

Reflectometric Systems for in-Situ Diagnosis on Carbon Fibre-Reinforced Composite Structures

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Abstract-In this work, the feasibility of the adoption of microwave reflectometry (MWR) for diagnosing the status of structures made of composite materials is investigated. In particular, two different “sensing structures”, based on microstrip and coplanar configurations, are considered.

The analysis focused on carbon fibre-reinforced composite structures, which are extensively used in aircraft industry. It goes without saying that, despite the widespread diffusion of this class of materials in the aircraft industry, there are two crucial requirements for which effective diagnostic methods are far from being adequately implemented. First, it is necessary to detect the possible presence of gaps between structural components after they are assembled. Secondly, there is the need to periodically control (during the service life of the aircraft) the amount of moisture that may have been absorbed by the composite structure. To this purpose, the present work intends to pave the way for future practical implementation of MWR based systems for these diagnostic requirements.

I. Introduction

Composite materials represent a pivotal class of engineered materials, and the possibility of tailoring their structure to suit specific needs allows the realization of materials with unique properties [1]. For example, fibre-reinforced composites can provide high mechanical performance while preserving light weight; for this reason, they have become widely used for the realization of many aircraft components (such as ailerons, brake discs, leading edges, vertical stabilizers, transmission shafts, and so on [2]).

With regards to the aircraft industry, there are two critical issues related to the possibility of monitoring structures based on carbon fibre-reinforced composites.

The first issue arises in the assembly procedure of structural components, for which stringent requirements in terms of dimensional tolerance are imposed. As a matter of fact, frequently, some air gaps remain between the assembled components and, to fill these gaps, the so-called plastic shims have to be specifically designed, manufactured and subsequently mounted. For this purpose, it is necessary to accurately map the profile distribution of the gap thickness. Typically, this operation is performed manually, by introducing capacitive probes between the two structures, thus resulting in spotted and inaccurate measurements.

The other major problem is to control the moisture that the aircraft composite structure may have absorbed during the service life. Although the very nature of the employed composites hinders the absorption of water, even the slightest presence of moisture can lower dramatically the mechanical performance of composite materials [3], [4]; therefore, it is necessary to periodically check on the amount of absorbed moisture.

The amount of absorbed moisture is remarkably low (but dangerous nonetheless), and in principle only methods such as the thermogravimetric analysis could provide reliable results: it goes without saying that the need to perform such controls on site and while the aircraft is still “operative” prohibits the use of this method.

On such bases, the present work intends to investigate the possibility of adopting microwave reflectometry (MWR) for diagnosing the status of structures that employ carbon fibre-reinforced composite materials. More specifically, the proposed strategy relies on embedding a transmission line on the structure under test (SUT).

Two configurations were considered: the first was a microstrip configuration, whereas the second was a coplanar configuration. The schematization of both the considered configurations, which will be described in detail in the following section, is reported in Fig.1 and Fig. 2, for the microstrip and coplanar cases, respectively.

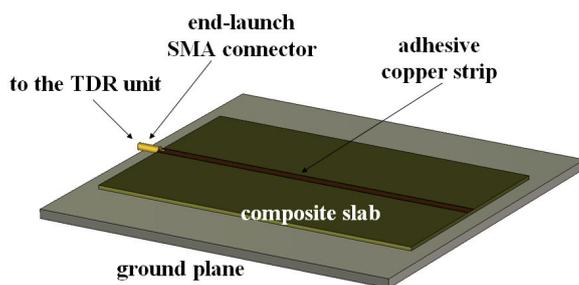


Figure 1. Schematic of the microstrip line configuration: the composite slab is directly in contact with ground plate (not to scale)

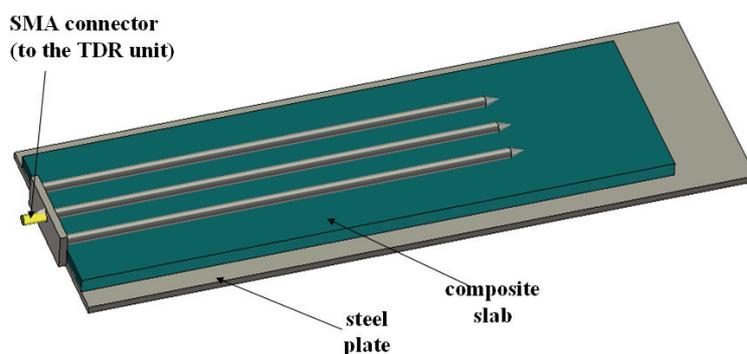


Figure 2. Schematic of the coplanar configuration: a three-rod probe is attached to the composite slab. The outer electrodes of the probe are short-circuited with the steel plate (not to scale)

It is worth emphasizing that both the investigated configurations allow preserving a non-invasive approach, and such systems could be tailored to suit the shape of the structures to be monitored.

