EWSHM 2024
11th European Workshop on Structural Health Monitoring

A Composite Fuselage under Mechanical Load: a case study for Guided Wave-based SHM

Maria MOIX-BONET [1], Daniel SCHMIDT [1], Benjamin ECKSTEIN [2], Peter WIERACH [1]
[1] German Aerospace Center (DLR e.V.), Institute of Lightweight Systems,
Lilienthalplatz 7, 38108 Braunschweig, Germany,
maria.moix-bonet@dlr.de
[2] Airbus Operations GmbH, Airbus-Allee 1, 28199 Bremen, Germany

Abstract. This study explores the use of Guided Wave-based Structural Health Monitoring for aircraft composite structures under mechanical loads. The research presents the results of a full-scale test on a composite fuselage panel involving realistic impact damage and quasi-static mechanical loading with representative load cases. The dataset generated is then used to analyse the interaction between operational factors and damage effects on guided wave propagation.
Keywords: Guided Waves, Environmental and Operational Conditions, Composite Structures, Aeronautic Structures

Introduction

The design of aircraft structures is driven by damage tolerance, a design philosophy developed in the 1970s. The use of composite materials in aircraft structures and the different behaviour of metallic and composite materials lead to a redefinition of the relevant damage types and the mechanisms causing structural failure ([1]). One of the main differences affecting the methodology for fatigue and damage tolerance compliance is based on the damage growth mechanisms and the visual detectability of impact damages in composite structures.

The Guided Wave-based Structural Health Monitoring (GW-SHM) technique is based on a network of permanently installed piezoceramic transducers for the excitation and reception of ultrasonic Guided Waves (GW). GW-SHM has been demonstrated as a monitoring technique to identify Barely Visible Impact Damage (BVID) in composite aircraft structures, typically in the form of delamination in the skin or debonding between skin and other structural elements ([2], [3]).

One of the main challenges for the application of this technique lies in the wide range of Environmental and Operational Conditions (EOC) of an aircraft as changes in EOC affect the propagation of GW. Because the GW-SHM technique usually employs baseline-based methods to detect damage, a variation in the reference data set due to EOC deteriorates the system's ability to detect anomalies if not accounted for. Numerous techniques to compensate for EOC have been developed ([4], [5], [6]) but an application in realistic conditions remains challenging for the available compensation techniques. Some of the challenges reside in the

Media and Publishing Partner

geometrical complexity of the monitored structure or the combination of several EOC, such as load and temperature.

This work considers the use of a GW-SHM system to monitor BVID on a full-scale composite fuselage structure undergoing changing load conditions.

1. Load Effects on GW Propagation

Structural loading causes deformation and stress, which in turn affect the GW propagation. Few works have focused on understanding the behavior of GWs in stressed media, particularly in composite structures. The available literature is mainly based on the acousto-elastic effect, which describes the change in ultrasonic wave velocity in stressed solids ([7]).

The acoustic-elastic effect of uniaxial tensile loading in isotropic metallic plates has been the subject of several studies. [8] showed that the acoustic-elastic effect is frequency-dependent, with the change in phase velocity increasing linearly with load at any given frequency. Furthermore, at a constant frequency, the transverse mode was found to be more sensitive to loading than the longitudinal mode. In [9], the GW propagation in stressed solids exhibited anisotropic behaviour in isotropic materials, with changes in phase velocity following a sinusoidal function along the direction of propagation. This anisotropic behaviour led to an increase in phase velocity in the direction of the tensile loading and a decrease in phase velocity in the perpendicular direction. Experimental studies by [10] demonstrated not only an increase in phase velocity but also in amplitude in the direction of tension, accompanied by a decrease in the transverse direction. The change in amplitude exhibited a linear relationship with load, similar to that observed in phase velocity. Other works have explored the load effect in composite plates ([11]), in combination with temperature ([12]) or in complex composite structures ([13]).

The understanding of load effects on GW remains limited to specific cases, such as isotropic metallic materials and uniaxial loads. There is a lack of literature concerning load effects on piezoelectric transducers and the bonding layer between the host structure and transducers. This represents a significant gap in the current understanding of GW-SHM, particularly in more complex scenarios involving anisotropic materials, multiaxial loads, and transducer configurations.

