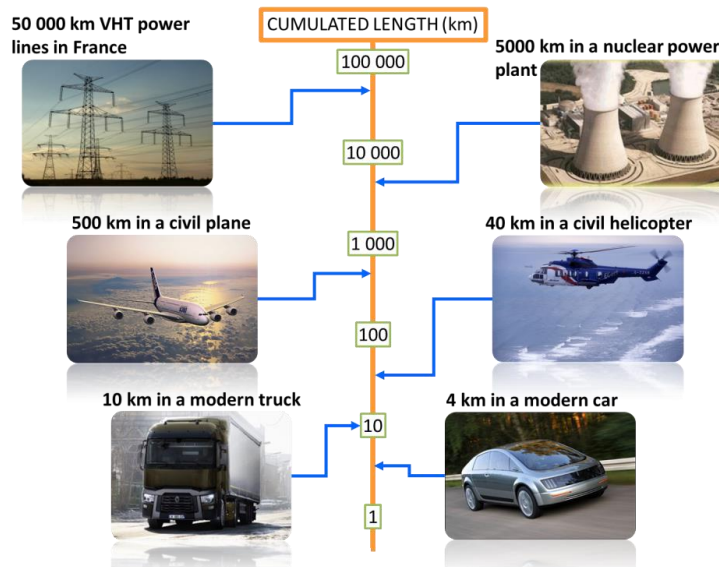


Figure 2 : Cumulated cable lengths in various application domains

In all these application domains the importance of maintenance is clear, but locating a small defect or even an open circuit in several kilometers of wires can be very difficult, considering that these cables may not be easy to reach. There are very few diagnosis and maintenance methods for wires, the most widely used being visual inspection. But it can't be exhaustive, especially in the case of very long or hidden wires. The need for more adapted diagnosis methods has grown and several new electrical methods have been studied and developed recently.

As of today, the most promising diagnosis methods for wired networks are based on the reflectometry principles: sending a probe signal down the wire [1]. This signal propagates and sends back a part of its energy when it reaches an impedance discontinuity. The analysis of the reflected signal – which is generally quite different from the input signal – provides information on detection, localization and characterization of the defects which generated the impedance discontinuities.

Some methods are well adapted for the monitoring of ageing cables [2] (e.g. LIRA, Line Resonance Analysis, which requires heavy equipment), some others are more dedicated to the detection of hard defects (open and short circuits) for maintenance purposes [3] (TDR and STDR, Sequence Time Domain Reflectometry) or embarked diagnosis (MCTDR, Multi Carrier Time Domain Reflectometry) [4] and sometimes of soft defects [5]. Recent developments have proven their efficiency for the cancelation of location ambiguities in complex topology networks [6]. These results have also been extended to the diagnosis of connectors [7], which are often considered as the weak points of an interconnection system.

Standard reflectometry systems are made of 3 basic blocks: signal generation and injection, measurement acquisition, data processing and fault localization. These electronic blocks can be studied separately, depending on the complexity of the chosen method, and each can be prototyped and realized with quite simple electronic design. Modern reflectometry-based methods use complex diagnosis signals with specific mathematical properties. The reflectogram is obtained by the correlation of the measured signal and the injected signal. Embedded diagnosis implies additional constraints such as: cost, low power, small size and harmlessness. The latter means that the diagnosis signal must not interfere with potential useful signals on the wire, and that the emitted EM radiation fulfills some EMC requirements. In the case of automotive and avionics, this last constraint is of extreme importance.

To this end, MCTDR method permits a precise control of the spectrum of the injected signals, and supports a distributed diagnosis architecture [8] that enables unambiguous and full diagnosis coverage for complex branched topologies. The diagnosis signal of MCTDR is designed as the sum of a finite number of sinusoids at a given set of frequencies, chosen outside of the useful signals and EMC (Electro Magnetic compatibility) spectra. Specific conducted and emitted electromagnetic interference measurements have proven that MCTDR does not radiate any harmful signal outside of the chosen frequency bands, thus guaranteeing zero interference with the useful signals of the network under test.

