On the Damage Sensitivity of Guided Wave SHM System Under Different Loading Conditions

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Abstract. Guided wave based Structural Health Monitoring (SHM) systems are a reliable and non-invasive approach to monitor structures in several fields. They provide indication about the occurrence of damage, but their large-scale industrial application is still challenging due to some aspects such as the operating loads affecting the structures. Actually, equipping damage tolerant structures with SHM systems can allow the continuous monitoring providing several benefits in terms of conditioned maintenance and repairing operations. This paper presents a numerical modelling technique, based on the Finite Element (FE) method, for the simulation of guided waves in a composite panel affected by loads. Guided wave propagation mechanisms have been analyzed also on a loaded damaged configuration of the panel, in order to investigate the damage sensitivity of the proposed SHM system. The combination of both damage and load allowed considering a scenario closer to the operating conditions of the structure, providing a contribution towards the implementation of SHM in industrial applications.

Keywords: Guided waves · Finite Element Method · Operating loads · Damage detection · Structural Health Monitoring

1 Introduction

Guided wave (GW) propagation is a well-recognized technique for the Structural Health Monitoring and damage detection in real isotropic and composite structures, because of their ability to travel long distances with low power consumption [1, 2]. GW based SHM approach is essentially based on the generation and sensing of elastic waves using mainly piezoelectric transducers (PZT) that can be surface-mounted or embedded in the to-be-monitored structure. By means of a low number of sensors, a large portion of the structure can be easily inspected using one or more excitation sources (actuators) and the pulse-echo or pitch-catch sensing approach. This way, it is possible to continuously and quickly monitoring primary and secondary plate-like components, preventing sudden failures. As a consequence, it is possible to further improve the design of damage tolerant structures, with great benefits in terms of weight savings and maintenance costs [3, 4].

In fact, the quasi-real time control of deficiencies through continuous monitoring provides greater safety and reduced repairing costs in both the medium and long term

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[5, 6]. Nevertheless, one of the major challenges when dealing with GWs is that they are multi-modal (different modes of different order are superimposed) and dispersive (each mode propagates with different speed depending on the excitation frequency) [7]. Additionally, in composites, GWs exhibit a fiber-related characteristic: the dependence of speed on the propagation angle (slowness phenomenon). Thus, the post-processing phase is crucial to extract the most useful information about the actual state of the structure (presence of the damage). Detection of damages is often accomplished by comparing actual signal dataset to a baseline one, recorded in the reference (undamaged) state of the structure.

GW SHM systems can find applications in the aerospace components, storage vessels, ships etc. For this reason, their damage detection robustness and accuracy can be easily threatened by additional undesired effects, the so-called environmental (temperature, humidity…) and operational (load, initial stress-strain state…) conditions (EOCs) parameters [8, 9]. For the mentioned applications, loadings may be unavoidable in the in-situ environment and induce initial stress-strain states into the components affecting the incident propagating wave, thus reducing the useful signal strength to interrogate any damage.

In order to cut experimental campaign costs, Finite Element Analysis (FEA) can be effectively used [10, 11] to simulate the GW propagation in real components, characterized for instance by geometrical complexity and subjected to EOCs. The explicit method is widely used for the simulation of GW since it is a dynamic phenomenon [12]. However, to accurately model the wave propagation in a loaded component, three approaches can be used, also depending on the type of load. For dynamic loads, the explicit formulation of the FE method can be used. For quasi-static loads, two modelling approaches can be used: the explicit formulation, by defining the loading and the boundary conditions following the well-recognized steps for the definition of a quasi-static simulation, and the implicit scheme. The former was investigated also by De Luca *et al.* in [9]. Authors proved that when a load affects a complex composite component, the GW speeds may be altered: the load determines an increase/reduction of the wave speed, depending on the propagation angle and on the stress-strain state. Relatively to the latter approach, Aslam *et al.* presented a comparative study of different FE procedures for wave propagation modeling in simple and unloaded plates: implicit scheme, explicit and implicit-explicit co-simulation. According to authors' results, the co-simulation model is more reliable and efficient compared to the other two models [13]. However, with respect to quasi-static loads, the use of the explicit formulation for GW simulation can cause some numerical issues: i.e., the stress-strain field induced by a quasi-static load, modeled according to both implicit and explicit (quasi-static) schemes, when imported as a predefined field in the GW simulation step, is treated by the solver as initial condition for the plate, becoming a time-dependent load. As a result, in this paper, the effects of the load on GW propagation mechanisms are treated according to the implicit formulation. A first step of the manuscript has been addressed to simulate GW propagation through numerical simulations via both explicit and implicit formulations in a simple plate made of carbon fiber reinforced plastic (CFRP) material. The modelling aspects in each case are detailed in subsequent sections. Simulations are carried out using the commercially available software package Abaqus® CAE 2021. Mode shapes obtained from the simulation schemes are compared for a specific frequency. Then, the effect of a quasi-static tensile load on GW has been investigated. In particular, for that purpose, the implicit scheme has been adopted to model both the load step and the GW propagation step. Results are reported again in terms of mode shapes and compared to the ones recorded at the unloaded configuration of the panel. Finally, a damage configuration has been investigated in the unloaded and preloaded plates in order to assess the damage sensitivity of the proposed SHM system.

