Debonding Detection in Aerospace Stiffened Composite Structures Using Ultrawideband Electromagnetic Tunneling

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ABSTRACT

This paper proposes a novel approach based on ultrawideband electromagnetic tunneling for detection of debonding in composite structures. The idea behind this approach is to place two transducers at the opposite ends of a closed section stringer and analyse wave propagation in the hollow structure to detect damage occurrence and severity. A preliminary experimental campaign is carried out at laboratory level to optimize the setup and define damage detection metrics in view of aircraft fuselage monitoring. Results show that tunnelling approach can be used to assess the presence and severity of defect when air leak is present because wave field gets altered. In particular, microwaves in the frequency band from 4-8 GHz are mostly sensitive to the defect. In addition, damage metrics allow quantifying the damage occurrence and discerning noise in measurements from actual debonding.

INTRODUCTION

Detection of debonding is of outmost importance for composite airframe, which typically includes a thin walled (host) structure stiffened by frames and stringers [1]. For composite structures, the accidental damage is likely to occur and drives the design [2]. In particular, the disconnection between host and stiffening components likely induced by low velocity impacts reduces the load bearing capability with a great impact on safety and design criteria [3].

Structural Health Monitoring (SHM) aims to overcome this issue implementing a permanent condition monitoring management in order to control damage phenomenon through a set of distributed sensors, able to detect the damage. Different solutions have been proposed in the literature, including the use of vibration response, electromechanical impedance and ultrasonic guided waves with the common challenge of properly addressing the process of damage detection [4], localization [5], and quantification [6] which may be collectively referred to as damage diagnosis [7].

However, these approaches usually need many sensing points and, as such, a high number of transducers is necessary with a negative impact on aircraft performance [8].

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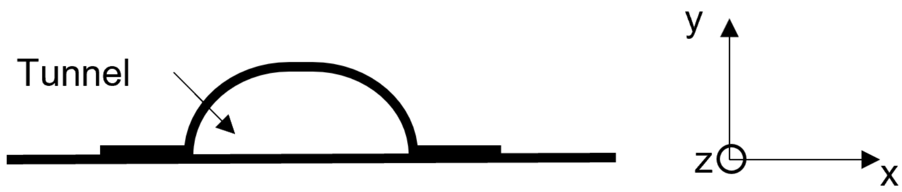

Figure 1. Schematization of UWB electromagnetic tunneling concept

A more recent approach based on ultrawideband (UWB) guided electromagnetic waves (GEMWs) [9] can be instead operated with the use of a couple of antennas placed at the two opposite sides of a hollow structure to detect the damage. The advantage in using GEMWs relies also on the exploitation of microwaves at GHz frequencies which are sensitive to any change in the waveguide. A flaw or a thickness variation on the inner surface as well as the stringer disconnection from the hosting structure (i.e., debonding) would disturb the propagation and generate a detectable echo in transmission or reflection mode. Since microwaves can propagate in a tube-like structure with low attenuation, non-destructive testing (NDT) techniqeus have been already explored to detect cracks [10], slits [11], biofouling [12] and wall thinning [13] in small diameter pipes. Instead, a tube of much larger diameter was inspected in a previous study using a antenna specifically characterized for the scope [14]. In this view, the papers proposes a novel approach based on UWB GEMW tunneling for debonding detection in composite structures in order to assess the feasibility of this technique, the sensitivity to debonding-like damage and the signal to noise ratio in using damage indicators to identify such a defect.

ULTRAWIDEBAND ELECTROMAGNETIC TUNNELLING

The principle of UWB-GEMW tunnelling approach is to let the microwave propagate in the hollow structure (closed section) formed by the host plate and the stiffener. This is the case of carbon fiber fuselages, whose omega stringers create a wide number of tunnels. Such a tunnel is a waveguide for UWB GEMWs, whose propagation is affected by the debonding according to its severity and depth. Any change at waveguide level can be monitored locating a double side antenna pair on the two sides of the stringer. This allows designing an SHM system based on guided electromagnetic waves trapped in the stringer tunnel. In detail, as shown in Figure 1, a hollow composite section works as a tunnel and can shield the UWB GEMW propagation in the direction orthogonal to the $x - y$ section. When the propagation is enabled, the dielectric properties of the fluid and the CFRP boundaries affect the electromagnetic wave field. Keeping constant the former one, UWB GEMW can have the potential to monitor a change of the latter one, appearing in form of damage. Specifically, a crack at the bonding line which increases up to a debonding varies the wave field because part of the energy trapped in the stringer flows outside. The airframe works as an electromagnetic cage polarizing the GEMW propagation along z direction. This latter can be generated using a bow-tie antenna as designed in [14]. Shaping the antenna substrate to adhere to the boundaries of the stringer on one edge, the wave is conveyed within the tunnel and can be detected on the other side by a twin antenna adhering to the other edge of the stringer. This allows maximizing the energy transmission and, as such, the sensitivity to any damage. The same inspection can be repeated by inverting the electromagnetic source antenna with the receiving antenna (converse

