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DESIGN OF ULTRASONIC GUIDED WAVES INSPECTION METHODS FOR REPRESENTATIVE AEROSPACE STRUCTURES USING CIVA SIMULATIONS

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ABSTRACT

The propagation of guided waves and their interactions with incipient defects in beam-like structure and thin multi-layered aircraft structures are simulated using the CIVA Non-Destructive Evaluation Platform. Lamb-wave based experiments are performed and the applicability of guided wave testing for flaw detection in representative aerospace structures is investigated. We theoretically and experimentally analyze the loss of reciprocity, the time reversal invariance for signal reconstructions and we quantitatively evaluate linear and non-linear features in the elastic response signal.

Keywords: Guided Waves (GW), reciprocity theorem, structural non-linearity, elastodynamic field, analytical propagator, aerospace materials, parametric study.

NOMENCLATURE

k	wave number
ω	radial frequency
C_L , C_T	Longitudinal and Transverse wave velocities
U	Displacement component
ξ	Variable in the local coordinate system
σ	Stress field
v	Particle velocity
Γ	Transmission coefficient

1. INTRODUCTION

Guided Wave Testing can be used for different purposes in Non-Destructive Testing (NDT) inspections and Structural Health Monitoring (SHM) of aerospace structures. Consistently developing maintenance methods aims to achieve correct diagnosis during Assembly, Integration & Testing (AIT) operations, long-term durability, higher safety of structures and false alarms rates' reduction. Examples of GW applications in the aerospace field include fatigue crack detection in load path carrying parts, poor bonding in multilayers structures, ice detection in aircraft wings, fuselage wall thinning, tear straps, lap joints, contaminants and critical crack detection in space structures. GW are dispersive and at high frequencies, several modes can coexist thus inducing complex signals. The Semi-Analytical Finite Element (SAFE) method which relies on modal decomposition is applied within CIVA for the wave propagation analysis and reciprocity relations are used to compute the elastic wave scattering coefficients. All structures used for the simulations have been designed in the CIVA included-CAD platform. Experimentally, we assess the feasibility of reconstructing a source signal using time-reversal acoustics in the presence of scattering from discontinuities and boundaries, with the aim of achieving adequate interpretations of sensors' readings without relying on a reference signal of the undamaged part.

2. MATERIALS AND METHODS

CIVA (Patch SP3) software is an NDT simulation tool, developed by the French Alternative Energies and Atomic Energy Commission (CEA) [1]. We apply in this study the Guided Waves Testing Module (GWT) to proceed with mode computations, beam computations, inspection simulations of simplified aerospace structures with a given flaw configuration and parametric studies to generate Probability of Detection (POD) data. The following structures are designed for the simulations: 0.8mm thick, 800-mm long Aluminum 2024-T3 flat S-shaped stringer (figure 2, right), straight I and T-shaped aluminum alloys profiles (simplified spars). 1mm to 1.6 mm thick aluminum alloys plate-like structures (to simulate outer wing skins), 500 mm x 500 mm Lap joints (figure 1) and 2500mm x 300mm adhesively bonded multilayers aluminum plates.

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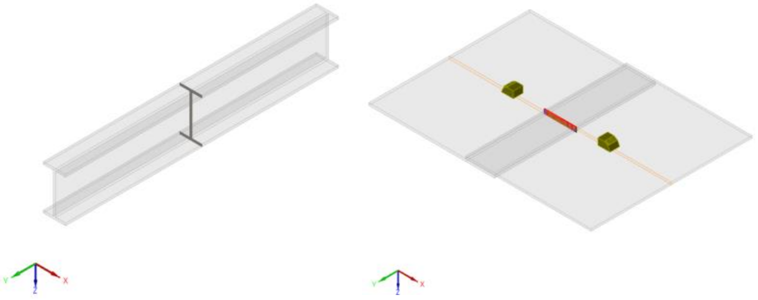


FIGURE 1: 1m- I-profile (FEM in the cross section) and a Lap-joint structure with transducers in pitch-catch transmission mode.

The following aerospace components are being currently used for SHM experimental GW investigations (figure 2): 0.8mm thick, 800 mm long Aluminum 2024-T3 flat S-shaped stringer from Dornier-328. And, the upper part of the Telescope Spectrograph Assembly Support Box from Sentinel 4 made of G-AlSi7Mg0.6, with the calculated longitudinal and transverse wave velocities of, respectively, 6286 m/s and 3168 m/s.