2 FE Modelling of the Test Article

The objective of this work is to propose a modelling approach to analyze the effect of the load on GW dispersion behavior in a composite panel. As first step, the implicit and explicit formulations for the modelling of GW propagation have been investigated. Analyses have been performed by means of Abaqus® CAE module.

The test article investigated in this work consists of a flat panel characterized by a square shape (310x310 mm^2), Fig. 1. It has a thickness of 1.5 mm and it is made up of 8 CFRP plies with a stacking sequence of [0, 90, +45, −45]s. Lamina mechanical properties are listed in Table 1. A network of 5 piezoelectric transducers has been modelled on the upper surface of the plate, to generate and sense the diagnostic GW signal. The thickness and the radius of the PZT disk are $t_{PZT} = 0.25$ mm and $d_{PZT} = 10$ mm, respectively, while their mechanical properties are reported in Table 1. As visible from Fig. 1, the mapped area is square-shaped, with the actuator in a central position and the 4 receivers at a 100 mm distance along the diagonals. This configuration permits the investigation of the slowness phenomenon.

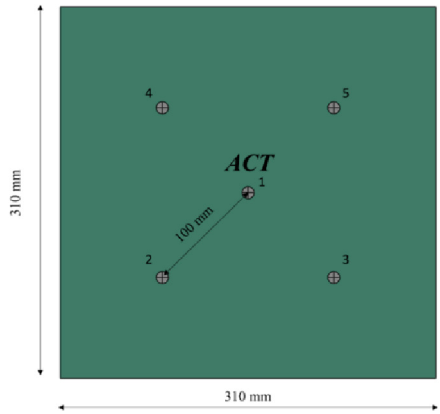

Fig. 1. Geometry of the investigated panel.

Two different modelling approaches have been used to model the plate and the PZTs: C3D8R solid elements have been chosen for plate and sensors modelling in the explicit formulation, according to the work [15], whilst C3D8I and C3D8E finite elements have

Table 1. Material properties of CFRP composite lamina and PZT (PIC255) sensors.

Material Properties	Symbol	Units	CFRP Lamina	PZT
Mass density	ρ	$[\mathrm{kgm}^{-3}]$	1, 534	7, 850
Young's modulus	E	[GPa]	–	76
Longitudinal Young's modulus	E_{11}	[GPa]	105.125	–
Transversal Young's modulus	E_{22}	[GPa]	7.7	–
Transversal Young's modulus	E_{33}	[GPa]	7.7	–
Shear modulus	G	[GPa]	–	29
Shear modulus	G_{12}	[GPa]	3.6	–
Shear modulus	G_{13}	[GPa]	3.6	–
Shear modulus	G_{23}	[GPa]	2.7	–
Poisson's ratio	ν	–	–	–
Poisson's ratio	ν_{12}	–	0.36	–
Poisson's ratio	ν_{13}	–	0.36	–
Poisson's ratio	ν_{23}	–	0.4	–
Dielectric constant	K_3	–	–	1, 280
Piezoelectric charge constant	d_{31}	$[10^{-9}\ \mathrm{mmV}^{-1}]$	–	−180

been used for plate and sensors in the implicit scheme, respectively [14]. In particular, C3D8E elements include the piezoelectric coupling by defining the piezoelectric coefficient and the dielectric matrices.

Plates and sensors have been discretized with an average element size of 1.0 mm and 0.4 mm, respectively. These values allow discretizing 20 NPW (nodes per wavelength) at 200 kHz carrier frequency, as reported in [12, 15]. To ensure the contact between sensors and plate, the tie constraints approach available in Abaqus® has been employed at the contact interfaces to simulate the adhesive layer between sensors and plate (not here modelled).

