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Low Power, Low Cost, Lightweight, Multichannel Optical Fiber Interrogation System for Structural Health Management of Rotor Blades

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Abstract

This paper describes progress towards the development and demonstration of a no-moving-parts, ultra-low power, light weight, and miniature size, multi-channel optical fiber interrogation (MOFIS™) structural health monitor system suitable for the in-situ non-intrusive integration to a helicopter composite blade to enable the in-flight distributed multi-point measurement of true-strain, temperature, vibration, and impacts associated with excessive loads, fatigue, and structural damage within the composite blades structure. The self-powered, wireless MOFIS™ system offers a versatile and powerful SHM tool to enhance the reliability and safety of avionics platforms, jet fighters, helicopters, and commercial aircraft that use lightweight composite material structures, by providing comprehensive information about the structural integrity of the structure from a large number of locations. The stand-alone multi-channel MOFIS™ transceiver interrogation system can interrogate an array (≥15-channels) of FBG sensor transducers deployed over a single sensor fiber with a spectral dynamic range of ±10,000-microstrains and a resolution of 0.1-microstrains suitable for the real time structural health monitoring of rotorcraft blades.

Keywords: Rotor Blades, Structural Health Monitoring; Composites; Multi-Point Strain and Load Sensing; Wireless Data Transmission; Battery or Energy Harvested Power.

Introduction

Composite materials and structures are widely used in the Aircraft Industry and have allowed engineers to overcome substantial weight reduction obstacles. Weight is everything when it comes to heavier-than-air machines, and designers have striven continuously to improve lift to weight ratios since man first took to the air. Composite materials have played a major part in weight reduction, and today there are three main types in use airplanes including fiberglass, carbon fiber, and fiber-reinforced matrix systems or any combination of any of these. The constituent materials retain their identities in the composites and do not otherwise merge completely into each other. Together, the materials create a 'hybrid' material that has improved structural properties over metallic structures. Composites are versatile, used for both structural applications and components, in all aircraft, rotorcraft, and spacecraft, from hot air balloon gondolas and gliders, to passenger airliners, fighter planes and the Space Shuttle. Applications range from complete airplanes such as the Beech Starship, to wing assemblies, helicopter rotor blades, propellers, seats and instrument enclosures.

Composite materials based aircraft and rotorcraft structures are progressively increasing in New Commercial aircraft such as the Boeing 787, the AirBus A380, and military aircraft such as the

B-2 stealth bomber, the F-22 & F-35 advanced tactical fighters, the F-117A stealth fighter, the V-22 tilt-rotor, and the Chinook H53 class military helicopters make extensive usage of composites with over 50% of the airframe structure made of composite materials.

In advanced rotorcraft structures such as those found in the CH-53K, H-60, H-1, V-22 and others, the main rotor blades and associated rotating hardware are some of the highest dynamically loaded parts found on rotorcraft. These dynamic parts have historically been hard to instrument without a significant weight penalty and are often inspected at intervals. A system capable of monitoring true strains, as well as damaging impacts during rotorcraft operation, without the usually associated weight penalties would have enormous benefits. Usage information taken from this system would enable implementation of on-site health and usage monitoring (HUMS) of the rotor system, allowing maintainers to be alerted when components are about to show signs of degradation, resulting in increased safety and reduction in unnecessary maintenance. Additionally, faster maintenance turnaround would translate into improved aircraft availability and lower life cycle costs.

Fiber Optic Sensors for Structural Health Monitoring

Fiber optic sensors also called optical fiber sensors use the intrinsic properties of an optical fiber as the sensing element. These sensors are used to sense some quantities like strain, temperature, pressure, vibrations, displacements, rotations, acceleration, and acoustics among others. They can also be used for chemical sensing applications. The ideal usage of fiber optic sensors in SHM applications is the possibility of realizing a fused sensor network system with multifunctional measurement capability in contrast to conventional electronics sensors. Specifically, fiber optic sensors can perform static strain measurement in a large scale (thousands of µstrains) at a low speed (200 Hz) for potential operational load monitoring as well as ultrafast strain measurement in a small scale (tens of fentostrains) at an ultra-fast speed (500 kHz) for potential damage detection. This significantly reduce the complexity of in-situ SHM systems and the costs related to SHM.