The proposed solutions were tested on some simple but significant configurations that were reproduced in laboratory. Preliminary results show that the adopted strategies are sensitive both to the presence of air and to the presence of water; hence, they could provide interesting solutions to the aforementioned age-old problems. The ultimate goal of the present work is to investigate the feasibility of the proposed method, so as to pave the way for its possible practical implementation.

II. Materials and Methods

As a general rule, MWR relies on the analysis of the response (in terms of reflected signal) of the system under test when this is stimulated through an “appropriate” electromagnetic signal [5]. MWR measurements can be performed through instruments operating either directly in time domain or directly in frequency domain. The former approach is usually less expensive (in terms of employed instrumentation) and relies on pieces of equipment that can be portable; hence, adaptable for measurements on site. On the other hand, the instrumentation that operates directly in frequency domain (i.e., vector network analysers) is generally more sophisticated and costly; still, it usually guarantees higher measurement accuracy.

Measurements reported herein were performed in time domain, through a time domain reflectometry (TDR) instrument: the corresponding frequency domain information was obtained through a specific algorithm.

In TDR measurements, a step-like electromagnetic signal is propagated along the system under test: the portions of signal that are reflected by the system under test are recorded by the TDR instrument and are displayed as a function of the electric distance that the signal has travelled (or, similarly, as a function of the time of flight). The TDR waveform is intrinsically dependent on the impedance characteristics of the system under test [6].

For the TDR measurements, a Digital Serial Analyser (Tektronix DSA8200), equipped with a TDR module (Tektronix TDR80E04) was used; the rise-time of the incident signal is approximately 23 ps. It must be pointed out that although the used TDR unit is a bench-top instrument, high-performance low-cost portable TDR instruments are commonly available on the market; and this may represent a great advantage in practical

implementation.

For the microstrip structure, the strip was made of adhesive copper: its length was 21.5 cm and its width 0.6 cm. The strip was attached to a 2 mm-thick composite slab, which acted as substrate. To feed the microstrip structure, an SMA end-launch connector was used. The inner conductor of the SMA connector was welded to the copper strip, whereas the outer conductor was connected to a stainless-steel plate that acted as ground plane. A schematic of the structure is represented in Fig. 1.

As for the coplanar structure, a 6 cm-long three-rod probe (the diameter of the each rod was 1 mm and the mutual distance approximately 5 mm) was attached, through some removable glue, to the slab of composite material: this ensured that the mutual distance between the rods remained the same throughout the experiments (this was done to make sure that any changes that could occur in the TDR waveform was due only to changes in the system under test and not to changes of the probe configuration). The outer conductors of the probe were short-circuited with the steel plate through the metallic slot housing the SMA connector.

The composite slab was made up of carbon fibres dispersed in epoxy resin. Fibres are oriented in four different directions (0° , $\pm 45^\circ$ and 90°): this is usually done to enhance the mechanical properties of the composite material along multiple directions. Thanks to their stiffness, strength, and light weight, carbon fibres are widely used for structural components of aircrafts. Nevertheless, the very presence of these electrically conductive fibres makes the investigation of the material somewhat more troublesome, also for the anisotropy of the material.

It is worth mentioning that, in view of practical in situ applications, the metallic aircraft components surfaces below the composite layer would replace the stainless-steel plate, and the rather large SMA connector could be replaced by a more compact typology.

III. Results and Discussion

A. Results for the microstrip configuration

To resemble different operating conditions, measurements were performed considering the composite slab in four different configurations: 1) placing the slab directly in contact with the ground plane (as in Fig. 1); 2) creating a 2-mm thick layer of water under the slab, and 3), 4) leaving a constant air gap (2 mm- or 4 mm-thick) between the composite slab and the ground plane.

