Investigations of the Potential of Ultrasonic Guided Waves Testing for Flaw Detection in Representative Aerospace Structures using CIVA

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Abstract

The implementation of Guided Waves Testing as a routine Non-destructive Testing (NDT) method for defect detection, localization and sizing in aerospace components other than plate-like structures and metallic pipes, is yet to be further investigated, automated, and standardized. Representative aircraft structures and one space component made of Aluminum 2024 and Cast Aluminum are studied in this paper by using CIVA simulations and, ultrasonic guided waves-based monitoring experiments combined with strain analysis. The aim of the investigations is to develop test protocols based on reproducible simulation approaches for anomaly testing, for relevant sample problems, that could be applicable for the inspections of hard to access areas.

1. Introduction

Sample problems related to fuselage wall thinning, material loss in wing skins, flaws in diverse aluminum profiles, multilayered structures and a use-case derived from the Sentinel-4 instrument are investigated using the CIVA Guided Waves Testing module. Damage features are extracted from the flaw response and time invariance is investigated for dispersive and multimode guided waves to obtain optimum focusing on scatterers. Experimentally, we assess the applicability of the derived procedures, on a complex space structure and an aircraft material sample, with artificial and real defects.

2. Method

CIVA is a software developed by the French Alternative Energies and Atomic Energy Commission (CEA) and its partners [1, 2]. We use the Guided Waves Testing Module (CIVA 2017 SP3 version) where the Semi-Analytical Finite Element Modeling (SAFE) method is applied. It consists of a finite element discretization that takes place at the cross-section of the structural waveguide and the use of an analytical solution in the wave propagation direction. Modal solution computations and mode amplitudes are used to determine the electromagnetic field in the guide.

Figure 1: The implemented simulation steps in CIVA

The energy distributions and wave structures of all modes are analyzed to determine the appropriate transient resonance pattern that shall be excited to detect flaws in a specific structure. The guided wave modes have different sensitivities to surface loading and defects, such as coating delamination, surface cracks, embedded cracks, part-through cracks, cracks of arbitrary shapes, strip defects, and internal voids. Therefore frequency tuning and designing a transducer geometry with an adequate selection of phase velocity are key in obtaining a waveform that will allow the anomalies to be detected.

Experimentally we investigate two use-cases: an Aluminum 2024-T3 stringer from an original Dornier-328 and the upper part of the support box of the Telescope Spectrograph Assembly (TSA) of the Sentinel-4 instrument. We monitor fatigue cracks in the stringer and shrinkage cavities and artificial change of boundary conditions in the TSA Support Box made of cast aluminum alloy G-AlSi7Mg0,6.

2.1. Uses-cases definitions and ECSS-Standards applicability

During the Assembly, Integration, and Testing (AIT) process of space structures, NDT inspections are conducted.
The space engineering fracture control ECSS-E- ST-32-01C Rev. 1 from the European cooperation for space standardization (ECSS) standards’ series is used to compare the detection sensitivity of standard NDT methods and derive the geometry of the crack that shall be used for the simulations on space structures. The ECSS fracture control standard is used to determine the requirements needed for the test protocols of space structure that have a safe-life design as it applies for the telescope spectrograph assembly support box structure case. Initial crack sizes and geometries are defined with the following parameters: type, position, size, shape, and orientation. [3]

2.1.1. Aircraft Use-cases

The following components are investigated: Multilayered aircraft structures (Aluminum-2024 with a 0.1 epoxy layer), plate-like structures to simulate large wing skins that behave as natural waveguides, Z-shaped stringers, I and T-shaped spars from the fuselage frame, as displayed in figure 2, and simplified lap-joints. The planar specimens that represent natural waveguides are investigated with strip defects along the surface and the 2D CAD components are investigated with specifically defined flaw geometries.

Figure 2: Example of a T-shaped profile with transducers placed in a pitch-catch configuration and with a rectangular block defect in the meshed area.