2. A Composite Fuselage Panel under Mechanical Loading

A full-scale composite fuselage structure was designed and manufactured for the European-funded project MAAXIMUS ([14][15]). The design of the composite panel is representative for a passenger door region of a wide-body fuselage, such as A350. The structure has a dimension of 4100 x 5700 mm and covers 9 frames, 17 stringers, 4 windows and the door surround structure. An overview of the test structure is shown in **Figure 1**.

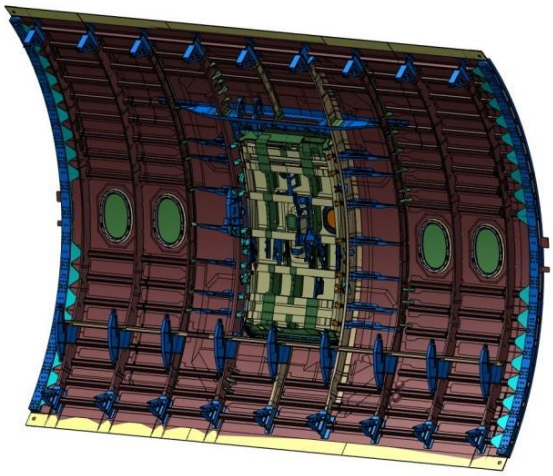

Figure 1: Full Scale Demonstrator Panel ([15])

A GW-SHM system was subsequently designed and installed on the fuselage panel. The design of the SHM system aimed for a practical application in an industrial environment. The distinguishing traits of this GW-SHM system are a robust transducer network, a reliable transducer connection and a modular network concept ([16]).

The fuselage panel was tested under representative loads using the test rig described in [17] and shown in **Figure 2**. The loads in the panel are applied by the test rig through a set of hydraulic actuators. These loads reproduce conditions representative of those encountered by an aircraft in actual operation, such as lateral bending and vertical bending. Three load cases have been selected for the current study: uniaxial tension (FXX), Lateral Bending Left (LBL) and Vertical Bending Down (VBD). **Figure 2** illustrates the basic load cases on a barrel level and the three selected load cases for the project.

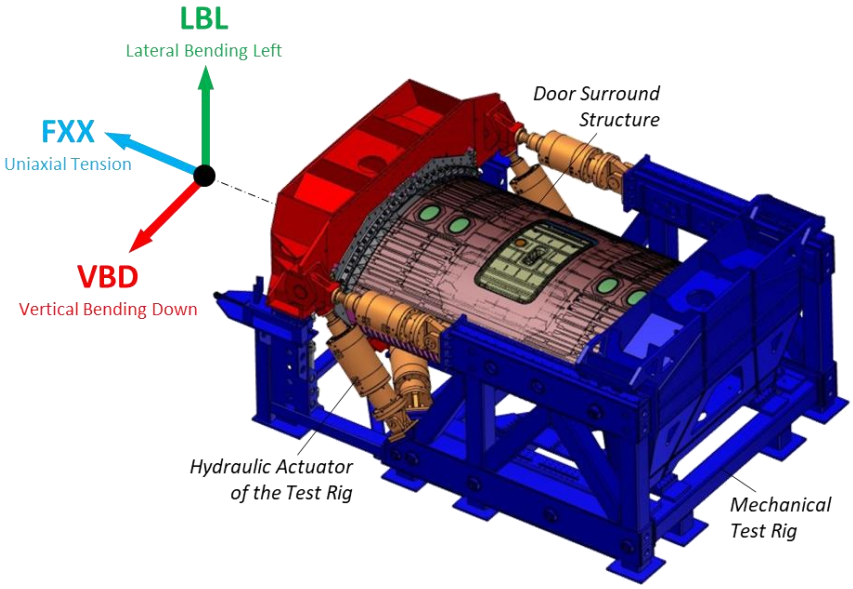

Figure 2: Test Set-up: Door Surround Structure Panel ([17])

The three selected load cases were applied until a load equivalent to the 75% of Limit Load in quasi-static test conditions. The Limit Load (LL) is defined as the maximum load the aircraft should endure during normal operation. The quasi-static test stopped at several steps between the unloaded condition and 75% LL so the SHM system could perform the measurements in static load conditions at multiple load levels.

