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Experimental investigations in embedded sensing of composite components in aerospace vehicles

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ABSTRACT

This paper summarizes the experimental investigations for smart embedded sensing in rotorcraft composite components. The overall objective of this effort was to develop smart embedded sensor technologies for condition based maintenance (CBM) for composite components in army rotorcraft. This paper presents the results of experimental investigations related to development and maturation of different types of embedded sensing solutions for structural health monitoring of composite components including Fiber Bragg Grating (FBG) sensors, phased and discrete piezoelectric sensor arrays. A discussion is provided relative to embedment of optical fibers into composites, and the results from embedded FBG sensors in a rotorcraft flexbeam subcomponent test specimen with seeded delamination subjected to dynamic loading. Likewise, results are analyzed of surface mounted phased array and embedded smart piezoelectric sensors in the flexbeam subcomponent test specimen with embedded delamination, subjected to fatigue cyclic loading. The paper also summarizes the lessons learned from efforts to nucleate and propagate delamination within composite components under dynamic cyclic loading.

1. Introduction

Modern rotor systems are highly complex structures comprised of the rotor hub and blades. They increasingly include composite components to minimize weight and fuel consumption [1–4]. The rotor systems for all composite blades contain components that have no redundant load paths and currently have no embedded sensors to monitor structural health. Damages to composite rotor and airframe components made are often not detected through visual inspection. Periodic inspection using non-destructive evaluation methods is time consuming and increases the ownership cost. Periodic inspections are often difficult to conduct and usually lead to numerous unscheduled maintenance actions in the rotor systems. Damages can occur to rotorcraft components because of the severe environment in which they operate. This environment comprises of dynamic and aerodynamic loads, engine vibration, cyclic loadings, foreign object and battle damage impact, lightning, and moisture absorption.

Rotor blades are typically connected to the rotor head by rotor spindles. This requires a highly loaded joint between the blade and spindle in articulated rotors or a highly loaded flexbeam that accommodates blade flapping, lead-lag, and torsional excursions of bearingless rotor systems. Rotor system structural health monitoring is extremely challenging due to the number of failure modes, structural complexity, hidden nature of primary structural elements, highly variable loads and elastic blade deformations that are a function of flight condition, and the need to transmit power and sensor data between the airframe and rotor system. In addition, it is also difficult to apply certain technologies that require excitation and monitoring of high-frequency vibration and stress waves in a high vibration environment. Accordingly, an integrated sensor system, that continuously monitors rotor structural integrity, can have a high payoff by reducing/eliminating inspections and unscheduled maintenance while increasing safety [1–42].

This work is focused on rotor health monitoring systems due to their complexity and the difficulty of inspecting internal structural members. A bearingless tail rotor system flexbeam is the preliminary intended target for initial technology development, validation and demonstration. The flexbeam is a safety critical, complex composite component that is highly loaded and susceptible to foreign

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object and battle damage. The tapered flexbeam geometry is susceptible to matrix cracking, edge delamination, fiber breaking/pull-out, hygrothermal strain, and manufacturing variations. Further, the flexbeam is contained within a pitch case making it difficult to inspect. Aerodynamic loading and flexbeam deformations are highly variable as a function of flight condition. Thus, the tail rotor flexbeam is a challenging and representative rotor system component that will allow most of the technical risks to be investigated in developing and maturing a hybrid rotor structural integrity monitoring system (SIMS) architecture from Technical Readiness Level (TRL)-2 to TRL-4.

Optical fiber sensors including (FBGs, FPIs), are used as strain sensors [8,9,15–36], and piezoelectric sensors, like PZTs, are used as guided waves or surface acoustic wave sensors [3–7,10–15,37–42] for in-situ structural health monitoring (SHM) of composite and metallic structures [1–42]. For monitoring metallic components, the SHM sensors are normally surface mounted or can be embedded within layers in a joint. For composite materials, the SHM sensors can be surface mounted or embedded within the material itself. Significant work has been done in the area of computational modeling [5–8,32] and experimental testing [9–42] of embedded and surface mounted sensors in composites. The initial part of this research, including the manufacturing and setup work, is already in existing literature [15]. The focus of this paper is mainly on the component integration and testing thereof of embedded sensors in a composite flexbeam.