2.1.2. Spacecraft Use-cases

Two use-cases are derived from the Sentinel-4 instrument and the crack geometry design is performed based on the ECSS standard introduced in section 2.1.1. The Sentinel-4 UVN Instrument, currently under assembly, is an imaging spectrometer that will be mounted on a geostationary Meteosat Third Generation Sounder (MTG-S) Satellite. It will provide data to generate hourly measurements of the chemical composition of the atmosphere, air quality, solar radiation as well as cloud and surface characteristics above Europe. The optics are integrated into a dedicated structure (the Telescope Spectrograph Assembly (TSA) structure), which forms the core of the Optical Instrument Module (OIM). The upper and lower parts of the support box are made of aluminum investment casting and are equipped with several stiffeners. The stiffeners are reduced in weight by large holes as shown in figure 3.[4,5]

The TSA support box is made of G-ALSi7Mg0.6, which has the following mechanical, impact, electrical and thermal properties: Young’s module: 70.6 to 73.4 GPa, Yield strength: 281 to 311 MPa, elongation 2 to 2.4% strain, fracture toughness: 20.7 to 23.9 MPa.m$^{0.5}$, toughness: 5.97 to 7.91 kJ/m$^2$, thermal expansion coefficient 20.9 to 21.9 µstrain/°C, thermal shock resistance: 181°C to 203°C, maximum service temperature: 150°C to 170°C.

Figure 3: CAD model of the telescope spectrograph assembly with the Optical Instrument Module. [4]

Situations that might lead to the support box structure being inspected with NDT tools are the following:
- An incident during the integration process (e.g. the structure is dropped or a voluminous object is dropped on the structure)
- Damage that might have occurred during the transport and which was indicated by triggered shock sensors on the transport box or the hardware itself
- A problem during testing, detected by acoustic monitoring and for which a severity assessment is needed.

2.2. Mathematical modeling of wave effects and guided waves scattering problems

2.2.1 Signal processing for damage features’ extractions

The investigations of wave propagations, scattering, simulations and computations of displacement fields aim to properly analyze response signals. The Semi-analytical Finite Element Method and the electromechanical reciprocity relations are well documented in the literature. [6,7,8 9]

For the simulations, one wave path from the sensor to the actuator is defined. For the experimental investigations where an SHM approach is possible, we are able to define several wave paths. Some of the features that can be extracted are the Hilbert transform and, the signal difference coefficient by using data sets acquired from sensor pairs and by computing the covariance between two signals as shown in equation (1). $\mathbf{s}_i$ represents the set of signals acquired from the undamaged sample or in some of our experiments those obtained just after the installation when the sample is kept unloaded at zero kN and $\mathbf{s}_k$ are the set of signals taken afterward, either in the presence of damage or after a certain number of cycles. [8]
Density energy metrics based on the Hilbert transform and time delays are possible features that can be applied for the experimental investigations. In order to identify a phase delay pattern, we rely on the time delay of one specific sensor from the first arrival wave package displayed in the time domain. The algorithm for the delay matrix computations consists of applying the Hilbert transform and calculating the duration of a wave package for every defined path in the system configuration. The analytic signal is defined as follows: [8]

\[
a(t) = u(t) + j h(t) \quad (2)
\]

Where \( u(t) \) is the original ultrasonic waveform and \( h(t) \) its Hilbert transform. The analytic envelope used to get the duration of a wave package is calculated as follows: [8]

\[
e(t) = \sqrt{u(t)^2 + h(t)^2} \quad (3)
\]

The sensor with the first arrival wave package and the time delay between the sensors are identified from the output signals. The cross-correlation factor as defined above shall be computed for every two sensors to estimate the wave packages’ delays.

2.2.2 Forward propagation, forward scattering, and backward scattering

When an incident wavelength is comparable to the structure thickness, a guided Lamb wave is generated. We assess the sensitivity in the reception of every mode to select the excitation region to be considered for the inspection simulation of flaws. Mode conversions due to the presence of arbitrary defects were the first indicator for the inspections simulations of the plate-like structures. The focus of this paper is on structures that generated complex dispersion curves and response signals.

When the independent normal modes generated through mode conversions are linearly superposed, the scattered field in elastic waveguides with geometrical discontinuities can be expressed as follows: [10]

\[
S_{DC} = 1 - \frac{\sum_{i=1}^{N} (s_i (t_i) - \bar{s}_i) (s_a (t_i) - \bar{s}_a)}{N \sqrt{\sum_{i=1}^{N} (s_i (t_i) - \bar{s}_i)^2 \sum_{j=1}^{N} (s_j (t_i) - \bar{s}_j)^2}} \quad (1)
\]

Where \( \frac{\sum_{i=1}^{N} (s_i (t_i) - \bar{s}_i)^2}{N} \) is the covariance and \( \frac{\sum_{j=1}^{N} (s_j (t_i) - \bar{s}_j)^2}{N} \) the standard deviation.