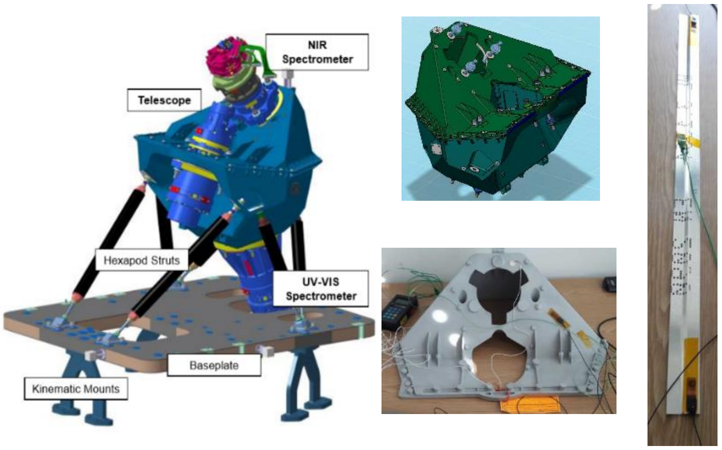
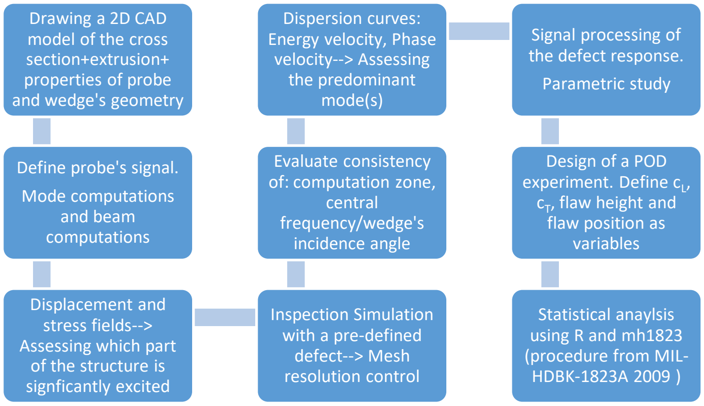


FIGURE 2: Sentinel 4 CAD Model (Left) [2], Telescope Spectrograph Assembly TSA support Box [3] and TSA upper-part (Middle), Stringer with two attached PZT sensors (Right).

The upper part of the cast structure contains shrinkage cavities which were milled out and reworked with a repair welding process. No baseline signal of the intact structure can be recorded. Therefore, we rely on (1) the reciprocity break due to a non-linear scatterer presence by comparing the waveforms of the response signals for every two transducers' paths and (2) apply the time reversal acoustic retro-focusing process for signal reconstruction. [4]

PZT single sensors from Acellent Technologies Inc.(with the ScanGenie Mini and the SHM Patch software) are used to excite a Lamb wave, alternatively on both sides of the areas with the two time-reversal sensors, using the same excitation signal. The minimum and maximum group velocities are determined experimentally for the complex TSA structure and using CIVA for the S-stringer.

2.1 Flow chart for the simulation steps and mathematical formulation



The SAFE model relies on finite element discretization in the guide section and modal decomposition for the propagation of waves along a guide. The particle displacements can be expressed as follows: [5]

$$u^{(e)} = \begin{bmatrix} u_x^{(e)} \\ u_y^{(e)} \\ u_z^{(e)} \end{bmatrix} = \begin{bmatrix} \sum_{l=1}^{3} N_l(\xi)U_{xl} \\ \sum_{l=1}^{3} N_l(\xi)U_{yl} \\ \sum_{l=1}^{3} N_l(\xi)U_{zl} \end{bmatrix}^{(e)} e^{i(kx-\omega t)} = N(\xi)Q^{(e)}e^{i(kx-\omega t)} \qquad (1)$$

Where N_l denotes the shape functions and $U_{\alpha\beta}$ $(\alpha = x, y, z;\ \beta = 1, 2, 3)$ denotes the nodal displacement of the node β in the α direction. $Q^{(e)}$ is a vector representing the particle displacements at the node positions. In a waveguide, the ultrasonic fields v (particle velocity) and σ (stress field) at coordinates (x, y, z) can be expressed as a linear serie of the eigenmodes v_n and σ_n at a given frequency, as follows [6]:

$$v_n = \sum_n A_n \tilde{v}_n\,(x, y)\, e^{i(k_n z-\omega t)} \qquad (2)$$

$$\sigma_n = \sum_n A_n \tilde{\sigma}_n\,(x, y)\, e^{i(k_n z-\omega t)} \qquad (3)$$

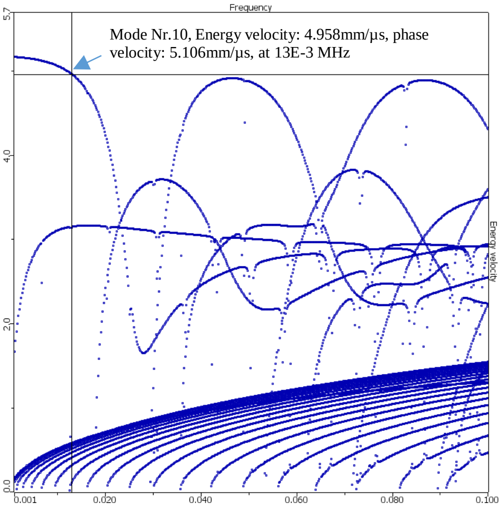
k_n and A_n are the wave number and amplitude of the nth mode. The modal solution $(k_n, \tilde{v}_n, \tilde{\sigma}_n)$ and the mode amplitude A_n are used to determine the elastodynamic field at any position in the guide. Auld's formulation, based on the use of the electromechanical reciprocity relations, is applied to the calculations of elastic wave scattering coefficients [7]:

$$\delta\Gamma = \frac{1}{4P} \int (v_1 . \sigma_2 - v_2 . \sigma_1) . \hat{n} .\ dS \quad (4)$$