Current achievements in various TDR-based systems have proven the possibility of diagnosing hard defects with localization accuracy close to few centimeters both for embedded or external purposes. A single acquisition phase is about 500ns – 1 μ s long. The signal to noise ratio can be improved by averaging several results, thus increasing the acquisition duration. To be able to diagnose soft defects, such as damaged insulator or shielding defect, new methods are currently under study [9].

3. The « Harness BITE » project

3.1 Rationale

The main industrial actors of aeronautics in France have worked in a cooperative research project called “Harness BITE”, led by Airbus, whose main objective is to develop a real time monitoring system of aircraft power distribution electrical wiring, aiming at detecting and locating wires defects, even intermittent (in flight), thus decreasing the maintenance costs.

This project allows to:

- Anticipate new FAA & EASA Airworthiness recommendations for EWIS,
- Anticipate new risks induced by High-Voltage (arc-fault detection and location),
- Create new on-board diagnosis systems for electrical harnesses,
- Reduce maintenance cost with defect location capability.

3.2 Electronic design

An innovative reflectometry-based method, called Multi Carrier Time Domain Reflectometry (MCTDR) has been developed. Several electronic boards were designed and realized (Figure 3) for the needs of the project, based on the use of FPGA (Field-Programmable Gate Array) components (Altera Cyclone III). The FPGA is in charge of signal generation and injection via a Digital to Analog Converter (DAC, @100 MSPS) and signal acquisition via an Analog to Digital Converter and signal processing. A specific IP has been designed and implemented for the analysis of measured signals and extraction of the useful information, i.e. defect detection, location and characterization.



Figure 3: Reflectometry electronic boards

The location accuracy in TDR-based methods depends directly on the frequency band of the injected signal, and the propagation speed of the cable, as shown on formula (1).

$$\delta x = \frac{c_0}{2\sqrt{\varepsilon}\Delta f} \quad (1)$$

Where c_0 is the light velocity in vacuum, ε is the relative permittivity of the insulator, Δf is the frequency band of the DAC. In our case, this leads to 1 m accuracy, which is not acceptable. An innovative oversampling process has been implemented [10], based on the hypothesis that the state of the cable does not change over a complete measurement phase. A sequence of N data acquisition desynchronized in time by a portion $\frac{1}{N\Delta f}$ of the DAC period is acquired and used to reconstruct a full reflectogram with N -fold enhanced location accuracy.

3.3 Description of the test benches

In order to incrementally validate the MCTDR based diagnosis methods, three test benches have been used, with an increasing level of relevance compared to a real aircraft electrical installation:

1. OFF-LINE bench (Figure 4): it is a purely topologic bench, not powered, wired with real electrical cables but without any load. The types and lengths of the cables (up to 30 meters) were characteristic of cables used in various aircrafts. The purpose of this first bench is to characterize the cables with different cable defects. Some parts of the harnesses can be replaced by defective ones.
2. ON-LINE bench (Figure 5): this bench, illustrative of the electrical installation and distribution aspects, is equipped with powered loads. The purpose of this second bench is to validate the performances with powered cables and the coupling with a protection device (AGFCB: Arc Ground Fault Circuit Breaker) and to test the ability to detect intermittent defects.

