eJNDT e-Journal of Nondestructive Testing - ISSN 1435-4934 - www.ndt.net

EWSHM 2024
11th European Workshop on Structural Health Monitoring

Towards reliability assessment of ultra-wideband microwave leakage monitoring in detecting stringer debondings in composite airframes

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Abstract. Ultra-wideband guided electromagnetic waves have been proposed recently for non-destructive testing and structural health monitoring applications. Among the multitude of possible microwave waveguides, recent works explored the concept of microwave leakage monitoring to detect stringer debondings in hollow carbon composite structures. The principle is to monitor the wave propagation characteristics within the cavity formed by the stringer and the airframe skin using transmission measurements. Changes in the transmission path, e.g. occurring from microwave leakage in the debonded region, can be assessed through a damage indicator approach.

To proof the reliability of this concept, an experimental campaign was carried out according to the building block approach typically used in aeronautics. First, a small-scale specimen with a debonded stringer was investigated in the laboratory to proof the methodology. Then, a large-scale fuselage segment was used for technology demonstration enabling stringer debonding with increasing severity through static and fatigue loading. The paper shows that the microwave characteristics in the waveguide (stringer tunnel) is affected by the debonding conditions according to its severity and depth. In addition, extending the same approach on a number of test cases, the probability of detection was carried out showing the minimum defect size which can be identified properly. This allows designing a reliable structural health monitoring system based on guided electromagnetic waves trapped in the tunnel.

Keywords: guided electromagnetic waves, composite structures, aerospace structures, airframes, structural health monitoring

NDTnet Media and Publishing Partner
https://doi.org/10.58286/29749

Introduction

Composite airframes suffer of barely visible impact damage which might result in critical debonding where the thin-walled host structure is stiffened by stringers [1]. The damage consists of a disconnection between those parts which reduces the load bearing capabilities with a significant impact on safety [2]. Hence, it is of outmost importance detecting this type of damage, ideally through continuous inspections. In this context, Structural Health Monitoring (SHM) can meet the safety requirements through permanent condition monitoring system to control damage phenomena through a set of distributed sensors that are able to detect damage. However, reliability assessment is required to put in place and deploy such an automated inspection system.

Various approaches have been proposed so far to detect, localize, and quantify damage in composite structures. Among them, ultrasonic guided waves based methods are particularly suitable for debonding detection in composite stiffened structures and many approaches are available in the literature using probabilistic imaging [3], ray tracing reconstruction [4], fusion-based damage diagnostics [5], and learning approaches [6, 7]. However, these approaches typically rely on sparse transducer arrays and often require multiple sensing points. Consequently, a large number of transducers is needed, with a negative impact on aircraft performance due to additional weight [8].

An alternative approach relies on ultra-wideband (UWB) guided electromagnetic waves (GEMWs) travelling through hollow structures to detect damage [9]. This approach, derived from UWB radar imaging, exploits the electromagnetic scattering and wave propagation characteristics in a cavity rather than the dielectric properties of the structure under inspection (note that multilayer carbon fibre composite laminates are normally not transparent for microwave radiation). When GEMW propagation is shielded by the cavity boundaries, it establishes a proper waveguide, like in tubes, where microwaves can propagate in, exhibiting low attenuation. When microwaves energy is confined within the pipe, an inner emerging flaw generates a scattering which can be exploited to detect and localize it [10, 11, 12, 13]. On top of that, the reliability of such an approach has been successfully demonstrated for NDT of pipes using probability of detection method [14].

The same GEMW approach can be extended to structural health monitoring introducing lightweight antenna and damage indicators to track changes in the waveguide [15]. Stringers in composite structures can be inspected likewise, as they can confine the GEMW propagation by shaping a waveguide. A flaw or variation in thickness on the inner surface, as well as disconnection of the stringer from the hosting structure (i.e., debonding), can disrupt the propagation and create a detectable echo in transmission or reflection mode [9]. In particular, the debonding leads to a microwave leakage according to the length and severity of damage. Using two bow tie-like antennas with a large practical bandwidth and tailored to the stringer tips, the interaction of the incident wave with structural defect can be monitored in pitch-catch mode by evaluating the amount of energy leakage occurred.