Concerning the GW propagation, radial displacements, calculated through the in-house code pre-processing phase, have been applied on the actuator upper edge [10, 15] for the explicit simulation. Whilst, for the implicit formulation, a voltage has been applied at the upper and lower surfaces of the actuator. In both cases, a 200 kHz carrier tone burst Hanning windowed excitation signal has been used in order to inspect the structure. Finally, the four corners of the plate have been constrained.

In the implicit method, there is no limit on the timestep size as it is unconditionally stable. However, a maximum increment of T/10 (where T is the analysis period) was chosen to obtain reasonable results [14]. On the other hand, explicit method is conditionally stable. Hence, the time step is chosen considering the wave speed and the minimum element length [15, 16].

3 Implicit vs. Explicit Formulation for GW Simulation

Results for both implicit and explicit formulations are herein discussed. Extracted signals have been firstly compared to highlight the differences between the two simulation schemes in a reference (no load) configuration of the investigated component.

Predicted signals at the sensor positions have been calculated as the average of the in-plane strains measured at all nodes defining each sensor [12] and then converted through the own post-process code.

The central sensor of Fig. 1 has been used as actuator, while the others ones acted as receivers. The normalized signals, recorded in both formulation schemes under a 200 kHz carrier frequency test, are shown in Fig. 2. For the sake of brevity, only the response of PZT4 and PZT3, located at opposite sides of the actuator, are reported: all signals are very similar each other because of the quasi-isotropy of the plate. The need to focus on signals from faced sensors derives from the very purpose of this paper: highlighting the effects on GW propagation of a non-symmetrical stress-strain state generated by a load, as described in the following.

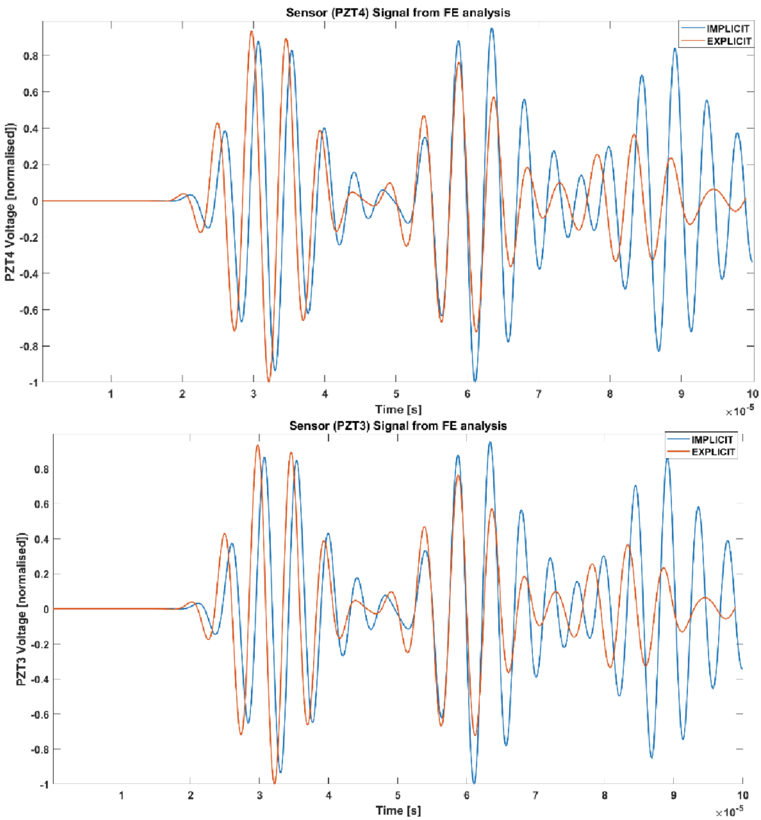

Fig. 2. Comparison of the recorded signals in the implicit (blue lines) and explicit (red lines) formulation schemes.

From Fig. 2, a slight difference between the signals predicted by the two simulation approaches can be noticed. In particular, the implicit modelling introduces a delay of the S0 mode with respect to the explicit one, whilst the A0 wave packets are almost overlapped. This delay was also found in [13]. The explicit formulation also has been widely validated against experiments, as reported in [12, 15], and it allows considerably reduced computational efforts and costs. However, despite such misalignment, the implicit scheme can be used to simulate the GWs in the pristine, damaged and loaded configurations. The damage detection is carried out by comparing quantitatively the signals predicted at different configurations of the plate, in a such way to extract features linked to both loads and damage and compensate the misalignment. As a result, the observed delay will not have any effect on the accuracy of the results. Also, with respect to the extraction of the group velocities, the delay between the explicit and the implicit schemes will not have any effect on their accuracy, since they are calculated based on the time spent by the specific GW mode to travel from the actuator to the receiver. In the implicit scheme, both actuation and receiving signals are affected by the same delay, so the latter is automatically compensated in the calculation of the Time of Flight (ToF).