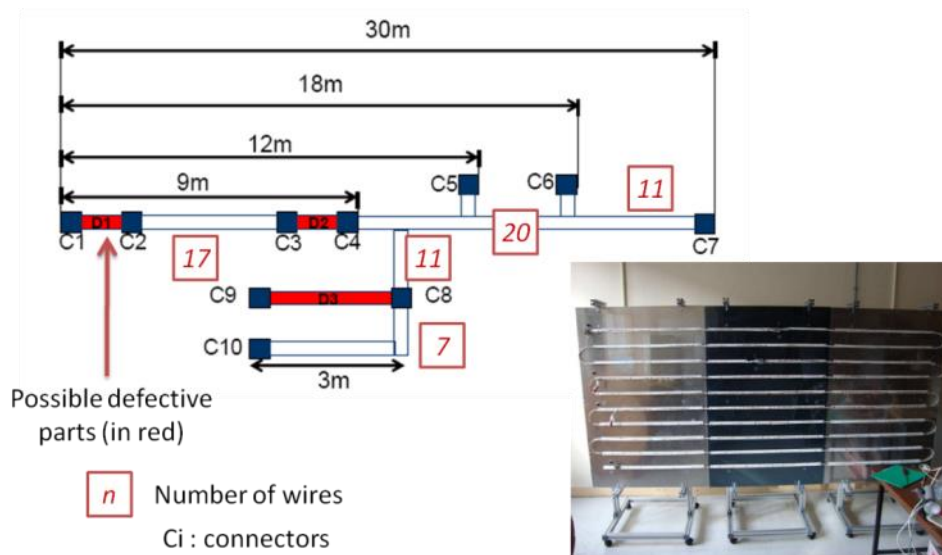


Figure 4 : OFF-LINE bench. Red portions can be replaced by defective ones.



Figure 5 : ON-LINE bench, equipped with real loads (lights, etc), powered by a real aircraft generator

- M2000 bench: this bench consists of the installation of a harness manufactured with an industrial process and of topologies representative both of the cabling rules and the electrical distribution architectures of the 3 end users involved in the project (Airbus, Eurocopter and Dassault Aviation).

Cabling performed on a Mirage 2000 fuselage (Figure 6 to Figure 9) includes the use of several kind of fastening (plastic or not) and paths (ceiling path, path with irregular interval between fixings).



Figure 6 : HB collars



Figure 7 : Plastic collars

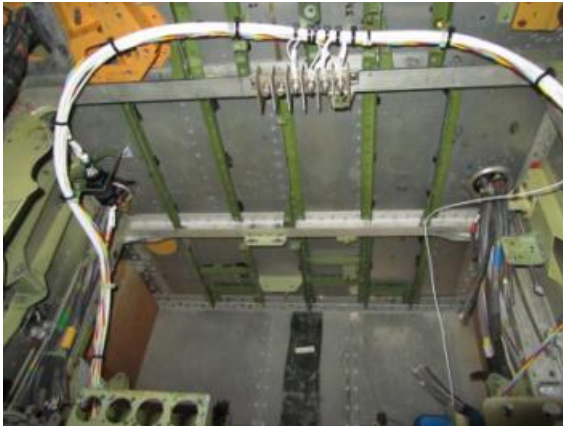


Figure 8 : Ceiling path

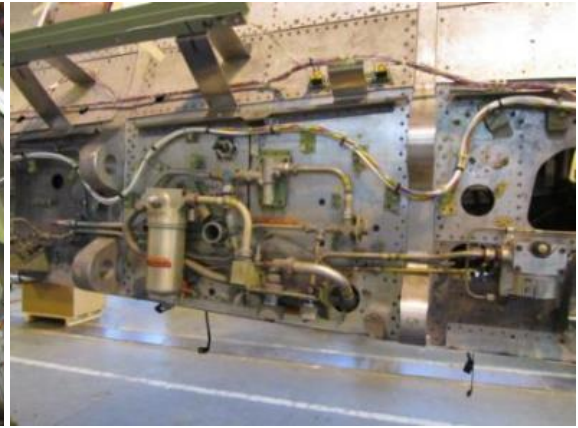


Figure 9 : Irregular interval between collars

Raceways used to ensure shield continuity in case of composite fuselage were also fixed to the M2000 fuselage (Figure 10).



Figure 10 : Raceway general installation view

The purpose of this bench is to validate performances with real electrical installation and powered loads, thus being as close as possible of a real aircraft environment but still on ground.

Benches definition is based on the aircraft / rotorcraft manufacturers' specifications in terms of cable lengths, electrical distribution topologies, types of cables and connectors, wire gauges and installation rules.

Loads are chosen in order to cover a wide diversity of characteristics and different types of cabling and electrical power (28V DC or 115V AC / 400 Hz): resistive loads such as lamps, inductive loads such as pumps, pieces of avionics equipment. For each load, return current path is achieved by the mockup structure; which is fully representative of a non composite aircraft installation.

Several configurations have been tested in order to evaluate the robustness of the MCTDR-based defect diagnosis algorithms:

- Longest path between the power supply unit and the highest power consuming unit,
- Path with the worst topology case (electrical bus with the maximum number of derivations),
- Path with the maximum number of cable segments and cut-off connectors,
- Path with the maximum number of heterogeneous cable segments,
- Path with the load closest to the power supply unit.