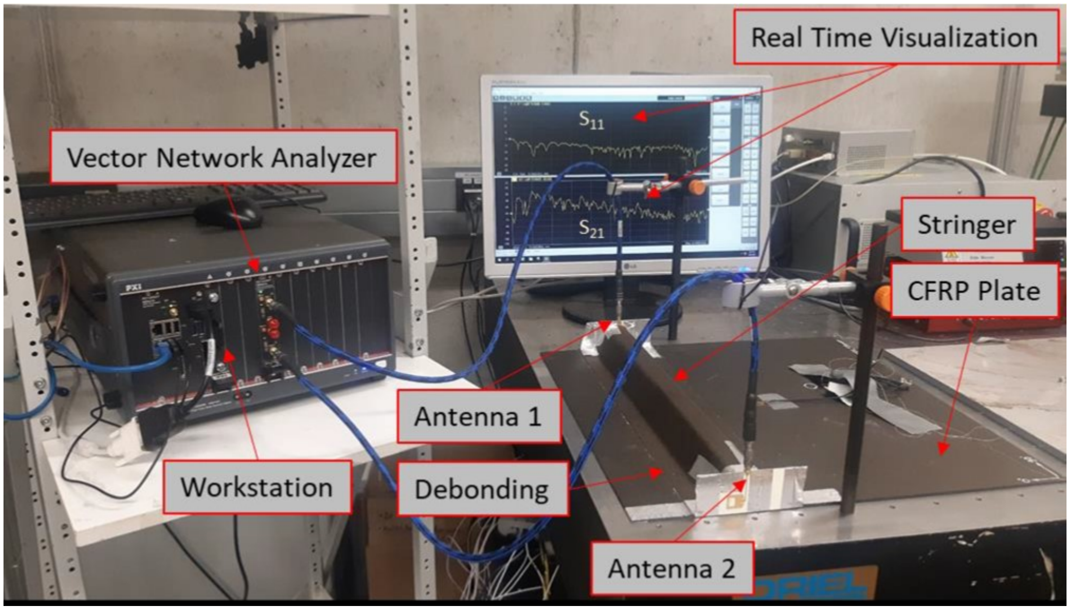

Figure 2. Experimental setup for UWB GEMW tunneling aiming at stringer debonding assessment

UWB-GEMW interrogation).

EXPERIMENTAL SETUP AND DATA ANALYSIS

Experimental Setup

The experimental setup shown in Figure 2 is used to measure the GEMW field in propagating within the stringer. A vector network analyzer (VNA) PXI records the scattering parameters up to frequencies of 44 GHz in reflection and transmission mode. A thin composite plate made of carbon fiber reinforced polymer (CFRP) is stiffened by an omega-shaped stringer co-bonded with the hosting structure, as typically designed for airframes. For the purpose of this work, the stringer is filled with air and equipped with two microwave antennas, which are installed at the front and back on the stringer and connected to the VNA. Finally, a workstation is employed to drive the VNA, visualize, download and post-process the GEMW signals.

Debonding-like damage in stiffened composite airframes is a quite remarkable and hazardous phenomenon whose simulation is not trivial. The onset is triggered by accidental conditions (e.g. due to impact loads) and the damage growth under fatigue load is low yet continuous, locally reducing the load bearing capability of the whole structure. As the no-crack growth capability must be demonstrated under fatigue cycles for composite airframes, also crack stoppers are usually mounted to prevent overcoming critical debonding sizes, which makes the structure heavier. Hence, the use of a reliable and cost effective SHM approach can facilitate a further weight reduction. To simulate the debonding in the laboratory experiment, part of the stringer was completely disconnected close to the tip, and then fixed back with tape (pristine condition). This was possible because a damage was preliminary created as described in [15]. The tape allowed to create the pristine condition. Instead, applying a thin hand-tool in between the stringer flange and the hosting structure, the simulation of damage is enabled (damaged condition). Removing the tool and pressing the stringer allowed to move back to the pristine condition. As showed in Figure 2, the antennas and connectors are well fixed to avoid any influence on measurement during defect simulation.