Backward scattering on the left boundary:

\[
u^{BF} = \sum_{j=1}^{L} \beta^j \tilde{u}^j = \sum_{j=1}^{L} \beta^j \left( \frac{\bar{u}_{x1}^j}{\bar{u}_{x2}^j} \right) e^{-j k x_1} \quad (4)
\]

Forward scattering on the right boundary:

\[
u^{FS} = \sum_{j=1}^{L} \beta^j \tilde{u}^j = \sum_{j=1}^{L} \beta^j \left( \frac{\bar{u}_{x1}^j}{\bar{u}_{x2}^j} \right) e^{-j k x_1} \quad (5)
\]

With \( \bar{u} \) the normalized displacement model function of the \( p^b \) mode propagating along the \( x_1 \) axis, \( \alpha \) the amplitude, \( k \) the wavenumber, and \( e^{-j k x_1} \) the time-harmonic term. \( \beta^j \) and \( \beta^l \) are respectively, the \( j^b \) mode reflected and \( l^b \) mode transmitted amplitudes on the boundaries.

The time-reversed acoustics, under investigation, consists of the following steps: (1) Ultrasonic waves in the waveguide are generated, (2) several path signals or one path-signal at the receiver are acquired. (3) The signal is processed, time-reversed and used as an input signal from the transmitter that was originally used as a receiver. [11, 12, 13]

2.3. Simulation results and analysis with CIVA

2.3.1 Aircraft Use-cases

The localization of defects in the studied use-cases and their geometries are derived from real cases documented during operational, intermediate and depot levels maintenance. To carry out an inspection of multilayered structures, the starting point is the analysis of the wave structure to determine which mode has sufficient energy.

The phase velocity dispersion curve (Frequency in MHz versus the phase velocity in mm/µs) of a 2500 mm x 300 mm x 2.2 mm aluminum 2024 multilayered structure is displayed in figure 4.

![Figure 4: Dispersion curves of a 2.2 mm thick multilayered structure. (The symmetric modes are displayed in blue, the antisymmetric modes in red and the shear modes in green)](image-url)
The sensitivity in the reception of the symmetric mode S0, at 1 MHz is high enough which allows a meaningful selection of the transducer phase speed (i.e. corresponding to this wave mode velocity). Examples of normalized displacements and constraints of the in-plane mode S0 at 1 MHz and 4 MHz versus the position in mm could be visualized and displayed as shown in figure 5. We analyze the stress fields and particle velocities across the plate thickness. An energy gradient close to the 0.2 mm thick epoxy layer and to the free surface indicates a good sensitivity for defects located at the aluminum-epoxy interface. The inspection simulations of defects with different heights and at different ligament positions are conducted with a transducer phase speed equal to the phase velocity of the fundamental mode and, with a signal center frequency of 1 MHz.

2.3.2. Spacecraft Use-cases

To evaluate the applicability of the Guided Waves Testing when detecting volumetric flaws in complex parts, a cross-section of the TSA 3-mm thick wall has been investigated. The longitudinal and transversal wave velocities of the cast aluminum sample are respectively equal to 6491 m/s and 3166 m/s. At the chosen A-A cross-section, as displayed in figure 6, the specimen has a rectangular shape of 75 mm x 60 mm. A pitch-catch transmission inspection mode and a non-symmetric mechanical configuration are used to simulate semi-elliptical defects of 1 to 4 mm in length and with a height of 1 mm. A total number of 40 modes exist in the designed cross-section when a Hanning signal with a center frequency of 0.16 MHz is selected. The simulations are also performed with a center frequency signal of 0.25 MHz and a mesh fineness of 1.5 (60 modes coexist in this case). The inspection simulations results are displayed in figure 7.
implemented procedure is reliable to recover pre-defined defects’ geometries (elliptical and semi-elliptical flaws). The group velocities allow selecting, when applicable, the minimum and maximum group velocities for the experiments. However, in this case, the complexity of the dispersion curves did not allow a comprehensive reading of the modes that could be activated during an inspection.