Implementing this approach, a comprehensive experimental campaign is conducted on a full-scale fuselage segment made of carbon composite. The real scenario representative structure is inspected through microwave leakage monitoring to assess the validity of the system in detecting operational defects. Hence, the fuselage is intentionally damaged with increasing severity of debondings on different stringers to test the potential reliability of the damage identification procedure supported by ultrasonic phased array measurements. This allows the calculation of the probability of detection and the quantification of the minimum detectable debonding.

1. Materials and Methods

1.1 Microwave leakage monitoring approach

UWB-microwave leakage monitoring approach relies on the propagation of UWB GEMWs within the cavity of the hollow section (delimited by the fuselage skin and the omega stringer). The wave excited at one end of the stringer gets polarized along the normal direction thanks to shielding of the cavity boundaries (carbon fiber fuselage and omega stringer) which act as electromagnetic cage (see Figure 1). In principle, changes of the stringer/skin interface affect the field distribution inside the waveguide generating a scattering and, when it gets to a debonding, part of the GEMW energy also leaks out. Shaping the antenna substrate to conform 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 opposite edge of the stringer. This allows for maximizing energy transmission and, consequently, increasing sensitivity to any microwave leak due to damage.

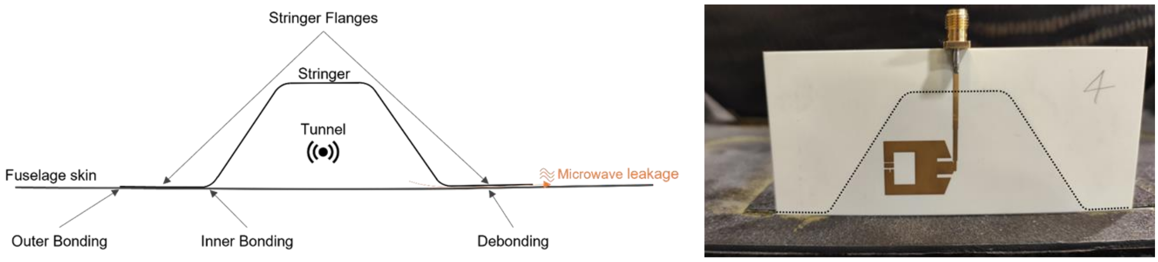


Fig. 1. Schematizing (left) and implementation (right) of UWB electromagnetic leakage monitoring approach conceptualized on the cavity created by an omega stringer. The electromagnetic wave generated at one end of the cavity propagates along the tunnel and interacts with any defect compromising the inner bonding [9].

1.2 Experimental setup

A full-scale fuselage segment including the door cut-out (door surround structure) representing a part of a mid-range jet aircraft (see [16]) is used to validate the microwave leakage monitoring approach in reliably detecting the stringer debonding. The dimensions of the structure are 5.1 m x 3.5 m while the skin presents a constant curvature radius of 3 m. The fuselage skin thicknesses moves from 8 mm around the door cut-out down to 2 mm on the rest of the structure. Furthermore, 44 omega stringers, 4 normal frames, a ladder structure and 16 intercostals stiffen the structural segment. An image of the structure is displayed in Figure 2. The structure has a rotational symmetry of order 2, so that every quadrant of the structure is symmetric. With the exception of the omega stringers located on the top and bottom of the door cut-out, all stringers present the same geometry. This regularity and symmetry in the fuselage structure mean that a total of 40 stringers have the same nominal construction. This property is used in this context to reproduce the experiments on five different stringers with debonding onset close to Frame no. 7, located on far left in Figure 2.

