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Laser Doppler imaging of delamination in a composite T-joint with remotely located ultrasonic actuators

G. Kolappan Geetha [a], D. Roy Mahapatra [a,*], S. Gopalakrishnan [a], S. Hanagud [b]

[a] *Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560012, India*
[b] *School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150, USA*

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ABSTRACT

This paper presents an experimental study on the interaction of ultrasonic guided waves with delamination in the web–flange interface of a co-cured, co-bonded composite T-joint. A complex interaction of waves is induced, first, by one, and, later, by two piezoceramic wafer(s) bonded on the inner surface of the flange. The flange surface velocity distributions are reconstructed from the scanning laser Doppler velocimeter (LDV) measurements to study the effect of a delamination overlapping the web–flange interface. The surface-bonded piezoelectric actuator(s) placed remotely on the flange produce primarily anti-symmetric wave incidence to the delamination. A two-stage wave mode conversion process, one due to the web and joint filler, and the other due to the delamination underneath the flange is observed. First, we address the problem of identification of delamination by ultrasonic contrast imaging of the web–flange interface using a single actuator. This study is extended further to enhance the ultrasonic contrast imaging at the web–flange interface using a standing wave. A quantitative methodology based on mode conversion strength is developed to monitor different structural features like free-edge, web–flange interface and delamination. The results show the complex nature of the conversion of flexural waves to in-plane waves through the deltoid and along the web–flange interface.

1. Introduction

Integrally designed and fabricated composite structural joints have several advantages such as a high strength to weight ratio, very good endurance against fatigue and wear, good corrosion resistance etc. Despite these advantages, quality control in the manufacturing of composite joined structures is highly demanding and subsequently the structure requires reliable inspection at periodic intervals to detect possible defects. An assembly of complex composite structures often requires efficient joining in the form of T-joints or T-stiffeners. The usage of co-cured, co-bonded composite T-joints in aerospace vehicles can result in a total reduction of structural components (bolts/fasteners) by 30% compared to the metallic structure [1]. The main part of the T-joint includes a flange, web, and radius filler. In a typical composite stiffened airframe, the flange interfaces with the skin; the web provides an interface for attachment of the substructure, and the radius filler provides continuity of load transfer between the web and flange. The T-joint transfers flexural, tensile, and shear loads from the skin to the web besides acting as a stiffener to carry bending and buckling loads directly. Particular design objectives involve, for example, the prevention of skin buckling during wing loading, increase of bending/torsional strength of the integral payload, a fuel tank attached to the airframe, etc.

A survey of the aircraft industry highlights the cost of maintenance per annum for ageing aircraft structures to the tune of about one-third of the aircraft cost [2]. According to another survey [3], about 90% of the aircraft structures skin inspections are conducted using visual inspections [4] and remaining the 10% are conducted using various other Non-Destructive Inspection techniques such as dye penetration [5], eddy current [6], radiography [7], ultrasonics [8] etc. Reviews of the current state-of-the-art of various Non-Destructive Inspection (NDI) techniques for composite structures with their limitations can be found in Ref. [9] and further references therein. Life extension of the ageing aircraft using embedded Fiber Bragg Grating (FBG) based Structural Health Monitoring on composite structures are described in Ref. [10]. The deployment of the NDI techniques mentioned above are restricted by the nature of disassembly required for complex structural components, geometry/material specific probes and associated attachments, and the level of accessibility to the damage(s).

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* Corresponding author.
E-mail address: droymahapatra@aero.iisc.ernet.in (D. Roy Mahapatra).

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Structural Health Monitoring (SHM) is the continuous, autonomous in-service monitoring of the physical condition of a structure by means of embedded/contact/non-contact sensors with minimal manual intervention [11]. It is aimed at assuring the structural integrity of the aircraft, replacing periodic scheduled based maintenance to condition based maintenance. The key motivations for SHM include gain over maintenance and design benefits. Maintenance aspects are increasingly significant for the reduction of Direct Operating Costs (DOC), since fuel bills, airport fees, etc. have little potential in saving expenses. Reduction of Direct Maintenance Cost (DMC) increases the availability of aircrafts. The motivation to use SHM for innovative design approaches is the need of the manufactures to offer aircraft with increased fuel efficiency. SHM will be used to get new concepts for structural design, which will lead to weight reduction for metal and composite structures up to 15% on component level [12]. The final idea of SHM is to imitate human nervous system.

In the present paper, we explore a new methodology and experimental results, which may be useful in addressing some of the problems above, particularly for monitoring inaccessible features and damage(s) in composite structures. Vibration/modal analysis-based methods for the detection of small damage(s) are less sensitive when compared to ultrasonic wave propagation based methods [13]. Wave propagation-based diagnose using ultrasonic guided waves have been demonstrated quite effectively in metallic structures with cracks [14], fatigue damage [15], corrosion [16] etc. and also for composites for debonding [17], delamination [18–20], matrix cracking [21] etc. Ultrasonic wave propagation in inhomogeneous and anisotropic media and the application of the wave characteristic based finite element method for efficient damage detection for Structural Health Monitoring (SHM) have been developed (see Ref. [22] and references therein). A mechanistic treatment explaining how guided waves are influenced due to delaminations and cracks in composite beams is discussed in Refs. [19,23,24]. This explanation helps in developing specialized schemes of damage detection.