Using this approach, 3 different scenarios are simulated and investigated. Including the baseline, the following structural states can be summarized:

- Case ”Base”: baseline condition with pristine structure;
- Case ”Open”: damaged condition with simulation of stringer debonding;
- Case ”Closed”: restoration of pristine condition after debonding;

The measurements are obtained by the following procedure:

1. One sensor excites a microwave signal and measure the reflection while the other one records the transmitted signal. (reflection mode is not considered in this paper).
2. Baseline measurement (without damage): there is not any damage in the host structure since the stringer is connected and tightly fixed to the host structure. Recorded signals are used as reference (or baseline) for data processing.
3. Detection of damage scenario: a damage is introduced by enabling debonding. The measurement is repeated every time to reproduce different scenarios as itemized above.

To achieve a good signal to noise ratio of the spectral response, a 1601 points frequency sweep from 0.10 up to 20 GHz is operated setting the VNA with intermediate frequency bandwidth of 10 Hz enabling maximum dynamic range.

Data Analysis

According to the measurement procedure described in the previous section, different signals from transmitter and receiver are post processed to detect the anomalies introduced in the structure through the different damage scenarios. The baseline data (S_b) is obtained for transmitter 1 (T_1) and receiver 2 (T_2). For each damage scenario, the measurement is repeated to get the current data (S_c) for each structural state. Finally, a damage index approach based on root-mean-square deviation (RMSD) is computed to discern the different states of the structure as follows:

$$DI = RMSD\left(\bar{S}_c(f); \bar{S}_b(f)\right) \tag{1}$$

where $S(f)$ is the scattering parameter $S_{i,j}$ selected for damage detection. It is worth noting that five concurrent measurements are carried out enabling the noise assessment of the system which allows to correctly evaluate the effectiveness of the damage detection approach. That is to say, the noise in the baseline (B) state is estimated by computing the average deviation of the n baseline signals $S_b(f)$:

$$DI_B = \frac{1}{n}\sum_{i=1}^{n} RMSD\left(S_{b|i}(f); \bar{S}_b(f)\right) \tag{2}$$

PRELIMINARY RESULTS

The identification of the stringer debonding in stiffened composite plate is based upon 15 sets of response data records that were collected from the microwave sensor under varying conditions. Figure 3 shows the scattered signals (S-parameters) of transmitter 1 (T_1) and receiver 2