The omega stringer is still made of carbon composite material bonded to the inner side of the fuselage skin, with which it forms a cavity of about 20 cm^2 section. A broadband bow tie antenna is designed and fabricated on RO4003 substrate with a thickness of 0.51 mm and a design based on [17], to make the antenna fit with the structure under investigation as shown in Figure 1. In addition, the bow-tie antenna miniaturization allows to fit the device within the area enclosed by the stringer and to enable the GEMW propagation along its normal direction. This customized design allows preventing energy loss. The two antennas are attached to the end of the stringer with double-sided tape and connected to a vector network analyzer through UWB cables via soldered straight jack PCB SMA connectors 32K101-400L5 from Rosenberger. A vector network analyzer (VNA) from *Keysight* records the scattering parameters up to frequencies of 20 GHz in reflection and transmission mode. Finally, a work- station is employed to drive the VNA, visualize, download and post-process the GEMW signals

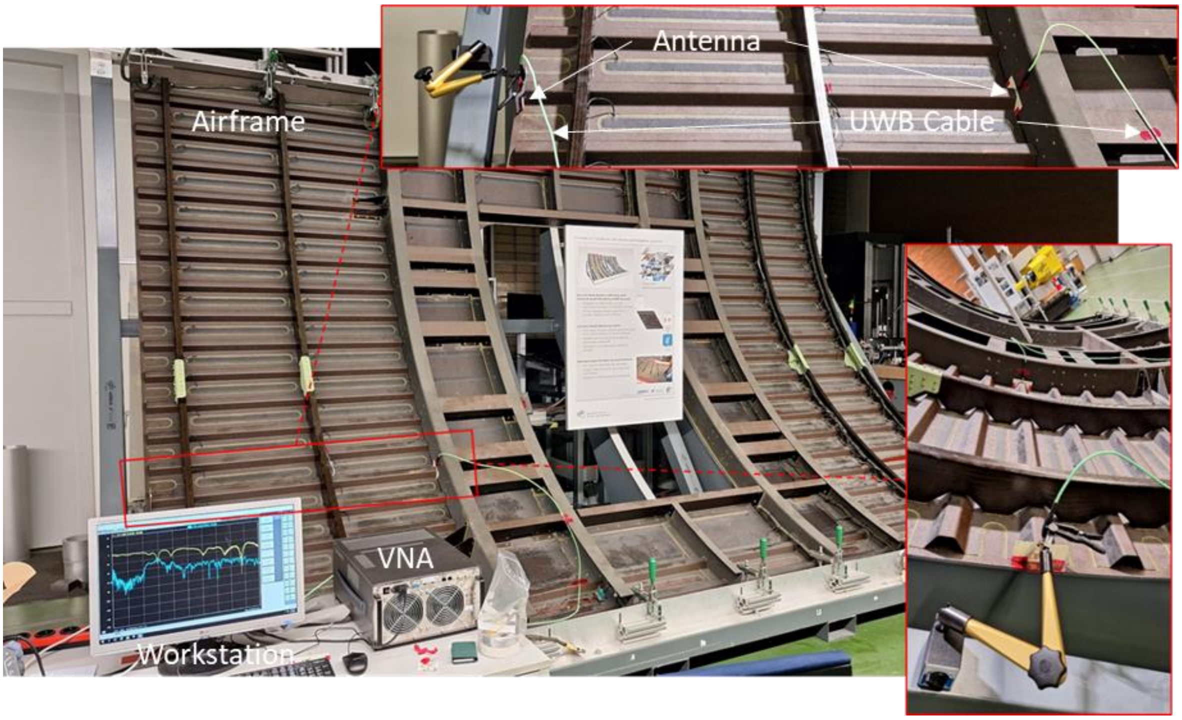


Fig. 2. Experimental setup for UWB microwave leakage monitoring aiming at stringer debonding assessment on the large-scale fuselage segment. The enlarged pictures highlight the placement of the antenna.

To test the microwave leakage monitoring approach, an initial debonding, which consists of an interlaminar fracture occurring at the interface between the stringer flange and the skin, is triggered by impact and then increased in a controlled manner. The debonded area is typically observed when the impact occurs close to the stringer run out, where the absence of any stiffening and connection to the frames leads to damage initiation and evolution at the interfaces. This defines the initial debonding length and it is unpredictable. Afterwards, increase in debonding length of about 5-10 mm is induced manually and checked via ultrasonic phased array non destructive testing. The same procedure is repeated on 5 different stringers obtaining initial and final condition of the stringers reported in Table 1. UWB microwave measurements are carried out in between as described in the next section.

