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Numerical Simulation of Guided Waves Propagation in Loaded Composite Structures

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Abstract. It is well known that Lamb waves based Structural Health Monitoring (SHM) systems have been founding increasing application for damage tolerant composite structures, thanks to the high sensitivity they offer in terms of damage detection, improvement of the design current practice and reduction of the maintenance and inspection costs. However, further investigations are still mandatory for the application of SHM systems on composite structures. Dispersion and slowness phenomena, together with boundary condition scattered waves may mask the presence of damages. In addition, the in-service loads may alter the guided waves propagation mechanisms, affecting negatively the sensitivity to damage detection of such systems. As a result, the development of numerical models aimed to simulate the propagation of guided waves may be helpful for designers to reduce such critical aspects, by allowing virtually investigating different sensors location and different SHM system operating parameters. The novelty of this paper can be found in the development of a Finite Element (FE) model for the simulation of ultrasonic guided waves in a pre-loaded composite structure. Results are herein discussed and the effects of the initial stress-strain state on the guided waves analysed.

INTRODUCTION

The application of ultrasonic guided waves technique for non-destructive testing and Structural Health Monitoring (SHM) evaluation has increased considerably in recent years due to the ever-growing request of damage tolerant composite structures (1). The use of composite materials, thanks to their high specific properties, is increasing in several transport fields, especially in the aeronautical and automotive ones where the need of lightweight vehicles is driving designers' efforts (2). However, the presence of damages and defects, due to both manufacturing process and in-service/accidental loading conditions, represents an important drawback for composites when compared with conventional materials. So, despite composites' superior properties, damages and defects, if not accurately detected/monitored, can lead to a significative decreasing of their residual strength (3-5), seriously compromising components integrity.

The design of new damage tolerant structures is strictly based on the development of established structural health monitoring approaches. SHM aims to implement systems able to detect the presence of damages in a non-destructive way (3-5) and able to continuously monitor the structural integrity of the whole structure during its real life. Several types of SHM systems have been proposed in literature. Among them, guided-(Lamb) waves based SHM systems

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seem to be the most attractive technology for the damage detection and inspection in metallic and composite structures (4). Guided waves can be activated in thin-walled structures through one or more piezoelectric actuators and, thanks to their lower consumption, their ability to travel over long distances and their sensitivity to detect structural anomalies, they appear to be the best candidate to monitor the integrity of thin-walled geometry, such as fuselage and wing skins (4-5). Specifically, the modes induced by the guided-waves can be recorded by means of piezoelectric receivers arranged, embedded in or surface mounted on, at different locations of a structure opportunely optimized.

Guided wave propagation mechanisms strictly depend on the material properties of the medium they propagate through. It follows that the onset and the evolution of a damage, which represent actually a local structural change, can alter the recorded signals which will be characterized by some features that can be linked to the presence and the severity of the damage itself. In fact, the presence of a damage or a defect alters the propagation paths, creating scattered and reflected waves. Consequently, by comparing the signals recorded in two different configurations of the structure, for example the undamaged, or pristine, assumed as benchmark, and the damaged ones, it is possible to determine the presence of the damage and to define its severity (4-5).

Despite the great potential of SHM guided wave-based systems, an accurate knowledge of the dispersive characteristics of guided waves (i.e. the solutions of the guided wave equation must be known at several frequencies) is necessary. Over the years, several methods, including theoretical analysis, Finite Element Method (FEM) and experiments, have been developed for isotropic and anisotropic structures in order to properly define their dispersion behaviour. For composites, due to their nature, Lamb waves dispersion equations do not generally have analytical solutions and, so, reliable and robust approaches are needed to efficiently define their dispersive characteristics.

Researchers are also trying to use guided waves for revealing the effect of an initial stress-strain state in waveguides propagation. In many practical applications, initial stresses are present due to mechanical or thermal loads or could arise as residual stresses in the manufacturing processes, significantly affecting the mechanical behaviour of the whole structure. The propagation of elastic waves in composites with initial stresses has long been of interest, and some achievements have been reported.

The effect of load on guided wave propagation over all frequencies range is not well documented. At the relatively high frequencies used in guided wave non-destructive tests (typically at frequency thickness products of the order of 1 MHz mm or above) the effect of load is negligible. At these frequencies the properties of guided wave propagation are governed almost entirely by the material stiffness of the waveguide (6).