Figure 8: Dispersion curves (Energy velocity, wavenumber and phase velocity) of the A-A cross-section wall

2.4. Experimental investigations

The experimental part focuses on the implementation and evaluation of a global active ultrasonic guided wave monitoring system. When applicable, the protocols generated with the CIVA simulations are used. The considered sample problems are a change of boundary conditions, the detection of shrinkage cavities (milled out and reworked with a repair welding process) in a space structure, cracks initiation and growth by mechanical loading in an aircraft stringer. For more accuracy, strain measurements and thermal field measurements are complementing the ultrasonic guided wave tests.

2.4.1 Active acoustic Monitoring: Investigations of the space cast aluminum structure

We assess the guided wave system capability for a complex structure, studied previously with CIVA. We select three locations as indicated in red circles in figure 9. Two locations with flaws already existing in the structure and one location on the wall where an artificial change of boundary condition is realized.

Two 25-mm diameter neodymium magnets are placed at both sides of the support box wall to change the boundary conditions and thus simulate an artificial flaw [14]. The measurements are performed with 3-cycles burst signals (250 kHz excitation frequency, 60 V amplitude signal). The data are acquired with the ScanGenie-mini and the SHM Patch Software (from Acellent Technologies Inc.) at a sampling rate of 48 MS/s. Four piezoelectric sensors are used on the wall part (single sensors 1,2 and 4: piezoelectric coefficient d31 equal to \(-175 \times 10^{-12}\) m/V, 0.254 mm thick and with a diameter of 6.35 mm (from Acellent Technologies, Inc.), and sensor 3: d31 equal to -210 pC/N, 0.22 mm thick and with diameter of 9 mm (from Reichelt Elektronik GmbH & Co. KG)). Sixteen paths are defined including paths in a pulse-echo mode (e.g. Path 1-1: Pulse-echo mode, Path 1-2 Pitch-catch mode).

For such a complex structure we cannot obtain representative dispersion curves and categorize the modes as symmetric, antisymmetric and shear modes. Therefore, several excitation frequencies are defined successively and the output signals’ qualities evaluated to select an adequate working excitation signal. The experiment was performed with the experimentally determined maximum and minimum wave group velocities. Signal processing is done using MATLAB R2018b. The analytic envelope of the normalized collected baseline signal is displayed in figure 10.

Figure 9: Isometric view of the upper part of the support box (left). The upper part with eight PZT sensors and the investigated wall with the red cross indicating the simulated damage (right).

Figure 10: Baseline design and its analytic envelope for the sensor path 1-2.
The response signal of the first case studied is displayed in figure 11. Successive guided wave packets could be observed: the incident wave, arrival of the reflections from the simulated damage and the arrival of reflections from the edges of the wall. The propagating speed of the wave packet at 85µs where the prominent scatter signal was detected is equal to 5.04 mm/µs. With a 250 kHz center excitation frequency, this mode wavelength is equal to 20.16 mm.

Figure 11: Experimentally obtained output signals from the TSA wall with an artificial change of boundary conditions.

The signal difference waveform is illustrated in figure 12, where the scale has a maximum amplitude of 0.1 V. In this case, the delay matrix is computed using twelve paths defined with four sensors. The baseline comparison was at first sufficient and successful to detect the presence of damage in the structure.

Figure 12: Scatter data

The deterioration of a structure, initiation, and propagation of cracks is realized with a dynamic loading test on an original 25 cm x 4 cm sample cut out of a Dornier-328 stringer with an average thickness of 0.78 mm. A 15-mm hole was made in the middle of the sample. Using a servohydraulic testing machine, the sample is subjected to cycling loading using a sinusoidal load profile with maximum fatigue loads of 1kN and 2 kN. The stringer sample has a static failure load of 6.31 ± 0.032 kN. The fatigue cracks were initiated and grown during dynamic loading at a constant amplitude (The test was performed at the following loading frequencies: 0.5Hz, 1Hz, 2Hz, and 10 Hz). The strain data were collected, using a Hottinger Baldwin Messtechnik MGC+ system, at a sampling frequency of 100 Hz or 50 Hz and a Bessel filter of 5Hz, 10 Hz or 20 Hz (depending on the selected loading frequency).