Table 1. Initial and final condition of the stringers inspected by microwave leakage monitoring approach

Frame	Stringer	Initial Debonding Length	Final Debonding Length
No. 7	No. 5	180 mm	291mm
No. 7	No. 6	123 mm	230 mm
No. 7	No. 7	140 mm	271 mm
No. 7	No. 8	195 mm	306 mm
No. 7	No. 10	153 mm	270 mm

1.3 UWB GEMWs dataset and reliability assessment

Using the setup described in Section 1.2, different scenarios are simulated and investigated, which includes the reference condition (baseline taken at the initial debonding length) and a number of altered conditions (damaged condition with simulation of stringer debonding). In particular, the reference condition was chosen to compensate the variability of the experimental setup, which changes for the initial debonding.
The GEMW measurements are obtained by the following procedure:

1. One sensor excites a microwave signal and measures the reflection while the other one records the transmitted signal. (reflection mode is not considered in this paper).
2. Baseline measurement (without damage growth): there is not any damage growth in the host structure since the stringer has an initial (static) debonding after the impact occurs. Recorded signals are used as reference (or baseline) for data processing.
3. Detection of damage scenario: a damage growth is simulated by enabling debonding length increase. The measurement is repeated every time to reproduce different scenarios.

To achieve a good signal to noise ratio of the spectral response, a 3201 points frequency sweep is operated setting the VNA with intermediate frequency bandwidth of 10 Hz enabling maximum dynamic range possible. In addition, the system (including VNA, port connectors and cables up to the antennas) is calibrated before the first acquisition. The calibration procedure is three-fold because it allows to: (i) correct the raw match, which is not excellent in principle due to the broadband nature of the VNA, (ii) adjust the directivity, by removing any residual coupling between emitted and reflected signal, and (iii) calibrate out the frequency response of external cables and connectors. To this end, a *Keysight* calibration module kit is adopted and the SOLT algorithm simulates short and open circuits, load, and port 1 to port 2 through transmission. A full 2-port calibration is accomplished correcting all four parameters, S11, S12, S21, and S22.

In the microwave leakage monitoring approach, the UWB GEMW travels confined by the waveguide in one dimensional propagation. A damage of any kind on the inner surface of the stringer prevents the surface current from flowing and therefore changes the electromagnetic field distribution, which in turn impacts the propagating mode, leading to a detectable scattering of the incident wave forward (transmission mode) or backward (reflection mode) [19]. Information about the flaw can be detected with the S-parameters when these ones are compared with a reference. This can be repeated every time the state changes to get a data history and monitor the health of the structure. To this end, the root-mean-square deviation among current (damage increase) and reference (initial debonding length) signal is computed to get to a scalar metric:

$$DI = RMSD\,(Sc(f\,);\; Sb(f\,))$$

Where $Sc(f\,)$ is the frequency representation of the current signal and $Sb(f\,)$ is the corresponding baseline signal. If the monitoring technique is reliable, the value of DI should show a linear trend versus debonding size. Then, the classical Probability of Detection (POD) approach using signal response versus damage size method can be adopted as described in MILHDBK1823 [18]. Therefore, the target damage size can be assessed through $a_{90|95}$.

2. Results

2.1 UWB GEMW signals and debonding effect

The identification of the stringer debonding in the stiffened composite structure is based upon n = 10 sets of response data records collected from the microwave sensors under varying conditions. Figure 8 (a) shows the transmission coefficient S_{21} of transmitter 1 (T_1) and receiver 2 (T_2) in between 0.05 GHz and 20 GHz obtained for baseline condition (reference taken after impact) and different scenarios (several damage increases), respectively. The plot clearly shows the signal response differences all over the frequency range when damage increases, with a strong transmission coefficient decrease in the frequency range [4-8] GHz, where the antenna shows high sensitivity. That is to say, when the debonding occurs, part of the transmitted energy flows out 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 assessment) and decrease (close to zero) when same condition is measured concurrently (stability of GEMW measurements).