The different types of studied defects are open-circuits, short-circuits between two wires or with the ground and intermittent defects (Figure 11 to Figure 13):

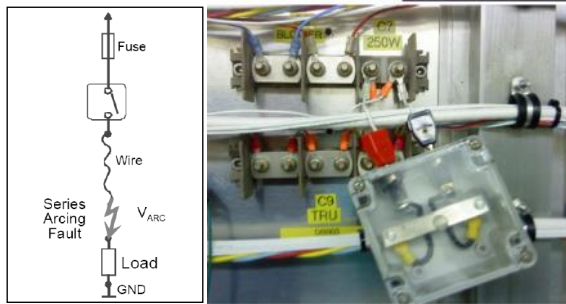


Figure 11 : Series Arcing Fault injection

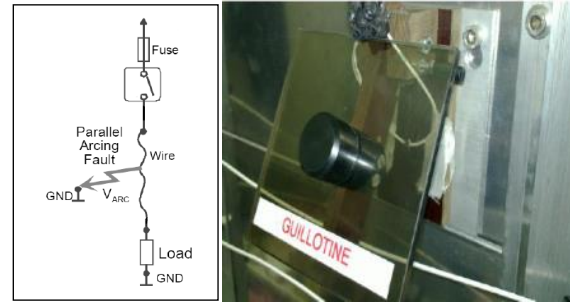


Figure 12 : Parallel Arcing Fault injection

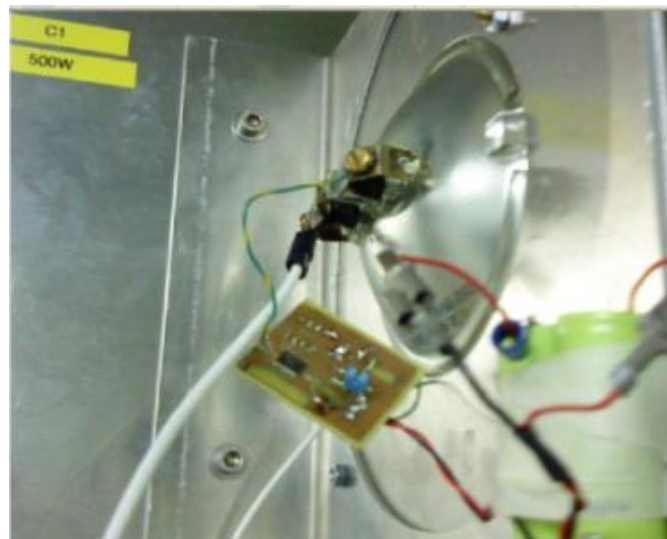


Figure 13 : Intermittent defect injection

3.4 Measurement results

Around 3000 different measurements were performed on the 3 test benches, according to a predefined test procedure. The objective was to be able to evaluate the diagnosis performances for almost all possible cables and defects configurations, representative of the 3 aircrafts types (helicopter, corporate jet aircrafts and airliners).

A few example are shown below. The cable topology shown on Figure 4 was duplicated on the ON-LINE test bench, with a load at connector C1 and energy supply of 28V DC. The reflectogram was measured for 3 different load configurations: normal load, open circuit (load was removed) and short-circuit (cables were connected). Figure 14 compares the 3 reflectograms: the curves change at distance close to 30 meters, which is the length of the line under test. The presence of voltage does not prevent from detecting the defect, and the signatures of open and short-circuits can be easily recognized. The peaks situated between distance 0 and the defect come from the impedance mismatch at the connection of the electronic board and the cable, and also from additional components and metallic structures between the board and the load. All these impedance changes create noisy signals that bounce several times before coming back at the reflectometer. However, as we are dealing with embedded diagnosis, the important feature for defect detection is the difference between the current measurement and a reference one, which is dynamically updated to take into account small and slow variations of the wire's state. A fast change, such as the appearance of a defect at the load can easily be isolated by simple comparison.

