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Guided wave propagation and scattering for structural health monitoring of stiffened composites

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ABSTRACT

Impact induced damages in stiffened composite structures are usually settled with constrained design criteria and recurring maintenance tasks, that affect weight savings potentialities of composite materials as well as operative costs. To overcome those penalties due to hidden damages, this paper deals with detection, localization and size assessment of stringers disbondings with monitoring techniques by permanently attached piezoelectric transducers (PZT) capable to excite and sense guided ultrasonic waves. A composite stiffened plate typically designed for wingbox structures is investigated to test a novel detection technique capable to predict arrival time of guided waves scattered from stringers detecting, as a consequence, any possible change in a specific scattering area. Theoretical aspects are investigated to correctly exploit the technique leading to a geometrical reduction which returns the optimal configuration of sensors. Several measurements are carried out to validate the hypothesis and the approach effectiveness. A promising result in agreement with state-of-the-art ultrasonic nondestructive testing is thus obtained and discussed. Furthermore it is shown that processing Lamb wave reflections signals is possible to improve the localization accuracy respect to a general purpose reconstruction algorithm while making use of fewer number of sensors possible.

1. Introduction

One of the major concerns of aerospace and transportation engineering during the last years has been related to increase performances and safety with energy savings. Composite materials have been indeed widely adopted with the aim to design high performance and lighter components without reaching fully up to now the expected results. Among other failure mechanisms, random impacts may induce barely visible or not visible failure due to the complex mechanics behavior [1,2], which leads to delamination arising among several layers or disbondings between structure and stiffener [3]. Consequently, composite structures need very strict maintenance operations and a design taking in account hidden failures due to impact damages, generally accomplished by limiting the design strain level for ultimate and limit combined load design criteria [4]. This rough damage tolerance approach therefore breaks down the benefits encouraging composites introduction.

To reduce operational costs as well as design constraints a sensorised structure providing monitoring of critical components appears a reasonable solution. A condition-based approach could be able to relax the maintenance strategy minimizing aircraft downtime as well [5]. Moreover the design constraints would be avoided further increasing the structural performance with a more ecological friendly aircraft. Although this is a very long time perspective, for the first demand Structural Health Monitoring (SHM) systems, providing information about the structural efficiency, appear to be the best solution. The European Union itself is deeply involved in research programs dedicated to suit the environmental goals set for regional aircrafts, that will enter service from 2020 onwards, performing low-weight aircraft configurations in which the continuous monitoring is a key concept [6]. In this manner, SHM integration becomes a feasible concept to enable in-service inspection cost reductions of up to 1% [7].

Innovative and effective techniques gathering information about current structural efficiency can be found within structural dynamic techniques using permanently installed sensors, providing easy structural integration. More specifically, ultrasonic methods are effective for non-destructive investigation (NDI) as well as continuous monitoring thanks to small power and dimension required by sensors [8]. For the latter demand, Lamb Waves [9] are able to interrogate the media because they propagate according to effective thickness and material

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properties [10]. They are practically formed by interference of multiple reflections and mode conversion of longitudinal waves (P-waves) and shear waves (S-waves) at the free surfaces [11,12] making possible the monitoring of the entire thickness and stiffeners according to wavelength. They appear suitable for SHM purposes in term of integration and effectiveness because they can be easily excited from a single location and they are such a “flexible” approach to be designed; they indeed show a multi-modal behavior, which can be exploited for optimizing monitoring of the specific flaw to detect [13].

For sake of simplicity, it can be asserted that the propagation changes when a detectable damage is encountered, making possible the structural diagnosis. However, the complexities of wave propagation while traveling in non-isotropic media [14] make quite difficult to relate few single sensing points to how the wave is propagating and eventually interacting with such a hidden flaw. Hence, the ultrasonic propagation has to be related to specific parameters (signal responses) which may be affected by unforeseen failure. Generally, the investigation on how signal response changes during lifetime is quite simple. Instead, the major concern regards the reconstruction of damage in terms of location and size. The last demand can be sometime simplified approaching statistical analysis to correlate the signal response to the actual flaw size. However, it requires a time consuming procedure [15] or a well-defined numerical correlation [16]. Instead, the first demand requires an algorithm capable to analyze signal responses and provide the more probable diagnostic. Since many years, Lamb waves are investigated to this purpose achieving many algorithms [17,18] and several signal processing techniques [19–21] which are able to account environmental compensation [22], different operative conditions [23] and complex aspects as well [24].