Using a gas gun, impacts were applied according to the standardized method to create BVID ([18]), creating delamination and debonding with sizes between 364 mm^2 and 3720 mm^2. Non-Destructive Inspection (NDI) based on phased array ultrasonics was performed at the impact locations for reference purposes.

The structure was instrumented with piezoelectric transducers, strain gauges and temperature sensors. A total of 148 piezoelectric transducers, distributed in 31 piezocomposite arrays with integrated multiplexing function were installed on the top-left quadrant of the fuselage structure. The piezoelectric transducers employed windowed 5-cycle sinus burst excitation signals with frequencies between 50kHz and 200kHz for GW actuation, capturing data from all actuator-sensor pairs within a 400mm radius. Additionally, 31 temperature sensors and 14 strain gauges were distributed throughout the area covered by the piezoelectric transducers.

3. Results

This section explores two primary factors influencing GW propagation during a full-scale structure test: mechanical loading and temperature. The ability to identify damage using a GW-SHM system under these conditions is then discussed.

3.1 Influence of Tension and Compression on GW Propagation

To observe the influence of loads on the GW propagation, a highly loaded and undamaged area has been selected. Two actuator-sensor paths have been selected, one in the load direction and one at a 90° angle from the load direction. The first actuator-sensor path is used to observe the effects of tensile loading on GW propagation, while the second path provides transverse compression. The fuselage section under high loads is shown in **Figure 3**, with the selected actuator-sensor paths plotted on the illustration.

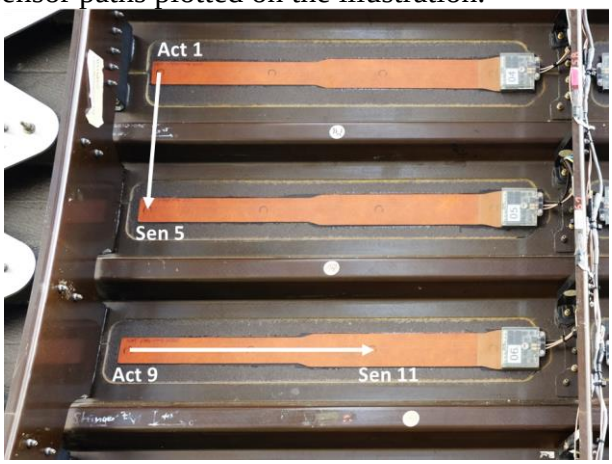

Figure 3: Fuselage Section with integrated Transducer Network and selected Actuator-Sensor Paths

3.1.1. Tension

To observe the effects of tensile loading on the GW propagation, the signal response sent from actuator 9 and received in sensor 11 has been selected. To monitor the strain on the area between transducers 9 and 11, an adjacent strain gauge installed in the loading direction has been selected. The strain in the loading direction during the tensile load case reaches a maximum strain of 1587 με.

The signal response for an actuation frequency of 90 kHz is plotted at several load levels in **Figure 4**. The two GW-modes present at 90 kHz are highlighted in the plot: the symmetric (S_0) and anti-symmetric (A_0) fundamental modes. In both the A_0- and S_0-modes,

the amplitude increases and the time-of-flight (ToF) decreases with increasing tensile load. But the observed effects are more moderate on the S_0-mode, both on the amplitude and ToF.

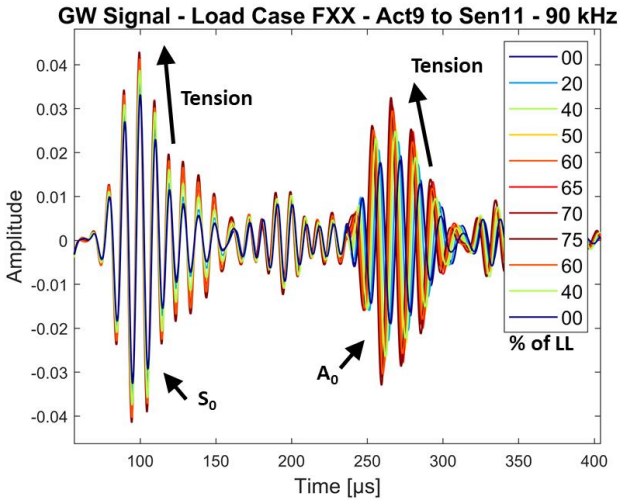

Figure 4: GW-Signal from Actuator 9 to Sensor 11 at 90 kHz - All Load Levels of FXX in Reference State