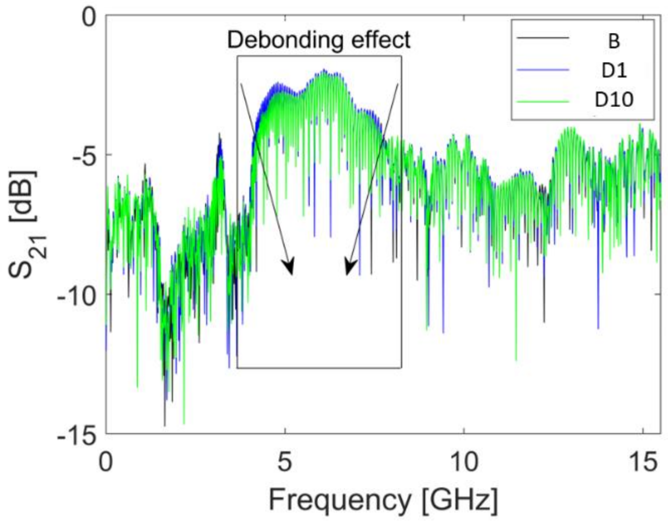
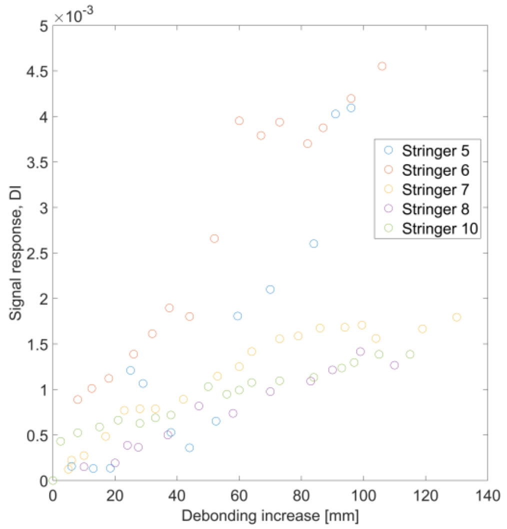


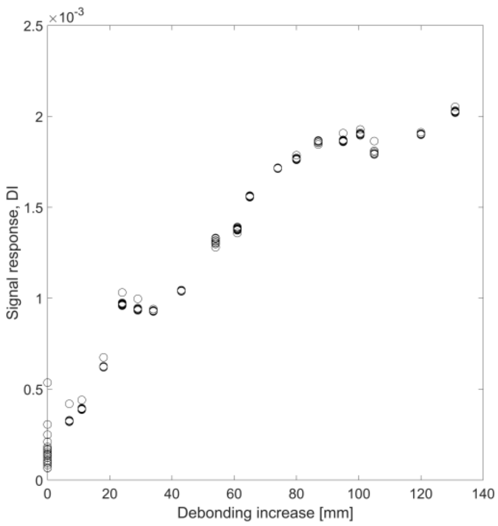
Fig. 3. Comparison of frequency spectrum in different damage scenarios. Signals are acquired after the initial debonding (B), after first damage increase (D1) and after tenth damage increase (D10).

2.2 Damage Index trends

Figure 4 shows the relationship between DI, which is taken as signal response, and the actual damage size, measured as debonding length increase. In particular Figure 4 (a) shows the results obtained processing data from the five inspected stringers while averaging the *n* measurements available. This shows a general increase of the signal response with the damage severity. However, this trend, confirmed for every stringer, does not show always the same rate. To better look into the damage index trend for a single stringer, Figure 4 (b) shows the effect of measurement variability taking into account the *n* concurrent measurements available for stringer 7. The results indicate that the variability is quite low and that the damage samples are quite well separated from the baseline samples. This trend is consistent for all data.



