Computational and Experimental Methods in Structures – Vol. 8

Structural Health Monitoring for Advanced Composite Structures

Editors

M H Ferri Aliabadi

Z Sharif Khodaei

World Scientific

Structural health monitoring (SHM) is a relatively new and alternative way of non-destructive inspection (NDI). It is the process of implementing a damage detection and characterization strategy for composite structures. The basis of SHM is the application of permanent fixed sensors on a structure, combined with minimum manual intervention to monitor its structural integrity. These sensors detect changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance.

This book's primary focus is on the diagnostics element of SHM, namely damage detection in composite structures. The techniques covered include the use of Piezoelectric transducers for active and passive Ultrasonics guided waves and electromechanical impedance measurements, and fiber optic sensors for strain sensing. It also includes numerical modeling of wave propagation in composite structures. Contributed chapters written by leading researchers in the field describe each of these techniques, making it a key text for researchers and NDI practitioners as well as postgraduate students in a number of specialties including materials, aerospace, mechanical and computational engineering.

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Preface

Structural health monitoring (SHM) is a modern technology with the potential to significantly improve damage detection in composites and therefore act as a viable alternative to the commonly utilized non-destructive inspection (NDI). The industry's quest for high efficiency and performance with reduced weight has resulted in the extensive use of composite materials. However, composite materials are sensitive to in-service impact damage and with today's NDI technologies, inspections are frequent and costly due to the fact that it can only be carried out if access to the area to be inspected exists or is provided during maintenance checks.

The basis of SHM is the application of permanent fixed sensors on the structure combined with the necessity of a minimum of manual intervention to monitor the structural integrity. This enables a continuous monitoring of the structure, and thus a detection of the defect at a very early stage to move away from planned maintenance and towards condition-based maintenance.

This book, for the first time, provides an overview of prominent SHM techniques for damage detection and localization utilizing ultrasonic-guided waves in composites. It covers not only the fundamental concepts in the SHM piezoelectric and fiber optic sensor philosophy but also the state-of-the-art on passive and active sensing methodologies.

Chapter 1 initially provides a comprehensive review of guided wave damage detection techniques, before presenting some of the key aspects required for establishing an effective SHM system for large complex composites structures such as optimization of sensor positioning and influence of changes in environmental conditions on damage detection algorithms. Chapters 2 and 3 present efficient and accurate numerical modeling techniques for wave propagation and their interaction with damage in composites. Electro-mechanical impedance and guided wave propagation methodologies based on special signal processing techniques that allow identification of signal anomalies caused by structure degradation are the subject of Chapter 4. In Chapter 5, constructive interference via beamforming is developed to increase the reliability of the SHM system with a phased array configuration. Chapter 6 presents the fiber optic (FO) sensors as effective sensors for strain monitoring due to their high sensitivity to strain measurement, light weight and immunity from electro-mechanical interference. Finally, in Chapter 7, application of SHM to in-service monitoring of impact events is presented through passive sensing algorithms. Particular attention is paid to data-driven methods using machine learning algorithm for determination of impact location and energy. A Bayesian-based optimization is presented for determining the optimal sensor configuration in complex structures.

About the Editors

M. H. Ferri Aliabadi is a Professor or Aerostructures and Zaharoff Professor of Aviation. He has been the Head of Aeronautics Department at Imperial College, London, since 2008. Prior to joining Imperial College in 2005, he was Professor of Computational Mechanics and the Director of Aerospace Engineering at Queen Mary, University of London (1997–2004) and Reader and Head of Damage Tolerance Division at WIT, Southampton (1987–1997). Since 2004 he is the head of the Department of Aeronautics at Imperial College, London.

Ferri's main research interests are computational methods and mathematical modeling, aerospace materials and structures, composites and material innovations and structural health monitoring. He has published more than 250 journal papers and authored and edited over 50 books.

Zahra Sharif Khodaei is a Senior Lecturer in Aerostructures. She obtained her PhD from Czech Technical University in Prague in numerical modeling of functionally graded materials in 2008. Prior to her lectureship post in 2014, she was a Research Associate at the Department of Aeronautics, Imperial College, London, since 2009 where she conducted research in fatigue modeling and analysis of metallic and fiber metallic laminates (FMLs) and more significantly in developments of technologies and methodologies for structural health monitoring (SHM) of composite structures. Her main areas of research are structural integrity and health monitoring of structures in particular composites. She has authored more than 30 journal publications including book chapters.

Contents

Chapter 1

Damage Detection and Characterization with Piezoelectric Transducers: Active Sensing

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This chapter presents an overview of prominent structural health monitoring (SHM) techniques for damage detection and localization utilizing ultrasonic guided waves (UGWs). The basic principles of SHM described include the application of permanently fixed sensors on the structure combined with the necessity of minimum manual intervention to monitor the structural integrity. The techniques used in SHM, especially tomography and delay-and-sum (DAS) approach, are described in detail. Particular attention is paid to the development of advanced technical capabilities for making the integration of sensors in modern composite structures practical and efficient so as to facilitate industrialization and certification. Therefore, key aspects that have been included are optimization of sensor positioning and influence of changes in environmental conditions on damage detection algorithms. The theoretical descriptions are combined with several benchmark examples involving finite element analysis and experimental measurements. Finally, application to a curved fuselage composite panel with frames and stringers is presented to demonstrate how a multilevel approach could be used to efficiently detect damage in complex structures.