Ultrasonic guided wave measurements using the hardware described in part 2.4.1 (Burst signal, 30 dB gain, 250 kHz) have been performed under two boundary conditions (zero applied load and under static stress realized with an applied load equal to the maximum force value defined for the sinusoidal load profile). The results were correlated, when possible, with strain field measurements and the uniformity of the load distribution assessed. Thermal imaging allowed better observing the crack tips.

The most adequate actuation frequency is determined experimentally in the range of 150 kHz - 450 kHz. The signals obtained at 250 kHz and 350 kHz are displayed in figure 14. Signals between 250 kHz and 270 kHz were the best in terms of signal to noise ratio, weak cross-talk, overlap with the first wave packet and signal saturation.

Figure 14: Output signals at two different center excitation frequencies

In figure 14, we observe the outgoing wave till 18 µs then the first arrival window, the echos from the cracks, and the boundary reflections. After 50000 cycles at a load frequency of 1Hz and a maximum force of 1kN, we observe the features of the guided wave due to crack closer effects under zero applied load in order to assess the features of the guided wave related to those effects only. We assess as well the output signals at different loading frequencies (0.5 Hz, 1Hz, 2Hz, and 10 Hz), during cycling. The corroboration of the guided
wave measurements with the thermal imaging worked at best with a loading frequency of 2Hz.

The first near-real-time analysis is done, by comparing the baseline signal, when provided, then by evaluating the loss of reciprocity in a sensor-receiver path and, by using the time delay matrix calculations where the Hilbert transform is computed as displayed in figure 15, following the procedure introduced in section 2.1.1.

For a baseline-free analysis, we assess the loss of reciprocity in the time domain between two sensors paths, for a damaged specimen. We assess whether the signals coincide perfectly or if there are deviations in phase and amplitude. The calculation of the signal difference coefficients after every 5000 cycles did show small increases. However, the tested stringer has a small angle along the surface and the PZT sensors were placed at one side where the crack did not significantly propagate.

The response signals acquired at different time intervals, load cases and after a certain number of cycles are displayed in figures 16 and 17. Reflections from the edges, the 15-mm hole, and the emanating crack are observed in the time-domain graphs and the wavelength is determined from the measured wave velocities of the wave packets. No visual measurements of crack lengths have been performed but thermal and strain analysis systems were used to assess the strain distribution during load cycling. At a force amplitude of 2kN, after 213771 cycles, a crack propagated from one side of the hole, as we increased the loading frequency from 0.5 Hz to 1Hz and then to 2Hz. The crack growth coincided with an increase in the temperature variations. A strain field distribution was determined using the thermoelastic stress analysis method and the crack could be well observed with the thermal imaging system from that point in time until the rupture of the specimen.
After 306,000 cycles, as the fatigue crack increases, a signal amplitude reduction is observed after 30µs, as illustrated in figure 18.

3. Discussion
The inspections simulations performed in CIVA for different uses cases offer the advantage of assessing the capabilities and limitations of the different guided wave system configurations. Only two cases have been presented in this paper to allow discussing the application of the guided waves testing for a complex space structure and during a load cycling experiment. The applied feature extractions rely on the fact that defects cause reciprocity break or act as an additional source in the wave propagation. Analyses in the time domain are performed for cases where the geometry is complex (i.e. the TSA Support Box structure) and where defects are not pre-defined with specific crack length and width only.

4. Conclusion
Simplified and complex structures are considered for the ultrasonic guided wave simulations and experiments. CIVA simulations provide a great opportunity in investigating different sample problems, including 2D CAD profiles and multilayered structures. The theoretical and experimental investigations allowed us to assess the applicability of the guided wave methods for more complex use-cases. The experiments under different loading and boundary conditions allowed assessing the type of features that are sensitive to changes in boundary conditions and to cracks initiated and grown during fatigue testing.

Acknowledgments
CIVA is distributed by EXTENDE S.A. in France. Airbus Defence & Space GmbH in Ottobrunn, Germany provided the Telescope Spectrograph Assembly Support Box of the Sentinel-4 instrument. Airbus Defence & Space GmbH in Friedrichshafen, Germany provided the Dornier-328 stringers. The fatigue testing was performed at the premises of the IABG Industriealanlagen-Betriebsgesellschaft mbH in Ottobrunn, Germany.

References