In order to quantify EOC effects, two features have been derived from the GW signal: amplitude and Time-of-Flight (ToF). The amplitude is defined as the maximal amplitude of the Hilbert transform over the selected wave packet. The initial ToF computation is performed using cross-correlation between the actuation pulse and received signal, while changes in ToF due to load variations are determined through local temporal coherence of the Cross Wavelet Transform, as presented in [19].

In **Figure 5** the amplitude and ToF of the A_0-mode have been plotted as a function of the load level. The plots contain the selected features over a frequency range between 40 kHz and 90 kHz. The effects observed on the signal response at 90 kHz in **Figure 4** are consistent for the selected frequency range: the amplitude decreases and the ToF decreases with increasing tensile stress. A linear regression has been fitted for each frequency, showing a good linear fit between the feature variation and the applied stress.

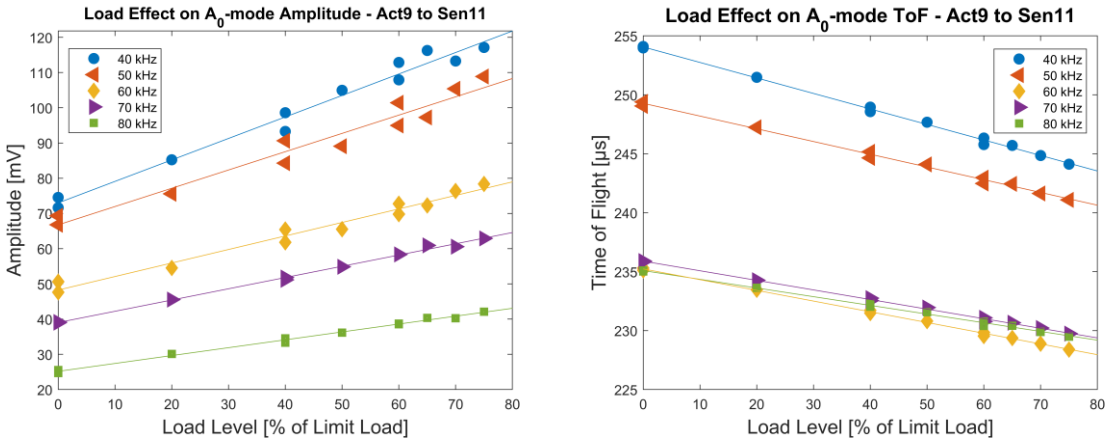

Figure 5: Effect of Load Case FXX on Amplitude and ToF of A_0-mode from Actuator 9 to Sensor 11

3.1.2. Compression

The guided wave signal at 70 kHz for the A_0-mode of transducer pair 1 to 5 is plotted for several load levels on Figure 6. The neighboring strain gauge installed in the direction perpendicular to the applied tensile load indicates a maximal compressive strain of -454 µε during the tensile load case. The effects of transverse compressive stresses on the signal response are a decrease both in amplitude and ToF. In compression the same effect as tension is observed for the ToF, while the opposite effect is found for the amplitude.

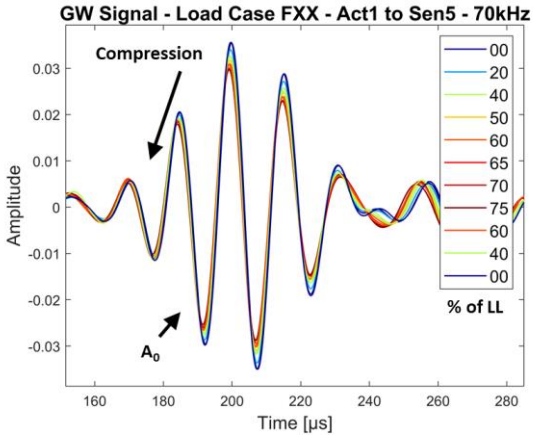

Figure 6: Guided Wave Signal from Actuator 1 to Sensor 5 - All Load Levels of FXX in Pristine State