Clearly, the second configuration does not strictly correspond to a “moistening condition”. As reported in the ASTM regulations, moistening composite materials is not an easy task (which, of course, is normally a positive aspect), and requires long exposures to moistening sources (which is the condition that aircrafts experience when they are exposed to environmental stress) [7].

For each configuration, the TDR waveform was acquired. Additionally, also the TDR waveforms corresponding to the short-open-load (SOL) calibration standards were acquired. A zoom of the acquired waveforms is shown in Fig. 3.

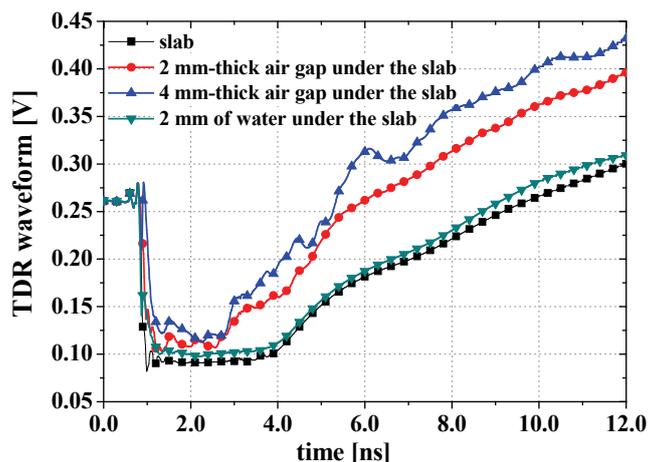


Figure 3. TDR waveforms for the four considered configurations obtained using the microstrip structure

As aforementioned, the TDR waveforms are directly associable to the impedance profile of the SUT, and hence to its characteristics. In particular, since the incident step-like signal generated by the used TDR unit has an amplitude of 0.25 V, the TDR waveform will display 0 V, 0.50 V and 0.25 V when a short circuit, an open circuit, and a 50Ω -matched load are encountered, respectively [6]. Starting from these considerations, let us analyze briefly the acquired waveforms for the considered SUT's (Fig. 3).

The portion of waveform at approximately 0.26 V corresponds to the 50 Ω cable that connects the TDR unit to the end-launch connector. At 1.0 ns, the amplitude of the TDR waveforms falls abruptly at approximately 0.10 V: the portion of the waveform that remains approximately constant at this value corresponds to the electrical length of the microstrip. It can be seen that the different configurations stay practically steady at different voltage values, thus indicating different impedances of the SUT's. The acquired TDR waveforms show that the characteristics of the obtained structure are sensitive to the impedance of the microstrip line. In particular, considering the slab on air, it can be seen that the waveform is the highest, with a steady voltage value that is closely related to the air gap thickness. This is in accordance with the transmission line theory; in fact, since the capacitance per unit length lowers, the impedance rises. Similarly, when water is placed under the composite slab, because of the high dielectric constant of water, the resulting structure exhibits a longer electrical length. Finally, at approximately 4.0 ns, the waveforms begin to slowly rise towards the open circuit (i.e., 0.50 V), which is reached at longer times (not reported in Fig. 3): the behaviour of the waveforms resembles a capacitive behaviour that is attributable to the fringing effect of the microstrip termination and, possibly, also to the presence of the conductive carbon fibres dispersed in the substrate.

The collected TDR data (along with the SOL calibration waveforms) were processed through a fast Fourier transform (FFT)-based algorithm, thus retrieving the corresponding frequency domain information, namely the reflection scattering parameter, $S_{11}(f)$. The used algorithm, which is described in detail in [8], takes into account some signal processing strategies that enhance the accuracy of results. Results for the reflection scattering parameters are shown in Fig. 4.