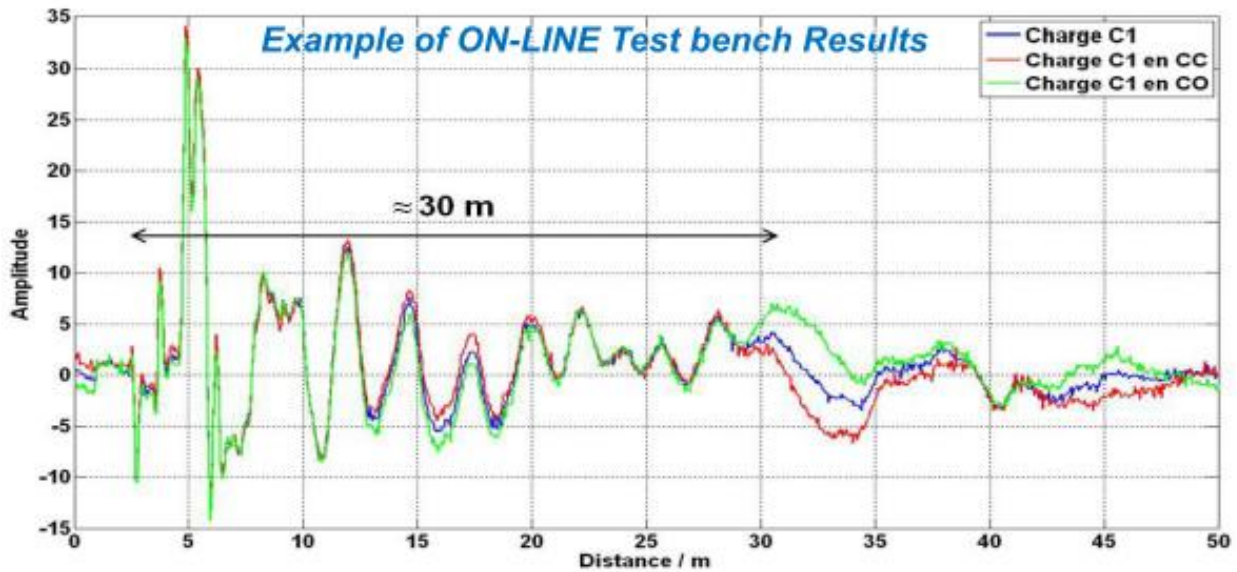


Figure 14: 3 different defects on a wire, ON-LINE testbench

Intermittent defects have been generated by specifically designed devices, and tested according to the appropriate standards (AS6019 for 28VDC & AS5692 for 115VAC).

Figure 15 shows a burst of the first 4 measurements done at the detection of an intermittent open circuit defect leading to a series arc fault on the M2000 test bench (Figure 11). The red curve is the last result just before the signal went above the detection threshold, and then come the green, blue and purple curves. Each measurement lasts for 160µs due to the averaging and oversampling processes. The difference between each curve is due to the fact that this defect lasts longer than the measurement phase: the detection device can monitor the appearance, the “steady state” and the disappearance of the defect, just as a camera would do.