For simple geometries such as plates and pipes, there are a multitude of analytical methods of producing dispersion curves. A first rigorous mathematical treatment of the problem can be found in the works by Biot (7-9), dealing with the theory of incremental deformations for the case of waves propagation in solids. Akbarov et al. (10) and Zamanov et al. (11) studied the influence of the initial strains in the wave propagation direction on the Lamb wave dispersion curves. Roy (12) provided an approximate treatment based on Biot's theory to study the wave propagation in a thin two-layered laminated medium under initial stresses. Williams et al. (13) used the harmonic analysis to get the phase-velocity dispersion curves for prestressed circular rods, flat plates and unbounded mediums considering both strain-rate-independent and strain-rate-dependent constitutive equations.

Nevertheless, studying such type of monitoring system in actual engineering structures may become difficult and unsuitable. In addition, experimental tests campaign is complex. For these reasons, numerical simulations of guided wave propagation in composite laminates for SHM applications are needed to support experimental tests to better understand physics of guided waves (14-16). Finite Element (FE) modelling techniques must be employed for the investigation of more complicated cross sections geometries. For instance, in their work, Chen et al. (6) proposed a three-dimensional finite element based procedure to predict the effect of axial load on the dispersive properties of guided waves in elastic waveguides of arbitrary cross section such as rods, plates and rails, validating the method at low frequencies by using analytical formulae for low order theories.

In this paper, Lamb wave propagation has been numerically simulated in a blended GFRP (Glass Fibre Reinforced Polymers) winglet for a general aviation aircraft. The effect of an initial stress-strain state, induced by a bending load, on guided-wave propagation mechanisms has been numerically investigated focusing on the extraction of the Time of Flight (ToF). In detail, the first wave packet of the signals recorded by a PZT sensors network has been used to determine the ToF of the signals in the analysed time domain. 8 measurement angles have been identified and used to determine the effect of the applied load on the propagation paths. Results have been reported in a polar graph.

TEST ARTICLE AND FE MODEL

The test article under investigation consists in a blended winglet of a general aviation aircraft. The winglet, already studied by authors in (5,17), is made of short GFRP laminates (with different lay-ups according to the region) and foam coring in the inner part, while the outer ones are entirely made of GFRP, as shown in Fig. 1. The mechanical properties of the lamina and the different lay-ups are reported in detail in (17). For the Lamb waves acquisition, twelve piezoelectric transducers, equally spaced, were bonded on the upper winglet surface (Fig. 1). The transducers can be used both as actuators and sensors and are characterized by the following material properties: E=62 GPa, v=0.34 and density ρ=7800 kg m^{-3}.

The numerical model of the winglet has been developed by using Abaqus® ver. 6.14 finite element code and proposed by authors in (5,17). In detail, 4-nodes quadrilateral (CQUAD4) elements, with an average characteristic length of 0.5 mm (corresponding to about 30 nodes per wavelength with a 100 kHz central frequency actuation signal), have been used to model the skins, while 8-nodes solid (CHEXA) elements have been used to model sensors and spar. Twelve piezoelectric sensors have been modelled according to experimental set-up (18) and bonded on the winglet, without modelling the adhesive layer, by means of tie constraints, which allow linking the degrees of freedom of the sensors elements to the winglet. As a result, the whole developed model counts a total of 1150527 nodes and 11347336 elements.

Finally, the winglet has been fully constrained at the root section while a 4.5 sine tone-burst with Hanning window actuation signal has been modelled by applying radial displacements along the actuator upper edge, following the same technique presented in (17).

This FE model will be referred as "unloaded" in the following.