4 Load Effect on GW Propagation

The study of GW propagation in a loaded structure is fundamental to assess the SHM system sensitivity for damage detection in actual in-service scenarios of the structure.

Starting from the reference (i.e., no load) configuration of the investigated panel (see Sects. 2 and 3), the load has been introduced focusing on the implicit formulation of the problem. A quasi-static tensile load, equals to 10 MPa, has been applied on the right side of the plate, whilst the left side has been fully constrained, introducing a not symmetric condition, see Fig. 3. Displacements field induced by guided waves assumes an order of magnitude of about 10^{-6} mm–10^{-7} mm, which is much smaller than the displacements field corresponding to the load. So, to facilitate the comprehension of the propagation mechanisms as well as the signals post-processing, the actuation signal has been numerically amplified by a factor of 10^5. This procedure does not affect the accuracy of the FE model since the received signals are normalized in the post-processing phase to enhance the damage detection sensitivity.

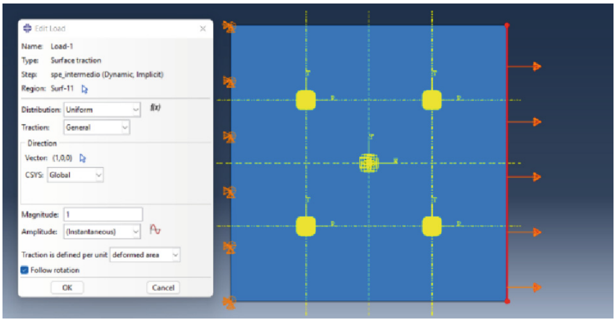

Fig. 3. Loaded configuration.

In a loaded structure, the presence of an initial stress-strain state on the guided wave propagation path may produce distinct changes in the amplitude, waveform and ToF.

The most efficient method to evaluate such effect is comparing the signal recorded in the actual (loaded) configuration against the baseline one, achieved in a pristine unloaded configuration of the test case. Again, the central sensor of Fig. 1 has been used as actuator, while the other ones acted as receivers. The normalized signals, simulated according to the implicit formulation under a 200 kHz carrier frequency test, are shown in Fig. 4. For the sake of brevity, only the response of PZT4 and PZT3, located at the opposite sides of the actuator, are reported.

As visible from the results in Fig. 4, the load affects the wave propagation mechanisms: the signals recorded by the sensors placed at the right side of the actuator, i.e., nearer to the load, are perfectly overlapped relatively to the S0 mode, whilst the A0 mode (PZT3 in Fig. 4) is highly affected. It can be clearly noticed that the presence of the initial stress-strain state causes slight variations in signals A0 mode amplitude for the loaded configuration, and this effect is more evident for sensors near to the load application zone.

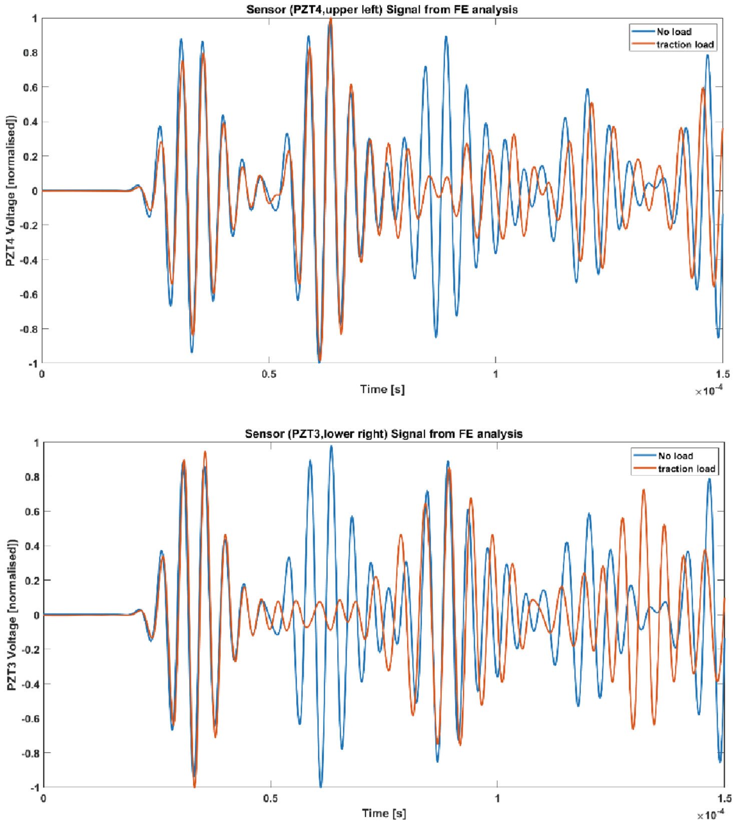

Fig. 4. Comparison of the recorded signals in the reference (blue lines) and loaded (red lines) configuration of the structure – implicit formulation.

