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Guided wave scattering behavior in composite bonded assemblies

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ABSTRACT

Composite bonded joints are prone to disbond when submitted to fatigue or extreme loads. The objective of this paper is to evaluate the integrity of a composite skin-stringer joint using the scattering behavior of the Lamb waves. The structure of interest is composed of three carbon fiber reinforced polymer (CFRP) plates bonded together by adhesive film as a typical representative of skin-stringer assembly. Two different bonding conditions are investigated for the joint: undamaged and damaged (with disbond). A circular disbond is introduced into the joint using Teflon tape during manufacturing. Two co-localized rectangular piezoceramics are used to generate plane guided waves at 180° and 135° incidence. A non-contact measurement is performed using a 3-D Laser Doppler Vibrometer (LDV) to extract the required information for evaluation of bonding condition. The results present the different scattered field of the guided waves at the joint as a function of frequency, mode, excitation angle and presence of artificial damage. It was found that the amplitude and directivity patterns of scattered fields are affected by the presence of damage, such that SHM design guidelines can be derived for efficient damage detection in the composite skin-stringer bonded joints.

1. Introduction

Stiffened-skin composite structures have been intensively used in aerospace structures as a noteworthy design choice for aircraft control surfaces like flap, aileron and even rudder and elevator skins. These structures mostly consist of either co-cured or adhesively bonded stringers at regular intervals. Composite bonded joints are also found in patch repairs to restore structural integrity. Experimental studies indicate that an adhesively bonded joint can restore the strength of the repaired structure up to 80% of the original undamaged laminate strength [1]. The joint area is known as a zone of potential weakness, because of load transferring phenomena taking place and causing possible disbond. Moreover, joints are prone to degradation of the adhesive over time, harsh environment or improper installation resulting in local disbond or porosity. These types of damage can significantly jeopardize the performance and safety of a structure with little advanced warning, and since they cannot be easily detected by visual inspection, Non-Destructive Testing (NDT) methods are being employed for detailed inspection of the structures.

Over the last 50 years, NDT techniques have attained maturity in engineering applications, playing a crucial role in assessment of the integrity and durability of composite structures. Conventional NDT approaches are usually conducted at regular scheduled intervals during the lifetime and cannot provide descriptive information about structural integrity. Moreover, almost all of the existing NDT methods require extremely time-consuming point by point inspection. Structural Health Monitoring (SHM) as an improved and retrofitted version of traditional NDT has been proposed for continuous inspection of the structural features including composite joint to evaluate health and integrity of the joints in a real-time manner. SHM systems aim at replacing scheduled maintenance with as-needed (condition-based) maintenance, thus saving the cost of unnecessary maintenance as well as improving the level of safety through the consideration of working condition updates [2]. It has been shown that an effective SHM could reduce the total maintenance cost compared to traditional NDI approaches by more than 30% for an aircraft fleet [3]. Among the different approaches of SHM, ultrasonic guided (Lamb) wave propagation with piezoelectric transducers has been proposed for effective monitoring of composite structures [4] since it is quick, repeatable, sensitive to small-sized damages and cost effective [2]. Guided

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waves can propagate in symmetrical or anti-symmetrical modes with respect to the neutral axis of the plate. Symmetric modes have more radial in-plane displacement of particles, whereas anti-symmetric modes mostly have out-of-plane displacement. Therefore, a symmetric mode often indicates thickness bulging and contracting while an anti-symmetric mode presents constant-thickness bending. Guided wave propagation has been successfully employed in the past for damage detection in repaired composites and bonded joints as well [5–9].

Previous studies demonstrate that two strategies can be employed for inspection of bonded joints using guided waves [8], namely "within-the-bond" and "across-the-bond". The first approach examined in the literature is the "within-the-bond" method by which bond-lines is used as a waveguide hence the influence of complex geometrical features on wave behavior is minimized [10]. It has been shown that using this approach, a primary anti-symmetric mode (A0) below 200 kHz frequency range is a good candidate for effective inspection of hybrid bonded structures [11]. The "across-the-bond" method is the second strategy which has been mostly employed in previous studies for inspection of metallic assemblies [12,13]. With this method, the degree of disbond in adhesive joints can be estimated by measuring the attenuation level of the A0 mode [14]. Although there are several studies, which investigated the Lamb wave scattering from the hole and rivet in metallic structures [15,16] the scattering of guided wave through the composite adhesive bonded joint has not been addressed in detail yet.