2. Fiber Bragg Grating sensors

The benefits of optical FBG sensors for SHM have been recognized for many years [9]. All types of optical fiber sensors are immune to electromagnetic interference, resistant to chemicals, electrically passive, compact, fatigue resistant, and lightweight and can be located distant to the interrogation electronics. Bragg grating sensors further provide an absolute measurement that exhibits minimal drift with time. Each sensor measures at a discrete position in the fiber and several sensors can be multiplexed for a complex network connected to a single interrogator along a single fiber. There are a number of advantages of embedding optical fiber sensors. The sensor is well protected inside the component and is less likely to be damaged by foreign objects. For aerodynamic surfaces, an embedded optical fiber does not alter the aerodynamic performance of the component. When using embedded sensors, consideration must be given to repair and maintenance activities and in ensuring the mechanical integrity of the component [15].

2.1. Sensor deployment

For applications where the requirement is to monitor an existing structure, the sensor needs to be retrofitted for metallic structures. Here embedding the fiber is not an option. A number of techniques are developed to ease the handling of the fiber and to ensure that the FBGs are correctly positioned. These mainly involve pre-mounting the fiber in a light composite patch. The design of this patch is such that it has an insignificant impact on the component being monitored while at the same time protecting the fiber. This protection avoids the risk of damage both during handling and in-service. It also provides a suitable environment for the fiber and protects against factors such as micro-bending which can adversely affect the performance of the FBGs. The patch can also be used to contain unstrained gages for temperature compensation and to manage the fiber between FBGs and the fiber's ingress/egress.

The ingress/egress requires particular attention as this can be a weak point where the patch may have to provide suitable reinforcement for the connector mounting. The patch is either bonded to the surface of the component being monitored or can be mechanically locked in place. The patch facilitates positioning of the FBGs and to ease bonding the patches can be shaped to closely fit the component. As they are normally larger than resistive strain gages they are more tolerant of bond irregularities. The materials for the patch are chosen to meet the required environmental conditions. When a composite structure is being designed from scratch, it is possible to consider the option of embedding the optical fiber at the outset. When the fiber is to be embedded there are two key issues that need to be considered. Firstly the fiber must be protected during the manufacturing process. One of the most severe examples of this is Resin Transfer Molding (RTM). In this closed mold process the fiber is subjected to considerable pressure and temperatures. The second issue is the fiber ingress/egress. In general, the connector designs involve the embedment of a pre-terminated fiber which is then exposed and the connector assembly built round it.

This task is to demonstrate the practicality of the fiber embedment process. The test specimen is tested to establish the functionality of the fiber optic strain sensors. The test article is a flexbeam subcomponent. This required development of the optical fiber architecture and embedment of the edge connector. The FBG sensor nodes are to be located near or at ply drop location where the seeded delamination is located. This is necessary to measure strain changes as the delamination propagates during fatigue.

2.2. FBG sensor array integration to TR flex beam component

There are significant advantages in using embedded optical fibers to measure strains and hence load in composite structures. The results from the coupon tests as noted in [15] demonstrate the appropriate method of embedding optical fibers in a component manufactured using high temperatures and pressures in a closed mold. The choice of fiber type and coating type are important considerations. The choice of acrylate coated SM1500 fiber with the designed connector is the preferred solution.

FBG sensors have been successfully embedded in a flexbeam representative specimen. The connector is placed partially above plies during the layup process (Fig. 1). After curing and fabrication of the flexbeam, the FBG sensor receptacle is connected to the embedded connector (Fig. 2). Initial static tests showed that all four embedded sensors are working. The specimen is also tested dynamically in the Tail Rotor Flexbeam Fatigue Test Rig with low amplitude tip deflection. The basic concept of the embedded connector is a success, but there is room for improvement on the reliability. Not all fibers are recognized each time the specimen has been connected to the interrogator. Alignment of each fiber within the connector is critical. Manufacturing tolerances of the connector and the receptacles are likely causes of this problem. All four sensors are recognized and responding to the FSI unit as expected.

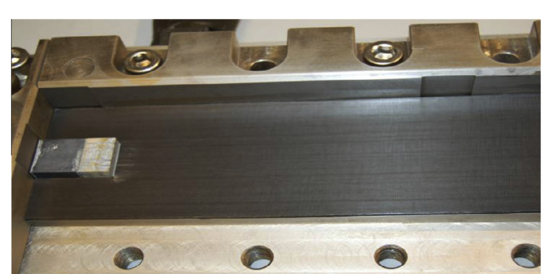

Fig. 1. Flexbeam specimen layup with embedded FBG sensors and connector.