Optical fiber sensors offer significant advantages to monitor strain, temperature, vibration, and impacts associated with excessive loads, fatigue, and structural damage within an entire rotor blades structure. In order to perform impact detection, degradation diagnostics, and fatigue damage monitoring, the low weight of the fiber sensor, and its immunity to electrical interference, are major benefits to this sensing method. In addition, these optical fibers can be embedded into composite material structures such a rotorcraft blades during their construction, giving them a layer of protection from environmental factors. Optical fibers can measure much larger strain ranges than traditional foil strain gages. An optical fiber system could also be used to assist blade tracking. By embedding these sensors into a rotor blade, the safety and cost of rotorcraft operations would be greatly improved.

Fiber optic strain gauge (FBG-sensor) technology offers a very feasible alternative solution to electrical strain gauges since they are produced within a flexible and mechanically durable optical fiber typically of the order of 50-µm to 250-µm diameter that can be readily surface mounted or embedded within composite material structures. Distributed FBG sensors provide high spatial resolution (> 1-cm) sensing over short (10's of meters) and long (100's of meters) over a single fiber length span to provide complete global monitoring of the structure. FBG sensors can be surface mounted or embedded within fiber reinforced (FR) composites during the manufacturing of the composite fabric, or structural part, with no effect on the strength of the part providing a closer look at internal hidden defects such as impact damage, fiber fracture, ply-delamination's, and cracks.

Fiber Bragg grating sensors are mass produced in either glass or polymer optical fibers by in-line UV imprinting of a periodic grating "Bragg-grating" within the core of the optical fiber. The periodic grating produces an optical, wavelength-encoded signal whose properties are dependent on the structural, and mechanical load/stress/strain environment of the sensor fiber. The fiber grating is typically 1-cm in length, and multiple gratings, each with a specific active wavelength, can be produced and distributed along the entire length of the optical sensor fiber from meters to kilometers long incorporating 100's of FBG sensors. The attractive properties such as the small size, immunity to electromagnetic fields, and multiplexing ability are some of the advantages of FBG sensors.

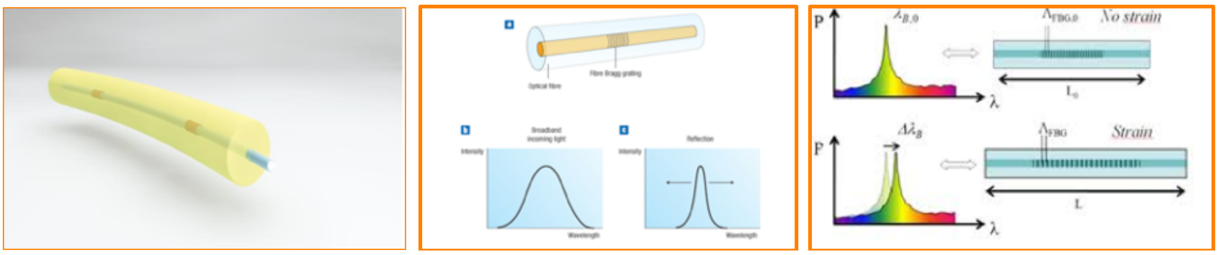

Fig. 2: Distributed Fiber Optic Bragg-Grating Sensors

A major drawback of existing FBG sensor technology is that commercially available FBG sensor interrogation systems are costly, relatively large, heavy, complex, and high-power devices not suitable for most on-board and in-situ aerospace applications where weight, size, and power are critical for operation. The sensor interrogator is the major component within the optical fiber system which drives the weight and power requirements. Mission-ready helicopter load-outs avoid slip rings due to their unnecessary weight and complexity; a fiber system, therefore, must be able to use the limited power available from energy harvesting methods. With a weight of several pounds (and high-power requirements), commercial interrogator units are unusable in the dynamic rotorcraft environment. An interrogator that is much lighter and smaller than these commercial units is desired. The system must be of low volume, light weight, low power, and be capable of interrogating a distributed array of multi-point sensing locations in a single blade and have no moving parts. The sensor interrogator should also be able to withstand the high vibrations and loads found in a helicopter rotor system in which it will be installed. The interrogator must be able to accurately resolve the large blade strains produced by a helicopter blade and be able to obtain data from each sensor at a rate of at least 1 kHz. The interrogator must also be able to operate efficiently under low power or ideally using energy harvested power.