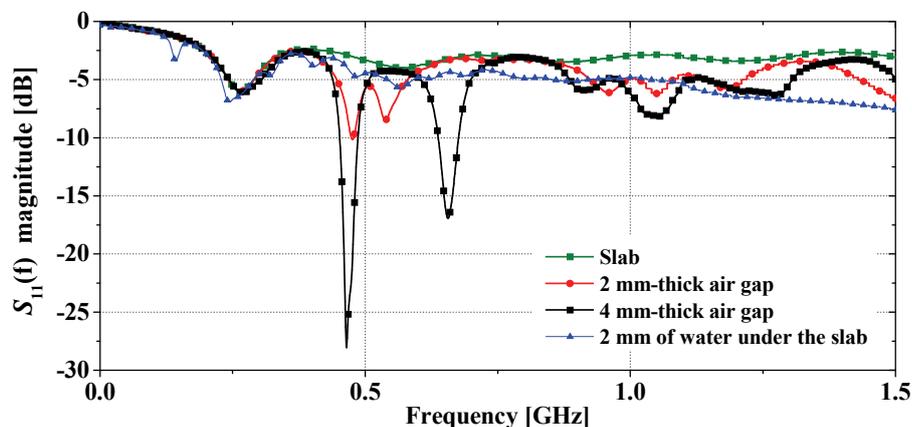


Figure 4. Magnitude of the reflection scattering parameters for the four different configurations obtained using the microstrip structure

The obtained $S_{11}(f)$ show the typical periodic ripple associated to the finite length of the microstrip structure. Clearly, the primary behaviour due to the microstrip line portion is distorted by the parasitic effects associated to the SMA connector to microstrip line transition and welding. Overall, the scattering coefficient in the presence of water exhibits lower values as the frequency increases, most probably as a result of dielectric losses of water. These results could not have been taken for granted; in fact, the non-perfectly dielectric behaviour of the composite slab (due to the presence of the carbon fibres) makes the measurements all but trivial.

On a side note, it is worth noting that by using adhesive copper to realize the microstrip, it is possible to attach it directly to the SUT, and to remove it after the measurement has been performed. Overall, this facilitates greatly the possibility of embedding several spatially distributed microstrips, so as to monitor, through a signal multiplexing, the component status over all its superficial extension. Finally, in practical applications, it could be useful to use a series of microstrips (appropriately distanced from one another), so as to directly provide a diagnosis of the status of the considered structure over a wider area.

On the other hand, one aspect that definitely needs further enhancement is the coaxial to cable-strip transition: it is well known from literature that less-than-perfect transitions provoke severe impedance mismatches that may jeopardize the measurement results.

B. Results for the coplanar structure

As aforementioned, additional experiments on the same composite slab were performed by considering a coplanar structure, as shown in Fig. 2, so as to enhance the mechanical stability in the transition from coaxial cable to electrodes.

Similarly to the previous configuration, the TDR waveforms for the different configurations are reported in Fig. 5. Also in this case, it can be noticed that as the air gap is increased, the amplitude of the TDR waveforms increases; this behaviour is due to the fact that the effective dielectric constant of the structure decreases as the air gap thickness increases. As can be seen from Fig. 5, this structure appears to be extremely sensitive even to the slightest variations of the SUT. In particular, this solution can clearly discriminate fractions of millimeter (e.g., 1.6 mm gap from 2.0 mm gap). The evaluated scattering parameters, corresponding to the 100-500 MHz frequency band, are shown in Fig. 6. Also in this case a clear trend can be observed as the air gap thickness is increased.

Two main advantages derive from the implementation of this sensing structure rather than the previous one. First, as clearly highlighted in the results, the enhanced mechanical stability of the transition section, significantly improves the sensing performance, in terms of residual parasitic effects. (i.e., any change in the TDR waveform is attributable to the sole changes in the SUT). Secondly, using this configuration, a specific calibration procedure could be implemented, such as the one described in [9], which is based on a triple short circuiting along the three-rod probe. This would additionally improve the overall final accuracy of the proposed method.

Nevertheless, these preliminary results anticipate promising practical applications; in fact, the electrodes configuration could be fine-tuned (in terms of length of the rods, mutual distance, diameter) to obtain a target measurement accuracy.