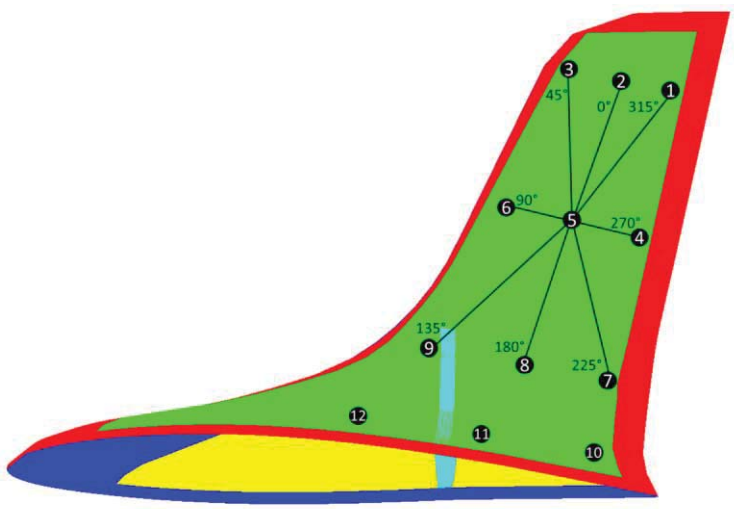


FIGURE 1. The investigated winglet and measurement angles.

LOAD CASE AND GIUDED WAVE PROPAGATION

The reliability and robustness of the proposed FE model has been assessed against experimental tests concerning: bending test, modal analysis and guided wave propagation tests performed by varying the actuator location and the central frequency of the actuation signal, as reported in detail in (17).

In this work, the FE model has been used to evaluate the effect of an initial stress-strain state on the guided wave propagation mechanisms. In order to determine a realistic initial stress-strain state, an aerodynamic load has been simulated: a mass of 28 kg has been applied at 1/3 of the winglet height starting from the root. In order to properly numerically reproduce an in-service condition, where the load is supposed to be like a distributed one, the kinematic coupling constraint approach has been used: the degrees of freedom of a set of nodes have been linked to a common reference point (master node), as shown in Fig. 2. Then, the mass has been applied on the reference point and the gravity load has been on the whole structure (along the y-direction of the reference system shown in Fig. 2) has been considered as well.

This FE model will be referred as "loaded" in the following.

The dependence of guided wave velocity on applied load is a fundamentally non-linear effect and has been modelled in a two-step FE calculation. Essentially the first step is to compute the displacement of the model under a quasi-static load and the second step is to model the wave propagation. The quasi-static analysis step is needed to be performed in explicit environment since the wave propagation analysis is a dynamic problem.

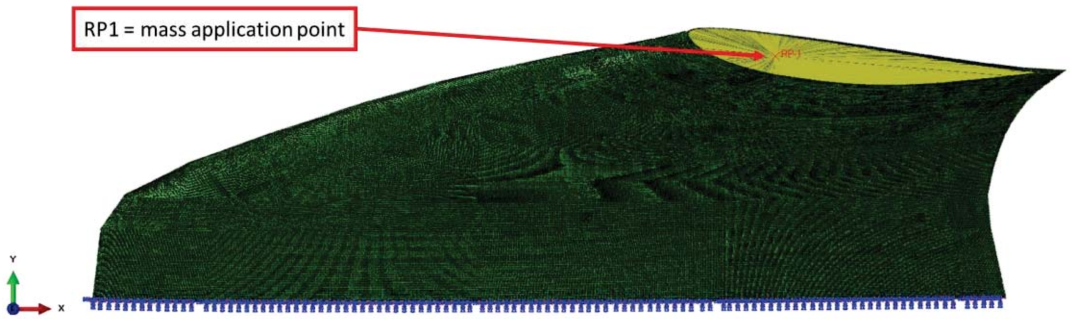


FIGURE 2. Boundary and loading conditions.

RESULTS DISCUSSION

In a loaded structure, the presence of an initial stress-strain state on the guided wave propagation path produces distinct changes in the amplitude, waveform and Time of Flight (ToF), i.e., the time need for an emitted wave packet to travel over the distance between two transducers (the actuator and the receiver).

Numerical analyses have been performed under 100 kHz excitation frequency and using the sensor 5 (Fig. 1) as actuator within the Abaqus explicit environment.

The most efficient method to evaluate such effect is comparing the signal recorded in the loaded configuration against the baseline one, achieved in the unloaded configuration of the winglet. This way, it has been possible to extract the ToF for each actuator-receiver propagation path.

The post-processing of the numerical results, in terms of recorded signals, has been made through an own Matlab® routine allowing transforming the signal absolute values by means of Hilbert function and calculating the ToF based on the energetic centre of signal envelope, ToF_{ec},, as shown in Figure 3.