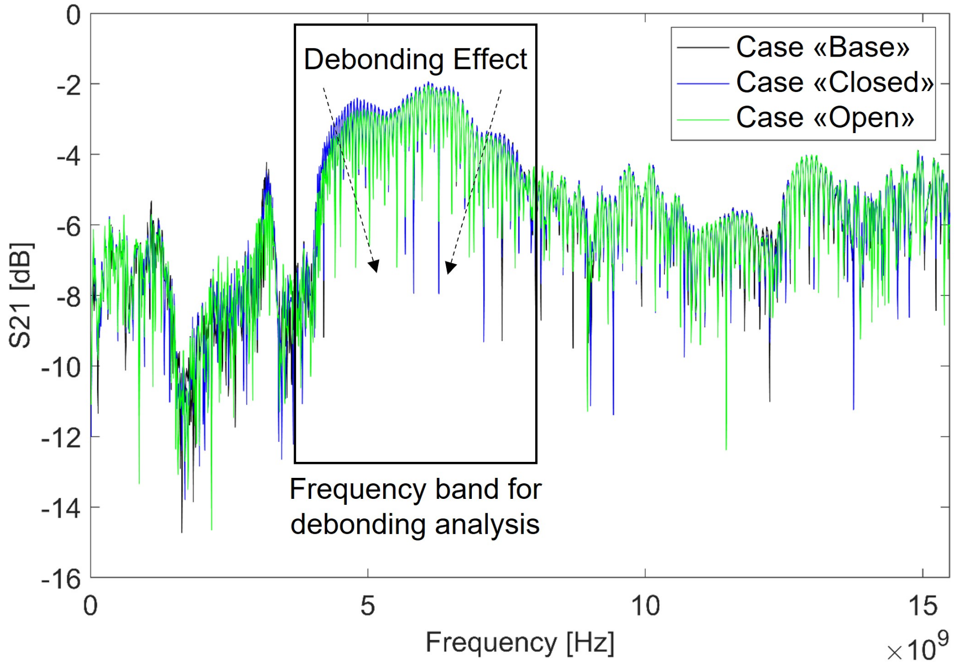

Figure 3. Comparison of frequency spectrum in different damage scenario.

(T_2) in between 0.10 GHz and 20 GHz obtained for baseline condition and different scenarios, respectively. These testing conditions are simulated opening and closing the artificial debonding. The plots clearly show that some differences can be detected all over the frequency range. In particular, as highlighted by the black dotted arrows, the curve goes clearly down in between [4-8] GHz, where the antennas show high sensitivity. Generally, part of the transmitted energy flows down due to the breathing debonding and the transmitted energy gets lower. It is worth noting how such a change should increase with damage severity (to achieve a quantitative evaluation of damage assesement) and decrease (close to zero) when pristine condition is restored (stability of GEMW measurements).

To better look into such a GEMW signal change due to different structural state, the damage detection approach is analyzed hereinafter. The results obtained are depicted in Figure 4, showing the damage indicator versus damage case (as a bar plot to highlight the effect of concurrent measurements). It is worth noting that a clear identification of debonding is possible because the DI value in case of damage is much higher compared to the baseline condition. Hence, it is clear that very small air leak due to debonding causes a energy decrease in transmission mode, with a consequent alteration of the wave field over the tunnel. Instead, after restoring condition similar to pristine state (case ”Closed”), the damage indicator decreases suddenly, demonstrating stability of the measurements. Finally, frequency and time domain analysis (not reported here for the sake of conciseness) result in very similar trend even though the time based computation returns higher DI value.

Having a better look at the repeated entries used for the DI calculation in all cases, it looks evident that the variability due to measurement repeatability is rather limited thanks to the good signal to noise ratio achieved during the measurements. In addition, this variability is much smaller than the DI increase due to debonding. Indeed, what is also worth noting is the signal to noise ratio achieved in terms of damage index. This latter, when related to pristine condition (Case ”Base”) shows a relatively low value. This is due to the good sensitivity of GEMWs to the

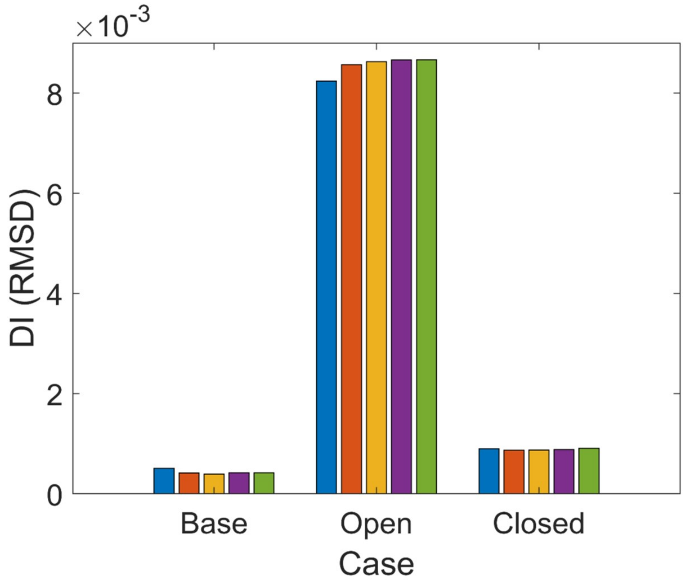

Figure 4. Damage indicators based on root mean square deviation of UWB-GEMWs. The indicators are evaluated in different conditions 1. Baseline ("Base"), 2. Debonded stringer with air gap ("Open"), 3. Reference state equivalent to baseline ("Closed").

defect, ensuring the effectiveness of this approach to warn the presence of damage. Finally, the case "Closed" shows values of DI proper of pristine condition, demonstrating that the approach allows to identify similar state conditions properly.