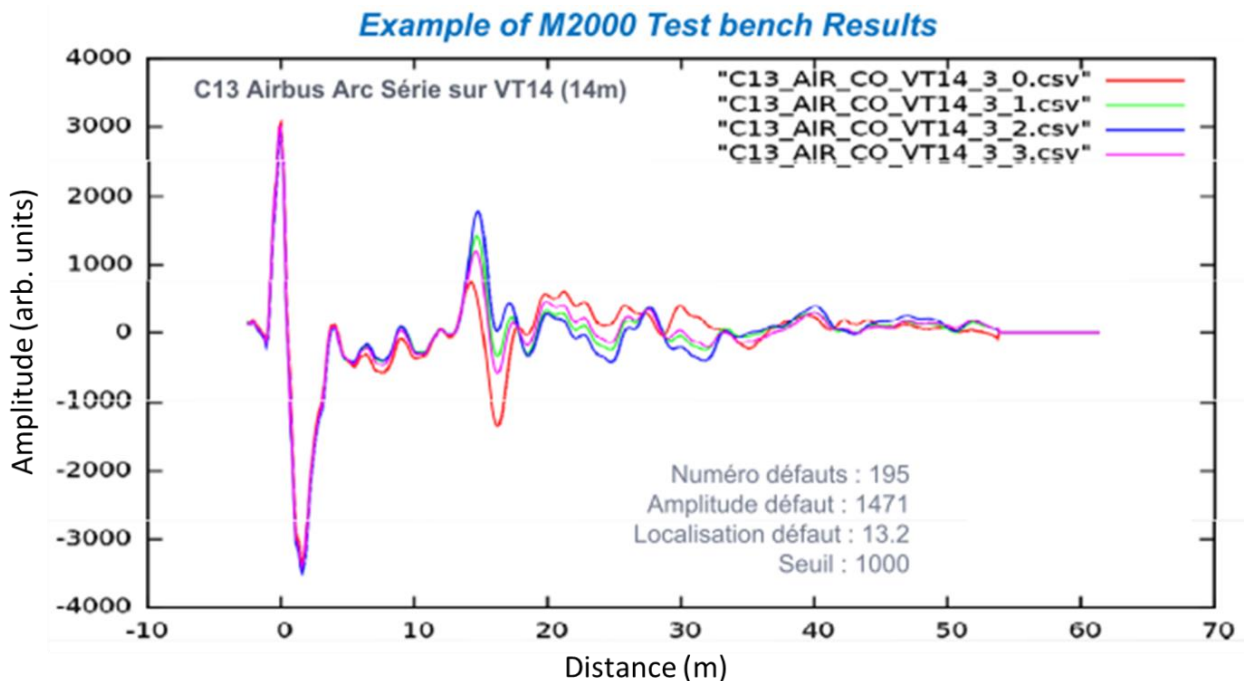


Figure 15: Intermittent defect detection

4. Way forward

Through this in-depth test campaign, the consortium has shown the adequacy of embedded reflectometry systems to avionics issues, and the technology developed in the project was labeled at Technology Readiness Level 4 (TRL4), i.e. the MCTDR technology was validated in laboratory environment, although very close to operational conditions (i.e. TRL close to level 5).

Based on the encouraging results of this first step, a second step is envisioned in order to increase readiness up to TRL6. Its goal is to validate a system approach, with reflectometry sensors embedded as an ASIC in electronic equipment, such as electrical power distribution center or Circuit Breaker, and globally or locally in order to detect and locate defects, even intermittent, during the flight.

Possible enlarging of the use of this wiring defects diagnosis technology to communication links (i.e. digital buses) will be also a new challenge of this second phase.

The results obtained during this second step will offer to trucks, aircraft or rotorcraft development programs new opportunities to take benefit of defect localization techniques. The main milestones are:

- Retrofit of an existing aircraft by only replacing in the harness the current AGFCBs by smart AGFCB versions embedding the cable defect localization function (wire by wire management),
- Test new vehicles' electrical architecture with an embedded Harness BITE system, including:
 - Wiring defects detection and localization sensors integrated in vehicle's Electrical Power Distribution Units or communication buses switches,
 - Sensors management and measures exploitation functions, including false alarms filtering (in case of normal avionics units power off for example),
- Tests improvement thanks to the coupling of the toolkit with the vehicle's ground database for a better wiring defect localization and quicker maintenance.

A longer term challenge for embedded electrical harness maintenance would be defect prognostic, taking into account wiring ageing.

5. Conclusion

To increase the reliability of wired networks or to ease their maintenance, MCTDR was identified as the most promising method for embedded EWIS diagnosis. Based on the injection into the network of a multicarrier signal which respects EMC and harmlessness constraints, this method provides information for the detection, localization and characterization of electrical defects (or mechanical defects having electrical consequences) in the wired network.

The application to avionics has been studied in this project, gathering a consortium of large industries such as Airbus, Dassault Aviation, Eurocopter, Labinal, Latelec, Crouzet and, Zodiac with upstream research from CEA LIST. Next step is to cover both avionics and automotive (through Volvo group's involvement in the project).

Location accuracy was evaluated close to 20 cm for twisted wires but was degraded for one wire above metallic ground, for up to 30 meters long cables. Branched networks are difficult to diagnose above 3 branches, but this only concerns less than 5% of wires in aircrafts. The ability to detect intermittent defects of less than 1 ms duration was proven.

The use of Off the Shelf components and an FPGA for embedded data processing paves the way for future ASIC design and system integration.

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7. Acknowledgement

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