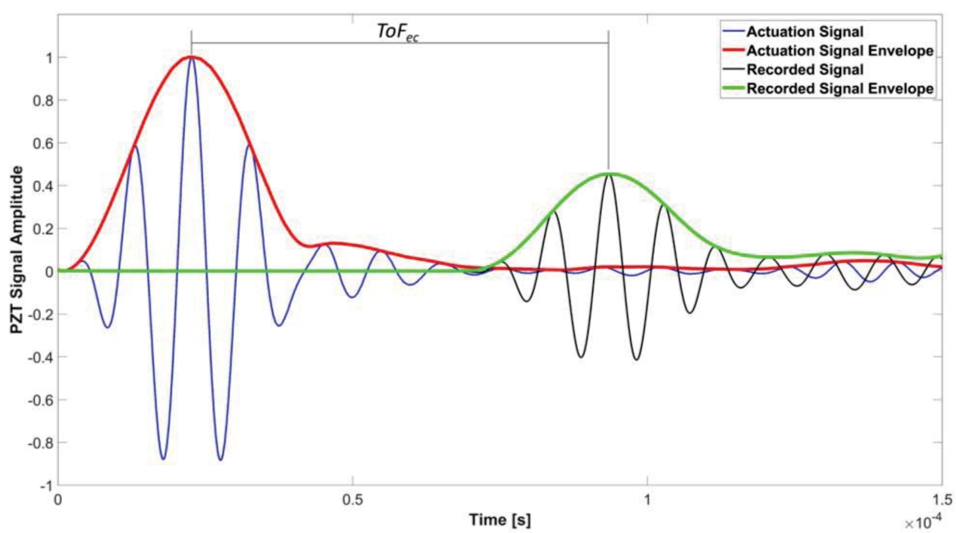


FIGURE 3. Example of ToF_{ec} evaluation.

Thus, the ToFs evaluated in the two analysed configurations are shown Fig. 4, in which the measurement angles are referred to the sensors location on the structure (Fig. 1). Figure 4 highlights how the applied load affects the Lamb wave propagation mechanisms. The load produces its maximum effect along the 135° propagation, with an increment of the ToF of about 40%. Such effect is still present, even if less intense, along 180° and 225° propagation paths while no evidence of the load appears in the remaining ones. Specifically, it can be observed that ToFs at sensors 7 (225°) and 9 (135°) are shorter, while ToF at sensor 8 (180°) is longer with respect to the unloaded configuration. This depends on the fact that the winglet design and the applied load are such to determine a combined bending and torsional effect and not a pure bending one. Torsional effect is higher in correspondence of sensors 7 and 9 (Fig. 5b and Fig. 6).
With respect to the other orientations, the signal propagation, and consequently the ToFs, is not affected by the loads. By neglecting the gravity over the whole structure, and assuming that the winglet is subjected only to a concentrated force applied on the reference point (RP) of Fig. 2, of about 274,68 N, the part of the winglet above the concentrated force can be considered unloaded (Fig. 6). As a result, since the actuator (sensor 5) is placed on the unloaded zone of the winglet, together with the receiving sensors from 1 to 4 and 6, the recorded signals are not being altered with respect to the reference configuration. It would have been different if the actuator had been placed on the loaded part.