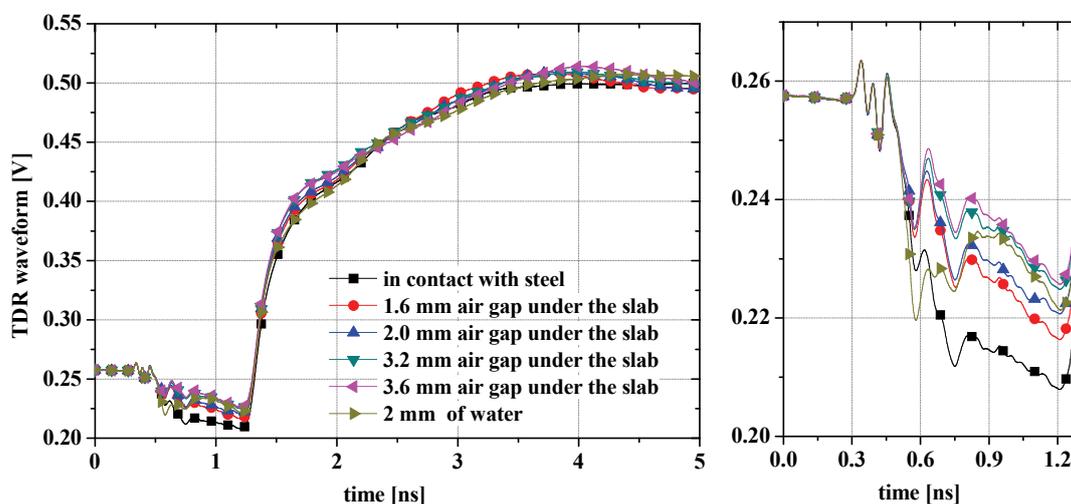


Figure 5. TDR waveforms for the five considered configurations (left side), and zoom of the first portion of the waveforms (right side), obtained using the coplanar structure

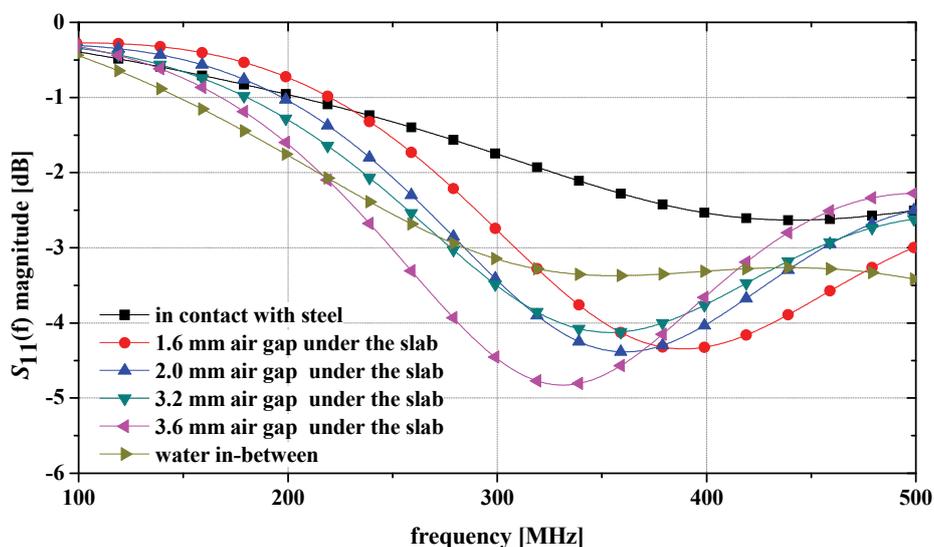


Figure 6. Magnitude of the reflection scattering parameter for the three-rod probe configuration

IV. Conclusions

In this paper, the feasibility of MWR for diagnosing the status of mechanical structures that employ composite materials was investigated. More specifically, starting from TDR measurements, the structure under test was considered as being part of a transmission line: it was demonstrated that the analysis of the changes in the parameters that characterize the line are referable to the configuration of the considered structure.

The reported results confirm that the proposed strategies, which combine the TDR technique with the realization of specific sensing structures, are appealing candidates for the in situ diagnosis of structures that involve fibre-reinforced composite materials, ensuring low cost, portability and adaptability.

On a final note, it is important to underline that the present work is still an ongoing study, and the obtained results motivate and encourage further experiments. First and former, for small amount of absorbed moisture, it would be important to perform repeated measurements, thus verifying whether the changes seen both in the TDR waveforms and in the $S_{11}(f)$ are higher than the uncertainty limit of the adopted measurement strategy. Furthermore, different configurations are being tested and specific calibration procedures have to be implemented. Nevertheless, the presented strategy may pave the way for interesting practical solutions for the aforementioned purposes. Additionally, measurements could be automated so as to provide a real-time diagnosis on the structures under test.

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