In Figure 7, the amplitude and the ToF of A_0-mode have been plotted as a function of the load level for several actuation frequencies between 40 kHz and 90 kHz. The compressive stresses induce an amplitude drop of ca. 19,7% and a minimal ToF decrease, less than 1 µs. The linear relationship between the signal features and the load level is observed in the compression case as well.

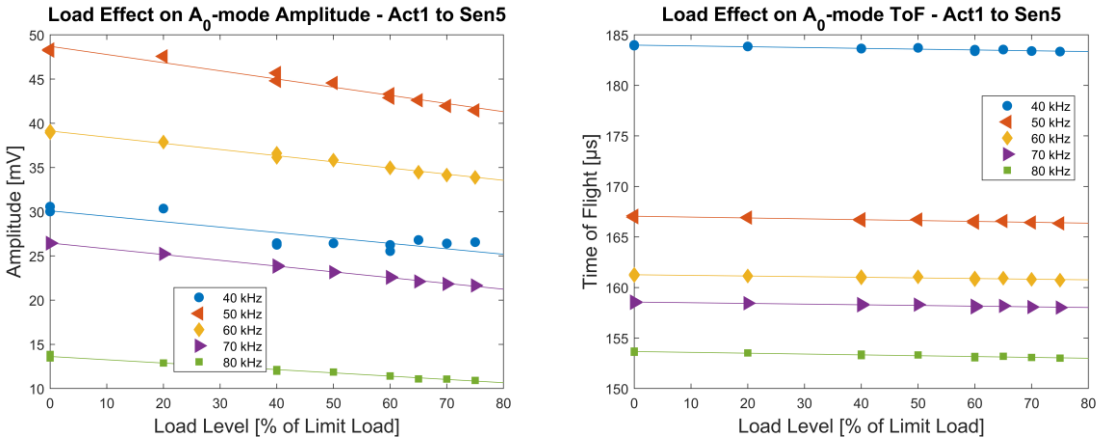

Figure 7: Effect of Load Case FXX on Amplitude and ToF of A_0-mode from Actuator 1 to Sensor 5

3.1.3. Discussion of Load Effects on Guided Waves

The effects of tensile and compressive load on guided waves propagating in composite structures have been observed for the asymmetric fundamental mode in a frequency range from 40 kHz up to 80 kHz. When observing the impact of mechanical loading on GW propagation at a specific frequency, a linear relationship becomes apparent between the load and changes in both amplitude and ToF. This relationship aligns with previous research presented by [8] and [9], which reported consistent linear behavior in phase velocity variations for fixed frequencies. Although differences in ToF are inversely proportional to phase velocity changes, at this scale, a linear change in phase velocity would be perceived as a linear change in ToF.

Notably, ToF decreases for both compression and tension cases, contrasting literature on isotropic metallic structures ([9]), which shows varying wave velocities based on load direction: increased velocity with tensile load and reduced velocity under compressive loading in the transverse direction. A_0-mode amplitudes have been analyzed, revealing that tensile loads increase signal response while compressive loads decrease it, consistent with [10].

3.2 Changes in GW Propagation on Large Structures

The complexity of the current application scenario relies on the extensive SHM sensor network, with hundreds of actuator-sensor paths being monitored. The GW propagation undergoes changes specific for each actuator-sensor path due to local load conditions as well as differences in the structure geometry.

To illustrate the variation load effect on GW propagation, the simulated strain has been plotted for a representative load case. The simulation model was developed within the MAAXIMUS project ([14]) and has been customized to fit the boundary conditions of the present structural test. It is worth noting that the load introduction in this study has been simplified compared to a real structural test of a fuselage panel, which results in a different strain distribution.