(a)

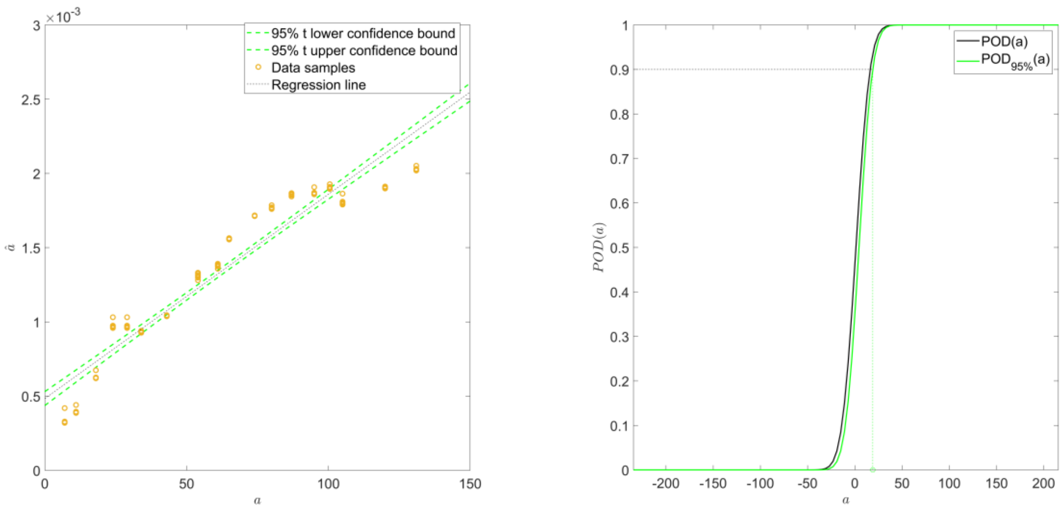


(b)

Fig. 4. Signal response obtained from different stringers (a) and by repeating measurements on a single stringer (b).

2.3 Probability of Detection analysis

Figures 5(a) and 5(b) present the reliability assessment of UWB microwave tunnelling in detecting stringer debonding. The first figure shows the distribution of signal response samples for stringer no.7 and the regression adopted for data model prediction around which the probability of detection is calculated. The confidence level is calculated as well and the probability is assessed accordingly. To define $a_{90|95}$, a threshold of 0.5×10^{-3} is set evaluating the baseline data samples and the statistical distribution thereof in order to have 10% probability of false alarm. The result reports $a_{90|95}$=19.99 mm for stringer no.7 and similar results for the other stringers (see Table 2). Nonetheless, the scattered behaviour shown in Figure 4 (a) does not allow to compute a single POD curve over the different stringers, suggesting a strong system dependent reliability. However, further normalization of the signal response is under investigation to determine a more general framework for the quality assessment.



(a) (b)

Fig. 5. Regression of signal responses obtained from stringer no.7 (a) and the probability of detection computed over the data (b).

Table 2. POD analysis results of several stringers having 10% probability of false alarm

Frame	Stringer	Threshold	$a_{90\|95}$
No. 7	No. 5	1.01×10^{-3}	84.45 mm
No. 7	No. 6	0.62×10^{-3}	25.48 mm
No. 7	No. 7	0.51×10^{-3}	19.95 mm
No. 7	No. 8	0.71×10^{-3}	29.93 mm
No. 7	No. 10	0.58×10^{-3}	21.28 mm

3. Concluding remarks

Ultra-wideband guided electromagnetic waves are proposed in this paper for disbonding detection in composite airframes through microwave leakage monitoring. The results obtained from an extensive experimental campaign on a fuselage segment showed the ability of this technique to recognize very small debonding growth. In addition, for the first time the reliability assessment of such an approach is carried out using classic probability of detection technique suggesting that debonding of less than 20 mm can be detected reliably by the conceived system.

The collaboration of the authors was supported by the DFG within the *ScientificNetwork Towards a holistic quality assessment for guided wave-based SHM* (project number 424954879). In addition, the authors gratefully acknowledge the financial support of this research by the Federal Ministry for Economic Affairs and Energy (Grant Number: 20Q1911C).

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