1. Introduction

For designing modern materials for aerospace structures, a balance between low weight and high safety is required. Modern aircraft design typically follows damage-tolerant design concept. Nevertheless, the presence of damage in the structure can jeopardize the operation and

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safety if not detected and repaired at the right time. The recognition that safety, integrity and low weight are key priorities in the design of airframe structures has to led to developing techniques for monitoring and maintenance of composite structures. Since composites are relatively new materials in aerospace structures, the conventional non-destructive examination (NDE) techniques, which have been optimized for the needs of metallic structures, cannot satisfy the requirements for the maintenance of composite materials with a high probability of detection (PoD). This has led to a rather conservative design of composites applying strict damage tolerance rules, i.e., no growth rule.[1]

As the detection of barely visible impact damages (BVIDs) currently could not be guaranteed, damage tolerance design requires the composite structures to be rather thick, so that impact events do not reduce the strength below the limit load (LL) (see regulation ACJ 25.603). Depending on the adopted philosophy for the design and maintenance of future generation aircraft, one can decide either to establish frequent inspections, which mean a probable early removal of defect from service, or select a conservative design. Indeed, even when a conservative design is chosen, the detection of any damage, for instance during a walk-around, requires certain follow-up measures to characterize the damage further, and to ensure the airworthiness of the aircraft. These measures are especially costly when they are unscheduled, either due to the fact that they are accompanied by an unplanned down-time for the aircraft or the necessity to call for certified non-destructive inspection (NDI) personnel. Some estimates have claimed that 27% of average aircraft's life cycle cost is spent on inspection and repair.

Structural health monitoring (SHM) is an emerging technology covering the development and implementation of technologies and methodologies for monitoring, inspection and damage assessment based on integrated sensors. The acquired data in combination with advanced signal processing techniques can provide maintenance actions on demand. The continuous monitoring of the aircraft can result in condition-based maintenance (CBM), reducing the ground time and the maintenance costs significantly.[2]

There are various damage detection methodologies based on the type of analysis and type of sensors integrated in the structure.[3,4] The most popular sensor technologies are fiber optic (FO) and piezoelectric (PZT) sensors.

FOs can be embedded or surface mounted on the structure and can be used as strain measurement sensors either for damage detection[5,6] and/or load monitoring.[7–9] FO sensors are passive sensors. However, they can be used in combination with PZT actuators to form an active sensing network: a hybrid system. In the hybrid system, PZT actuators are used to excite the structure and FOs act as sensors to record the strain waves and can be used to monitor the state of composite structures.[10–12] FOs are an attractive sensor solution due to their light weight, high sensitivity to strain and ability to compensate for temperature effects. PZT transducers are used as actuators for exciting ultrasonic guided waves (UGWs) as well as sensing the propagating wave owing to their electro-mechanical coupling. They are an attractive solution due to their light weight, small size and low energy consumption. PZT transducers can be used for damage detection by actuating and sensing UGWs in the structure,[13–16] in vibration analysis[17–19] or by measuring the electro-mechanical impedance (EMI) response of the structure.[20–22]

An overview of the fundamentals of UGWs will be given in this section followed by the methodologies developed based on guided waves for damage detection and characterization.

Once an SHM system is designed based on the sensor technology and damage detection methodology, the decision to have a permanently installed sensor network for structural prognosis will be driven by its reliability, cost and the added weight of the system. The optimal placement of sensors/actuators in order to detect, with high probability and reliability, any damage before it becomes critical is a key factor in uptake of any SHM system. The interference of the sensor system with the design of the aeronautical part is required to be minimum. On the other hand, the SHM system must be able to detect various probable damage scenarios with high reliability and PoD. Therefore, optimization analysis needs to be carried out to find the best sensor layup (number and location) while minimizing the additional cost and weight of the system.

In this chapter, an overview of damage detection methodologies based on UGWs will be provided. The fundamental concepts of wave propagation together with key parameters in the design of any UGW-based SHM system is described in Section 2.1. Since the developed SHM system must work under the operational conditions of an aircraft, the effect of parameters such as temperature, humidity and vibration on the guided waves is also described. Different methodologies for damage detection based on sensor data are described in Section 3 and some of the most popular methods are further detailed and assessed. Once the damage detection methodology is developed, the next important question is how many sensors are required and where they should be located, which leads us to the optimization techniques outlined in Section 4. Finally, the applicability of the methodologies is assessed and validated by experiments on a large composite stiffened panel.

2. Overview of Ultrasonic Guided Wave Damage Detection

In this section, an overview of the basic principles of Lamb wave propagation in solids in the context of their application to NDE is outlined.

2.1. *Fundamentals of Guided Waves*

In general, elastic waves in solid materials are guided by the surface of the media in which they propagate. Rayleigh wave, defined as a surface wave, exists along the free surface of a semi-infinite solid decaying exponentially in its magnitude of displacement depending upon distance from the surface. However, in thin plate-like medium (such as aerospace panels), they are guided by the free upper and lower surfaces and are called guided waves. If the range of excitation frequencies is above 20 kHz, they are called ultrasound. The UGWs cause three types of motion in an elastic solid: waves polarized in the plane perpendicular to the plate are compressional (often called extensional) and shear (often called flexural) and waves polarized in the plane of the plate are called shear horizontal (SH) waves.

The governing differential equation of motion in an elastic filed can be written as

$$\mu u_{i,jj} + (\lambda + \mu) u_{i,ji} + \rho f_i = \rho \ddot{u}_i \quad (i, j = 1, 2, 3), \tag{1}$$

where u_i and f_i are displacement and body forces in the ith direction respectively, $\ddot{u}$ is the acceleration, ρ and μ are the density and shear modulus of the plate respectively and λ is the Lame constant. Equation (1) can be decomposed into two uncoupled parts under the plane strain condition, i.e., no SH waves (using Helmholtz decomposition[23]):

$$\begin{aligned} &\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2} \quad \text{governing longitudinal wave mode,} \\ &\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{1}{c_T^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{governing transverse wave modes,} \end{aligned} \tag{2}$$