Figure 8 shows the normalized strain in the longitudinal axis – or flight direction – for the VBD load case with. The left side of the depicted fuselage was fixed on the test rig, while the load was applied through hydraulic cylinders attached to the right side of the structure (see Figure 2 for reference). The black arrow on the right indicates the load direction, along the normal axis of the plane, in a simplified manner. The quadrant of the structure monitored with the SHM system is highlighted in Figure 8. In the selected quadrant, the color scale illustrates the high positive strain values observed on the left-top corner in the in-flight direction.

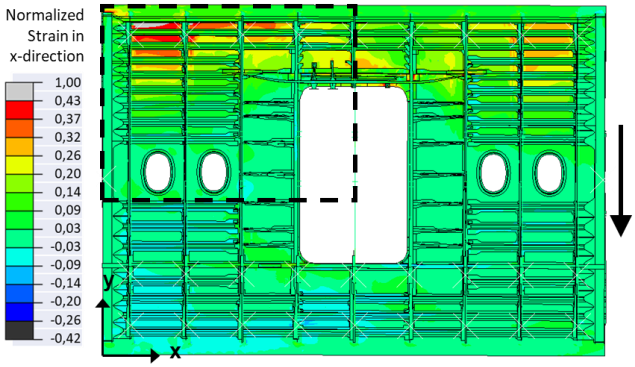

Figure 8: Normalized strain in flight direction for Vertical Bending Down load case

As observed in section *3.1*, the strain causes changes in the ToF and amplitude of the GW fundamental modes. The changes on ToF between the unloaded state and the load cases VBD at 75% of limit load have been calculated for all actuator-sensor paths under a 300 mm length for a frequency of 70 kHz. In Figure 9 the shift in ToF calculated for these two load cases has been plotted. The actuator-sensor paths are colored according to the time shift value observed for the corresponding path. Thus, the influence of the load cases on the GW propagation can be visualized for the entire structure.

The areas of the fuselage with the highest shift in ToF are roughly in agreement with the high positive strain zones indicated in Figure 8. When the structure is subjected to the VDB load case, the larger time shift values for Guided Waves are in the longitudinal direction at the top-left corner. Figure 9 shows that both positive and negative strain lead to an increase in wave velocity.

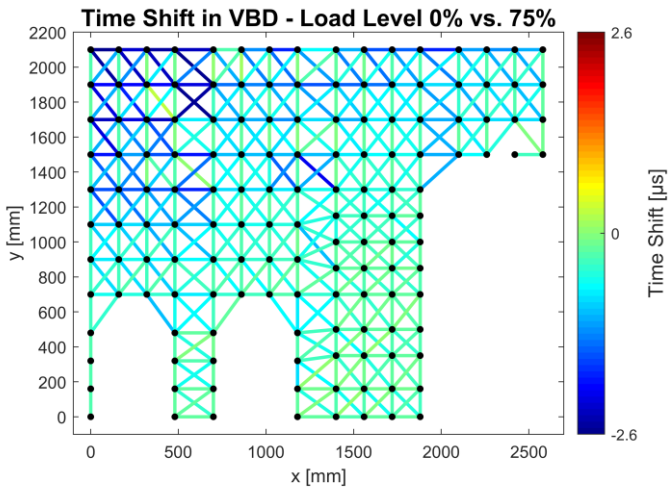

Figure 9: Difference in ToF for load cases VBD at 75% of Limit Load

3.3 Damage Detection under Changing Load Conditions

This section aims to assess the damage detection capability of a GW-SHM system within the current application scenario: detecting BVID in a composite fuselage structure under representative flight loads.

To examine the influence of damage combined with load, an actuator-sensor path featuring damage presence have been selected. The previously selected signal features, namely amplitude and ToF, are employed for this analysis as well. In Figure 10 , these two features are graphically presented twice. The first plot emphasizes the impact of loads, while the second plot distinguishes between two damage states. This visual representation provides an insight into the interaction between operational factors and damage.