In order to investigate the damage detection of the developed SHM system under an operating load, a damage has been modeled by means of a through-thickness square notch [17] within the unloaded and preloaded plates, see Fig. 5. Subsequently, the damage detection algorithm proposed by authors in [9] has been used to identify the damage location.

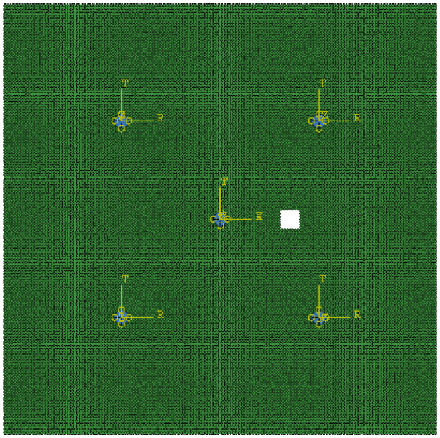

Fig. 5. Damaged plate.

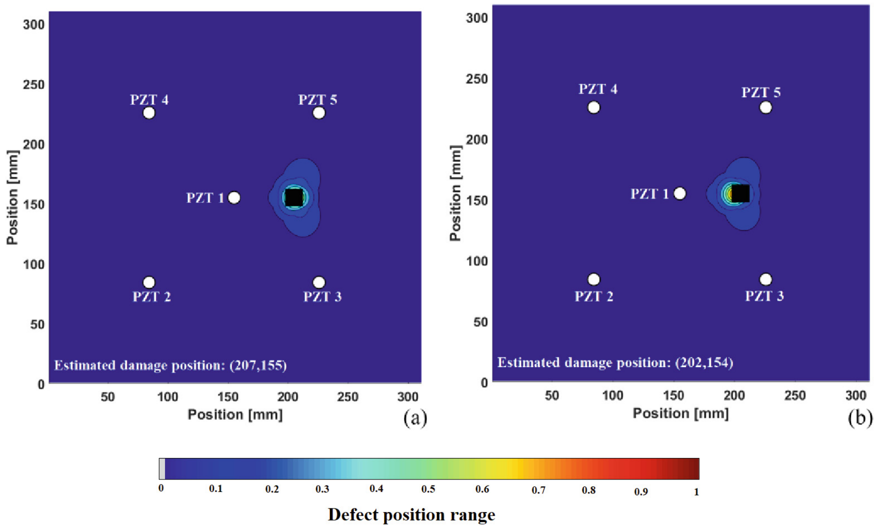

Fig. 6. Damaged detection in: (a) unloaded and (b) loaded plate configurations.

According to Fig. 6, although the presence of the initial stress-strain state causes variations in signals, the damage detection algorithm appears capable to compensate such effects, providing a good level of accuracy. The compensation of the load is carried out automatically by the damage detection algorithm, just by focusing on the S0 waves packet.

5 Concluding Remarks

In this paper two modelling techniques have been compared, both based on the FE method, to analyze the differences in GW propagation mechanisms in a composite flat panel. In particular, the implicit and explicit formulations have been investigated. Then, the effect of a uniaxial traction load, which characterizes for example aircrafts, tanks, pipes, etc. in actual in-service scenarios, on GW propagation mechanisms has been investigated.

Specifically, the simulations in the two schemes highlighted a slight variation of the S0 mode propagation velocity for the implicit formulation, compared to the explicit one. In particular, the implicit modelling introduces a delay of the S0 mode with respect to the explicit one, whilst no difference has been observed for the A0 wave packets. Relatively to the loaded configuration of the component, it can be stated that the presence of an initial stress-strain state causes slight variations in signals A0 mode amplitude with respect to the reference (unloaded) configuration, and this effect is more evident for sensors near the load application zone. Vice versa, no difference has been detected for the S0 wave packets. By taking advantage of such aspect, the damage detection algorithm pointed out to be very accurate in terms of damage location identification despite the load effects.

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