Although promising results have been obtained, the post processing of ultrasonic data appears to become further challenging when complex structures are considered, activating multimodal behavior, multi-point reflection and damage interaction when present. Several techniques can be combined with algorithms capable to localize and reconstruct damage and based on arrival time of ultrasonic signals [25], model comparison of differential signals [26] or probabilistic analysis of propagation features [27,28]. However, those approaches usually account only the first direct wave or even including various echoes, they do not detail any information from late arrival echoes which may improve system performances using fewer transducers than traditional approaches as well [29].

In this context, a typical problem regards the stiffened composite structures where the stringers adopted for reinforcing thin walled structures [30] may be affected by not visible disbondings even when subjected to low energy impacts. This fact leads to the separation between the stringer and the hosting structure preventing the collaboration between parts with a dangerous drawback for loading absorbing. Due to this latest issue, usually disbonding stoppers are included into the design to avoid separations between stiffeners and skin above the maximum size ensuring collaboration [4]. Moving towards a condition based approach, it appears crucial the deterministic diagnosis of damage in terms of size and severity.

Although the direct waves propagating in complex media are able to return the detection and position of disbonding [3], size and severity of damage are not directly assessed even when ultrasonic features are sensitive to such a hidden flaw [31]. On the other hand, multiple ultrasonic echoes caused by reflections from the plate’s boundaries can be leveraged to enhance imaging performance [32], complex structures may be used to redirect lamb waves to ensure the monitoring of a specific area [33] exploiting its scattering capabilities or ray path models can be assessed to locate and size the damage [34]. Hence, the reflections of wave interacting with stiffeners can be analyzed to improve the diagnostic or design new strategies.

Within the last demands, this paper deals with the scattering of propagating waves for identification, localization and size and severity assessment of disbondings in stiffened composites, which are rarely investigated in the literature. Due to the complexities involved, a simple geometrical reduction is used to describe the propagation of the first antisymmetric Lamb wave mode (A_0) using the object of investigation itself as scatterer. Including boundary reflections into the reconstruction model provides high performance diagnostic reducing transducers and pattern complexities of conventional techniques.

2. SHM strategies

Structural Health Monitoring deals with the analysis of structural performances in view of condition-based maintenance as well as integrated oriented design. However, an health management system is a *complex environment* in which the diagnosis is the crucial but not the only critical task to perform. Different stages can be identified and likewise different methodologies can be exploited to perform different tasks. Among several possibilities, different techniques available for damage detection are explained and the metrics for structural assessment are related and discussed.

2.1. Proposed methodologies

Generally, a SHM system may provide a multi-level diagnostic, depending upon the information collected and the algorithm adopted to interpret test data sets. It mainly deals with diagnostic phase and should be supported by a prognosis tool to obtain a self-sensing smart structure with a condition based lifetime strategy. The health management system can be broadly divided in four different steps:

- Damage detection, oriented to identify mostly the presence of the damage when a certain metric overcomes a defined health threshold (decision making output).
- Damage localization, which deals with the identification of the more probable location of the detected damage (position output).
- Damage dimension assessment, aimed to provide the extension and/or severity of the flaw (severity output).
- Remaining life, which deals with the prognosis of the current expected lifetime of the component considering the dimension of damage and the prescribed load history (prognosis output).

The first three outputs constitute the diagnosis of a comprehensive SHM system while the last one is the prognosis demanded as input for the management of the monitored component in order to deliver aircraft release or repair. From this breakdown, it is possible to define the multi-level diagnostic necessary for condition monitoring approach.

The crucial issue is the damage detection, whose reliability affects the remaining steps. The target of the system, i.e. the minimum detectable size with a defined confidence level (usually approached with *Probability of detection* analysis [15]) is crucial for application purpose. Regardless the detection capability of the metric, the quantification of a SHM system [35] is strongly affected by the decision level adopted for the identification which needs a careful unsupervised [36,37] or supervised [38] analysis of data and it should be optimized in view of the aircraft lifetime management [39]. Moreover, the relation between signal response and flaw size can be primarily assessed approaching a statistical analysis to correlate the specific feature to the damage dimension and/or severity [15,40]. Thus the system provides simultaneously the presence and the severity of damage scenario. To finally assess the location of hidden flaw, a dedicated algorithm should analyze the (non-censured) data sets available after decision making.

As a matter of facts, a comprehensive diagnostic output may be simply achieved but it is crucial to: (i) chose a signal response that is sensitive to such a hidden flaw as well as increasing with the severity of damage and (ii) estimate at least the position of damage as a spatial point using a reconstruction algorithm. However, a critical point is the type of damage scenario induced by low velocity impacts which may be different depending on the impact location. Typically, delaminations