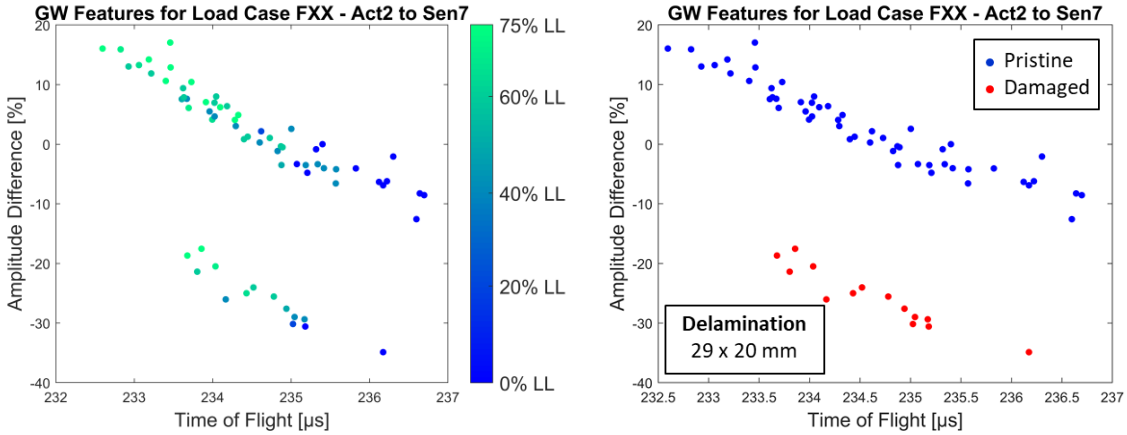

Figure 10: Amplitude difference and Time-of-Flight of A_0-mode at 70 kHz of one path with damage presence, highlighting the load level (left) and the damage state (right)

The damage case in Figure 10 involves a path within a heavily loaded region affected by a delamination induced during the test campaign, measuring 29x20 mm in size. The load effect manifests as variations in ToF and Amplitude. A consistent reduction in amplitude is observable under all tested load conditions, indicating the presence of delamination.

The remaining damaged areas have undergone a similar analysis. In summary, each type of damage exhibits a distinct impact on the A_0-mode. While certain damages may be detected without additional load information, instances with smaller damage sizes or complex geometries require the integration of load data along with multiple signal features to clearly distinguish between pristine and damaged states.

4. Conclusion

A GW-SHM system has been successfully designed, manufactured and installed on a representative composite fuselage structure. A full-scale test, including quasi-static mechanical loading with three representative load cases and the induction of BVID, has generated a comprehensive dataset. This dataset provides a robust foundation for the application of GW-SHM in realistic scenarios, offering insights into the system's performance under conditions that mimic representative flight loads and damage within a composite door surround structure.

Guided waves in composite structures under tensile and compressive loads reveal a linear relationship between load changes and amplitude/ToF at constant frequencies. Data shows ToF decreases for both tension and compression, with amplitude increases under tension and decreases during compression. Distinctive GW propagation alterations due to damage topography and structure geometry require effective discrimination strategies for successful damage monitoring.

5. Acknowledgements

Without the allocation of the necessary funds, the implementation of the project would not have been possible. This research project has been funded by the Federal Ministry of Economics and Climate Protection (BMWK) within the framework concepts LuFo V and LuFo VI with grant agreement numbers 20Q1725D and 20D2105G. The project results achieved are the result of close cooperation between the partners involved. The piezocomposite arrays were manufactured and installed by Invent GmbH, the mechanical tests and the NDI were performed by IMA Dresden, while the fuselage panel has been generously made available by Airbus Operations GmbH.

References

[1] European Union Aviation Safety Agency. (2018). Easy Access Rules for Large Aeroplanes (CS-25) (Initial issue)

[2] Ricci, F., Monaco, E., Maio, L., Boffa, N. D., & Mal, A. K. (2016). Guided waves in a stiffened composite laminate with a delamination. Structural Health Monitoring, 15(3), 351–358. https://doi.org/10.1177/1475921716636335

[3] Moix-Bonet, M., Eckstein, B., Loendersloot, R., & Wierach, P. (2015). Identification of Barely Visible Impact Damages on a Stiffened Composite Panel with a Probability-based Approach. 10th International Workshop on Structural Health Monitoring 2015. https://doi.org/10.12783/SHM2015/290