$\hat{n}$ being the unit vector normal to the surface surrounding the scatterer, P the incident power and, $\delta\Gamma$ the difference between the probe's electrical transmission coefficients in two different states (with and without scatterer).

3. RESULTS AND DISCUSSION

Modal solutions of the waveguides with the designed cross sections of the structures introduced in part 2 are determined using the SAFE method in CIVA 2017 SP3. The discretization of the waveguide section resolves a 3D-2D dimensional reduction. The energy velocity curves illustrated in figure 3, where 30 modes are activated, are obtained for the middle part of an S-shaped stringer that has been determined from the modal displacements (the eigenvectors) as being the region of interest. Since we are in a non-canonical form of structures, the modes cannot be separated as symmetrical, non- symmetrical and shear horizontal modes, and are identified with numbers only. We further analyze the components of the stress field $(\sigma_{xy}, \sigma_{yy}, \sigma_{zy})$ to appropriately re-define the most efficient computing area.



Mode Nr.10, Energy velocity: 4.958mm/µs, phase velocity: 5.106mm/µs, at 13E-3 MHz

FIGURE 3: Energy velocity curve computed for the 800mm long, 0.8 mm thick S-stringer in Aluminum 2024-T3.

Modes computations in, for instance, a multilayer plate (2500mm x 300mm) with two 1mm -thick Al2024 plates with a 0.2mm thick epoxy sealant layer (c_L= 2488 m/s and c_T=1134m/s) allow to separately visualize the mode shapes of all modes. As in figure 4 where at 1MHz, the fundamental symmetric mode S_0 indicates a significant energy gradient in the sealant area (at 1.2 mm). Thus, for the 21 excited modes in the structure, we determined from the plotted wave mode shapes those with a larger displacement (at the plate surface and close to the sealant area) which would result in higher sensitivity to defects at the interface epoxy/Aluminum and at the free surface.

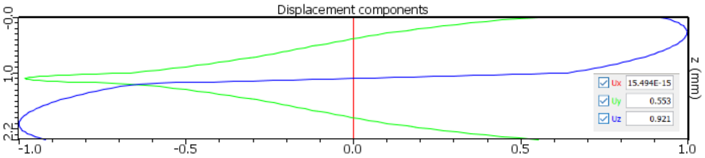
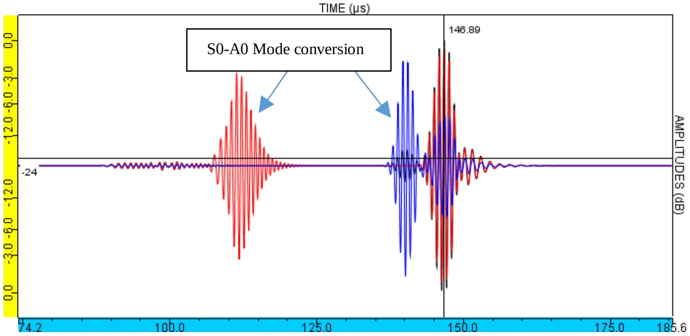


FIGURE 4: Displacement components of the S_0 mode at 1MHz.

After completing the mode computations, the steps in part 2.1 are followed and the inspection simulations with a pre-defined defect are investigated. We evaluate damage indicators for the structures introduced in part 2. First results from a simulated flaw response, in a 1mm thick 500mm x 500mm Aluminum Al2024 structure with a transducer having a central frequency of 1.2 MHz at which a symmetric fundamental mode is dominant, prove that the S0-A0 mode conversion is well observed for defects along the surface and with heights of minimum 0.05mm, as illustrated in figure 5. The maximum amplitude in 100 amplitude-scans are computed in the parametric study and POD curves are created using R/mh1823. The same simulations are being transferred to 2D-CAD structures from figure 1 with rectangular defects (1 mm x1 mm), semi-elliptical and multifaceted defects. Smaller defects are considered for space materials.



S0-A0 Mode conversion

FIGURE 5: A-scans showing a mode conversion due to defects of 0.05 mm height (black), 0.25 mm height (red) and 0.5 mm height (blue).

4. CONCLUSION

Theoretical calculations and simulations based on the SAFE method, the reciprocity theorem, signal reconstructions were investigated to quantitatively evaluate the potential and limitations of the Guided Wave Testing method for the inspections of aerospace components, in terms of critical damage size detection and structural complexity.

ACKNOWLEDGEMENTS

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