Piezoelectric Wafer Active Sensors (PWAS) bonded on composite structures can be designed to perform integrated SHM using Lamb waves [25]. Optimization studies involving actuator and sensor configuration(s), types of excitation signals and procedures for the diagnosis of pre-existing damage(s) such as delamination, matrix crack(s), through thickness hole(s) etc. in test coupons have been reported in Ref. [26]. The distributed sensing behavior of piezoceramic patches embedded in composites subjected to static and dynamic fracture has been studied in Ref. [27,28]. The delamination of composite panels and joints due to impact loads is a major concern. Low velocity impact damage has been identified using the amplitude of the piezoelectric sensor signal [29]. Damage in composites has been identified using distributed piezoelectric transducers [30]. Ultrasonic signal focusing and steering in isotropic plates by an array of transmitters using a delay-and-sum algorithm have been reported in Ref. [31,32]. Due to the directional dependencies of group velocities in anisotropic composites, the slowness curve is not circular [33]. Furthermore, for dispersive guided waves, there is a different slowness curve for each frequency of every wave mode. Yan et al. [34] have demonstrated that, for certain frequencies, the slowness curve for a specific mode can be nearly circular, and under such a condition the delay-and-sum algorithm can be applied to ultrasonically scan a probable damage area. The effect of delamination in Carbon Fiber Reinforced Polymer (CFRP) plates on the lobe pattern has been analyzed using a linear phased array of piezoelectric transducers [35]. Ultrasonic wave field imaging with non-contact LDV is another offline NDI technique that can efficiently utilize actuator-induced ultrasonic guided waves and the surface velocity scan data can be algorithmically analyzed, thereby minimizing physical hardware complexity for focusing and steering ultrasound through probable damage zones. The problem of detecting delamination in composites and identifying the size, particularly when the delamination is in the joint, is addressed in the present paper. This is a challenging problem as nearby structural boundaries alter the propagation of a guided wave. A brief summary of a damage diagnosis and structural wave field imaging using LDV is given below before we illustrate our scheme of delamination imaging in a composite T-joint.

While performing an ultrasonic C-scan of the joints, the ultrasonic wave is deflected in different directions, and, hence, the received amplitude is less, leading to a dark area in the C-scan image. By using non-contact ultrasonic sensors, the problems due to liquid couplants or dry couplants and the associated variations in signal sensitivity due to an impedance mismatch between the couplant and the structure etc. can be avoided. Among the various different laser-based techniques for vibration measurement, such as holography, Electronic Speckle Pattern Interferometry (ESPI), shearography, and laser Doppler velocimeter (LDV), we consider LDV in our present research. One of the distinct advantages of LDV is its high sensitivity to the high frequency vibration of optically reflecting surfaces. LDV-based studies involving small/large area sensing and damage diagnose can be found in Refs. [36–43]. Vibration excitation at a single point using a physically wired transducer and measuring the structural dynamic response at various points using LDV is commonly employed. Ultrasonic imaging using non-contact laser excitation at multiple points and a structural dynamic response at a single point without scanning has been demonstrated in metallic and composite structures by Sohn et al. [41–43]. This method is based on the principle of the linear reciprocity of ultrasonic waves. This reciprocity relation does not hold when the wave path is not reversible. This irreversibility of the wave path may be a factor if multiple dissimilar transducers are used for actuation/sensing, or when the time windows of sensing at various different points are different or when boundary scattering appears in a certain propagation path that disturbs the reciprocity of the wave field. Another practical limitation here is the measurements involving boundary scattering due to which the uniqueness of the wave path is lost. Alternatively, an ultrasonic contrast-based imaging method is developed in the present study. Subsequently, we propose the concept of a standing wave filter and a Laplacian image filter that clearly improve the image contrast. These are highly effective in regions where the waves experience multiple reflections and transmissions from the defect boundary. The technique poses certain limitations in cases where the defect boundary overlaps with the structural features as in the case of a delamination overlapping with the web–flange interface. In this case, the defect boundary may not be clearly distinguished from the structural feature boundary.

Frequency–wavenumber filtering is another approach where boundary reflection may be separable if an accurate model of boundary reflection is known [44]. The formulation of damage indices based on strain energy and techniques like spatial decimation and frequency–wavenumber filtering have been reported in Ref. [45]. However, the ultrasonic contrasting of an inaccessible zone in the rear-field for a complex-shaped structure poses significant challenges. The applications of wave filters are also limited as they assume unidirectional propagation of a single wave mode at a time, whereas structures like composite T-joints produce near-field conversion of various wave components in various different directions. The present effort is the first of its kind to resolve the complexities involved and to quantify wave mode conversion near the vicinity of a delamination.

The paper is organized as follows: first, the fabrication process for a composite T-joint test specimen is described in Section 2. The details of the actuation and sensing schemes are explained in Section 3. The mathematical modeling background for the