CONCLUDING REMARKS

The main objective of this work is the investigation of Ultrawideband Guided Electromagnetic waves for debonding detection in stiffened composite structures designed for airframes. The main hypothesis examined in this work is that UWB-GEMWs can be tunnelled in closed section stringer and the damage occurrence alters the wave field so that the use of scalar damage indicators can be exploited to detect debonding reliably. A preliminary experimental campaign is carried out through which signals for the intact and damaged structure are generated. The measurements carried out at laboratory scale offer the possibility to verify the hypothesis and proof the underlying concept. Differences in the spectral response can be observed considering either the reflection or the transmission loss. Post processing those signals from transmitter and receiver in a damage index approach enabled accurate flaw detection with good signal to noise ratio. In particular detection is possible in the frequency region [4-8] GHz, where the energy of the transmitted wave decreases with debonding due to air leak. In addition, signal to noise ratio is enough to properly distinguish between pristine state and damaged conditions as well as to recognise similar state conditions.

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REFERENCES

1. 2009. "Composite Aircraft Structure, U.S. Department of Transportation," Tech. Rep. AC 20-107B, FAA, Washington, DC.
2. Soutis, C. 2005. "Carbon fiber reinforced plastics in aircraft construction," *Materials Science & Engineering A*, 412:171–176.
3. 2011. "Damage tolerance and fatigue evaluation of structure document information." Tech. Rep. AC 25.571-1D—, FAA, Washington, DC.
4. Moll, J., C. Kexel, J. Kathol, C.-P. Fritzen, M. Moix-Bonet, C. Willberg, M. Rennoch, M. Koerdt, and A. Herrmann. 2020. "Guided Waves for Damage Detection in Complex Composite Structures: The Influence of Omega Stringer and Different Reference Damage Size," *Applied Sciences*, 10(9):3068, ISSN 2076-3417.
5. Memmolo, V., N. Boffa, L. Maio, E. Monaco, and F. Ricci. 2018. "Damage localization in composite structures using a guided waves based multi-parameter approach," *Aerospace*, 5(4), doi:10.3390/aerospace5040111.
6. Memmolo, V., E. Monaco, N. Boffa, L. Maio, and F. Ricci. 2018. "Guided wave propagation and scattering for structural health monitoring of stiffened composites," *Composite Structures*, 184:568–580, doi:10.1016/j.compstruct.2017.09.067.
7. Farrar, C. R. and K. Worden. 2007. "An introduction to Structural Health Monitoring," *The Royal Society – Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 365:303–315.
8. Cusati, V., S. Corcione, and V. Memmolo. 2022. "Potential Benefit of Structural Health Monitoring System on Civil Jet Aircraft," *Sensors*, 22.
9. Memmolo, V., L. Fox, J. Moll, and V. Krozer. 2023. "Structural Health Monitoring of Metallic Tubes inducing Guided Electromagnetic Waves," in *Proceedings of 17th European Conference on Antennas and Propagation*.
10. Abbasi, K., S. Ito, and H. Hashizume. 2008. "Microwave detection of longitudinal crack and identification of its location in straight pipe," *Journal of Power Energy Systems*, 2:538–544.
11. Chen, G., T. Katagiri, N. Yusa, and H. Hashizume. 2020). "In-pipe crack detection for multiple diameters using TE 11 mode microwaves," *International Journal of Applied Electromagnetics and Mechanics*, 64:39–46.
12. Liu, L. 2015. "Application of microwave for remote NDT and distinction of biofouling and wall thinning defects inside a metal pipe," *Journal of Nondestructive Evaluation*, 34:1–8.
13. Chen, G., T. Katagiri, H. Song, N. Yusa, and H. Hashizume. 2020. "Investigation of the effect of a bend on pipe inspection using microwave NDT," *NDT & E International*, 110:102208.
14. L. Fox; J. Moll, V. K. 2022. "Monitoring of Pipelines using Microwave Structural Health Monitoring," in *Proceedings of 10th European Workshop on Structural Health Monitoring*.
15. Pawel, K., R. Maciej, M.-B. Maria, W. Christian, L. Yevgeniya, B. Jannis, T. Kilian, and M. Jochen. 2022. "Dataset on full ultrasonic guided wavefield measurements of a CFRP plate with fully bonded and partially debonded omega stringer," *Data in Brief*, 42:108078.