In this paper, the integrity state of a composite skin to stringer is studied by characterizing the scattered guided waves field through a bonded joint. The guided waves are generated by a co-localized piezoceramic device, and non-contact measurement of the in-plane and out-of plane velocity is performed using a 3-D Laser Doppler Vibrometer (3D-LDV) over a circular grid of points. For a given frequency and mode, by comparing the sensitivity of the scattering field with respect to bonding condition, SHM design guidelines are extracted justifying the guided wave method's ability for disbond detection.

2. Structure description

Composite bonded joints are usually selected as a typical candidate of hybrid or composite assemblies, co-cured stiffened panels or repairs in the aerospace industry. The structure of interest is selected based on a project between industrial and academic researchers, namely (CRIAQ) DPHM 501, where structural features and design parameters have been identified, extracted and filtered for their relevance from an extensive list of aerospace structures of interest [17]. Based on the reduced list, the structure presented in this paper is chosen as a classic representative composite assembly commonly used in aircraft structures. It is composed of three quasi-isotropic panels made of out-of-autoclave plain weave prepreg (CYCOM 5320) with the same properties in the warp and weft directions. The layup is $[0/45/90/-45]_s$, where each ply represents a woven layer and the 0-degree direction is the warp direction. The elastic material properties of the material used in the paper are given in Table 1. However the disbond should ideally be an interlaminar crack to model a real case, a circular (diameter of 25.4 mm) disbond is introduced into the joint using Teflon tape. Two pieces of inserted Teflon tape can simulate the disbond between the skin and the stringer, and is a reliable way to model a defect of a known initial size. The skin dimension is 304 mm × 914 mm and the two stringers are 76 mm × 304 mm each bonded using Cytec FM® 300–2 M as depicted in Fig. 1. The thickness of each lamina is 0.212 mm. Since each individual part is made of 8 plies, thickness of stringers and skin worked out to 1.7 mm each and that of the stiffened region of the skin to 3.40 mm including the thickness of adhesive 0.09 mm. In a "co-bonding" strategy, the skin is cured and the stringer is laminated onto the skin (with the help of the adhesive) and then cured; while in a "secondary bonding" strategy both parts are cured separately and then glued together using an adhesive. In this study the three components of the assembly are laid up, vacuumed bagged simultaneously and cured in one step using the "co-curing" strategy.

3. Experimental methodology

Two basic configurations are usually employed in guided wave techniques for damage detection: "pulse-echo" and "pitch-and-catch". In the former, both transmitter and receiver are located on the same side of the targeted zone, and the sensor receives the echoed wave signals from the defect or structural feature; therefore, the sensitivity is mainly governed by the magnitude of the wave back-scattered from the damage. In the latter method, waves are emitted from an actuator to travel across the inspection area, while a sensor on the other side of the area captures the wave signal propagated through the inspection area. Hence the sensitivity of the latter configuration is governed by the magnitude of the forward-scattering wave signal across the inspection area. Such configurations cannot locate the defects unless a sparse network of transducers is used to offer multiple forward-scattering and backward-scattering wave signals [3]. In this research, an LDV and a "scattered-based" approach, benefiting the forward and backward scattering waveforms, are used as tools to improve the configuration of actuator-sensor pair-based method for efficient inspection of composite skin-stringer assemblies. Therefore, the diffraction pattern, i.e. wave scattering level at different orientations around the joint can be determined to help understand guided wave interaction with disbond and allows deriving guidelines for SHM system design.

3.1. Guided wave generation and sensing

In order to characterize the scattering of the guided waves through the pristine and disbond cases, a calibrated and repeatable device capable of generating a specific guided wave mode is required. For this purpose, plane wave generation was chosen in order to allow focusing the energy on the selected area and avoiding geometrical spread induced by finite size transducers. The designed device illustrated in Fig. 2 consists of two co-localized rectangular piezoceramics (50 × 5 × 0.45 mm) maintained on both sides of the structure using high strength magnets. The two actuators can be driven in- and out-of phase in order to generate symmetric or anti-symmetric modes respectively. However, due to slight misalignment or tilt, this strategy requires optimization in order to be efficient experimentally. For this purpose, the mode selection is achieved in post-processing by adjusting amplitude

Table 1
Material properties from manufacturer of woven CFRP (CYCOM 5320) and adhesive film (Cytec FM-300-2).

Material	$E_{11} = E_{22}$ (GPa)	E_{33} (GPa)	$\upsilon_{12} = \upsilon_{13} = \upsilon_{23}$	$G_{12} = G_{13} = G_{23}$ (GPa)	ρ (kg/m^3)
CFRP	64.6	14	0.042	4.13	1300
Adhesive	1.0	1.0	0.3	0.38	1420