[4] Konstantinidis, G., Drinkwater, B. W., & Wilcox, P. D. (2006). The temperature stability of guided wave structural health monitoring systems. Smart Materials and Structures, 15(4), 967. https://doi.org/10.1088/0964-1726/15/4/010

[5] Douglass, A. C. S., & Harley, J. B. (2018). Dynamic Time Warping Temperature Compensation for Guided Wave Structural Health Monitoring. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 65(5), 851–861. https://doi.org/10.1109/TUFFC.2018.2813278

[6] Worden, K., Cross, E. J., Antoniadou, I., & Kyprianou, A. (2014). A multiresolution approach to cointegration for enhanced SHM of structures under varying conditions – An exploratory study. Mechanical Systems and Signal Processing, 47(1–2), 243–262. https://doi.org/10.1016/J.YMSSP.2013.10.012

[7] Hughes, D. S., & Kelly, J. L. (1953). Second-Order Elastic Deformation of Solids. In Physical Review (Vol. 92, Issue 5). American Physical Society. https://doi.org/10.1103/PhysRev.92.1145

[8] F. Chen, & P.D. Wilcox. (2007). The effect of load on guided wave propagation. Ultrasonics, 47(1–4), 111–122. https://doi.org/10.1016/J.ULTRAS.2007.08.003

[9] Gandhi, N., Michaels, J. E., & Lee, S. J. (2012). Acoustoelastic Lamb wave propagation in biaxially stressed plates. The Journal of the Acoustical Society of America, 132(3), 1284–1293. https://doi.org/10.1121/1.4740491

[10] Roy, S., Lonkar, K., Janapati, V., & Chang, F.-K. (2014). A novel physics-based temperature compensation model for structural health monitoring using ultrasonic guided waves. Structural Health Monitoring, 13(3), 321–342. https://doi.org/10.1177/1475921714522846
[11] Palanisamy, R., Haq, M., Deng, Y., & Udpa, L. (2021). Structural Health Monitoring: influence of stress fields in propagation of Guided waves in composite. https://speautomotive.com/wp-content/uploads/2021/02/ET_Palanisamy_Structural-Health-Monitoring-Influence-of-Stress-Fields-in-Propagation-of-Guided-Waves-in-Composites.pdf
[12] Michaels, J. E., Michaels, T. E., Lee, S. J., Chen, X., Gandhi, N., & Shi, F. (2012). Understanding and Exploiting the Effects of Loading on Ultrasonic Sensing Systems for Structural Health Monitoring.
[13] Eckstein, B., Bach, M., & Moix-Bonet, M. (2015). Analysis of loading effects on guided ultrasonic waves and damage assessment in a full-scale CFRP fuselage structure. Structural Health Monitoring 2015: System Reliability for Verification and Implementation - Proceedings of the 10th IWSHM 2015, 2, 19–25. https://doi.org/10.12783/SHM2015/5
[14] EU-funded Project MAAXIMUS within the 7th framework program with grant agreement number 213371 https://cordis.europa.eu/project/id/213371
[15] Kruse, F., Kühn, M., Krombholz, C., Ucan, H., & Torstrick, S. (2015, September 2). Production of a Full Scale Demonstrator-Structure within the FP7 Project "Maaximus." 5th International Workshops on Aerostructures.
[16] Schmidt, D., Moix-Bonet, M., Galiana, S., & Wierach, P. (2023, September). Integration von angepassten und dezentralen Structural Health Monitoring Systemen in Faserverbundstrukturen. Deutscher Luft- Und Raumfahrtkongress (DLRK).
[17] Sachse, M., Götze, M., Nebel, S., Berssin, S., & Göpel, C. (2020). Testing approach for over wing doors using curved fuselage panel testing technology. Lecture Notes in Mechanical Engineering, 831–837.
[18] Federal Aviation Administration. (2018). Certification and Compliance Considerations for Aircraft Products with Composite Materials. https://doi.org/10.1016/B978-0-12-803581-8.09944-6
[19] Eckstein, B., Moix-Bonet, M., & Bach, M. (2014, July 8). Analysis of Environmental and Operational Condition Effects on Guided Ultrasonic Waves in Stiffened CFRP Structures. 7th European Workshop on Structural Health Monitoring. https://inria.hal.science/hal-01020370