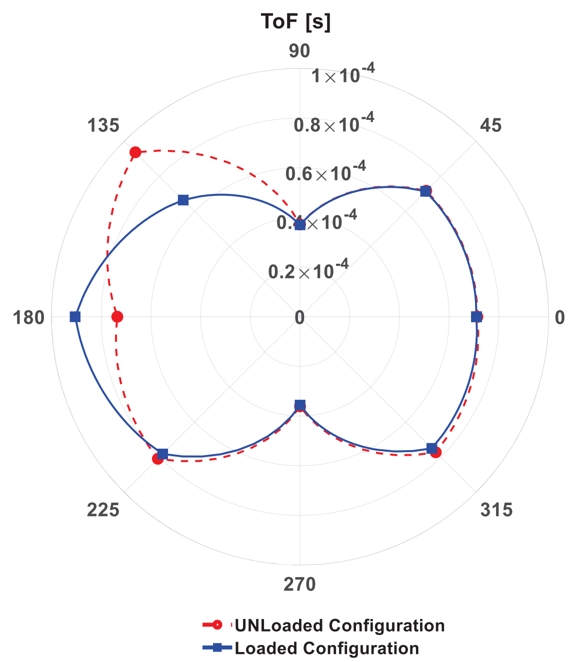
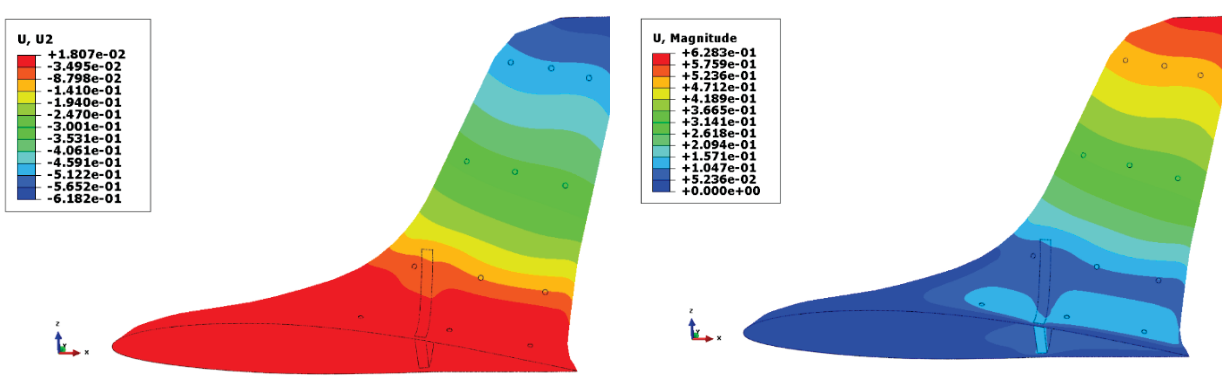


FIGURE 4. Guided waves ToF (markers refer to measurement angles of Fig. 1).



(a) (b)

FIGURE 5. (a) displacement along the loading direction; (b) global displacement (all units are in mm).

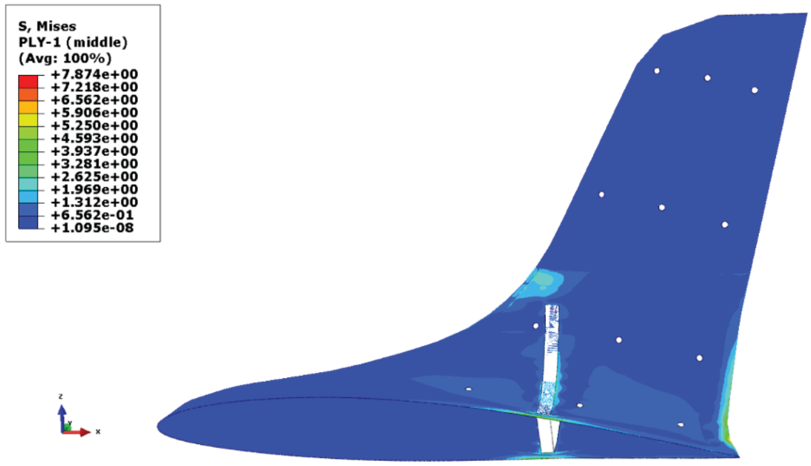


FIGURE 6. Von Mises stresses (all units are in MPa).

CONCLUSIONS

In this paper, Lamb wave propagation has been numerically simulated in a blended GFRP (Glass Fibre Reinforced Polymers) winglet for a general aviation aircraft. The effect of an initial stress-strain state on guided-wave propagation mechanisms has been numerically investigated focusing on the extraction of the Time of Flight (ToF). In detail, the first wave packet of the signals recorded by a PZT sensors network has been used to determine the ToF of the signals in the analysed time domain. 8 measurement angles have been identified and used to determine the effect of the applied load on the propagation paths. Results have been reported in a polar graph. The load produces its maximum effect along the 135° propagation, with an increment of the ToF of about 40%. Such effect is still present, even if less intense, along 180° and 225° propagation paths while no evidence of the load appears in the remaining ones. Specifically, it was found that the combination of both torsion and bending stresses affects differently the guided waves propagation mechanism with respect to the zones of the winglet where torsion can be neglected.

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