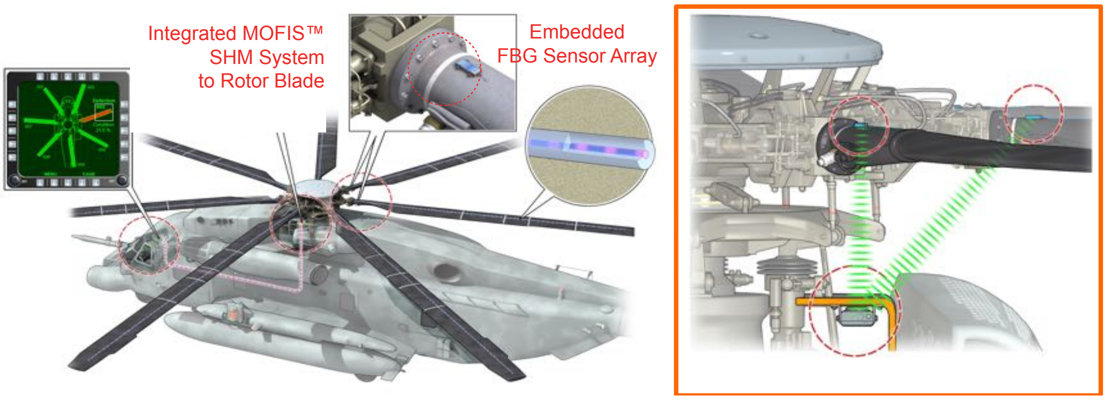

Fig. 2: Fiber Bragg-Grating Sensors for In-Situ SHM of Helicopter Rotor Blades

Small Size, Lightweight, and Low Power
Multichannel Optical Fiber Interrogation SHM System

Based on the need for an aircraft ready fiber optic sensor SHM system, our research group is in the process of developing and demonstrating the performance of an innovative fully integrated with no-moving-parts, ultra-low power, light weight, and miniature size, multi-channel optical fiber interrogation (MOFIS™) structural health monitor system suitable for the in-situ non-intrusive integration to a helicopter composite blades to enable the in-flight distributed multi-point measurement of true-strain, temperature, vibration, and impacts associated with excessive loads, fatigue, and structural damage within the composite blades structure.

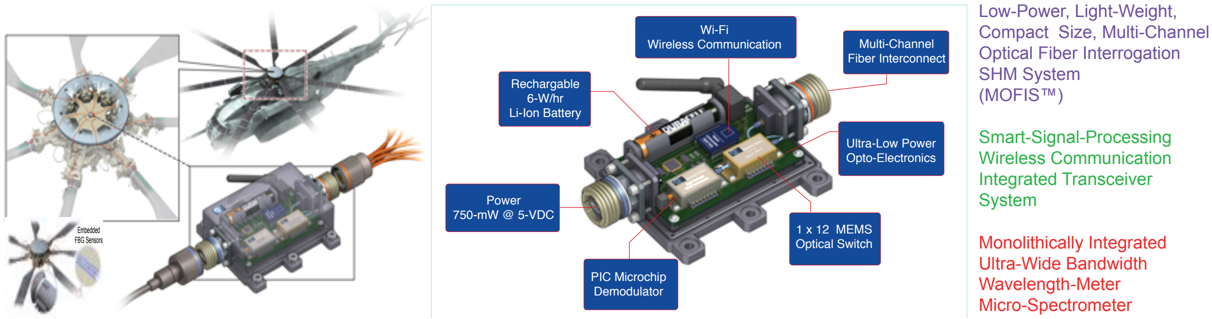

Fig. 3: Miniature, Light Weight, Low-Power, Low Cost, Wireless Optic Fiber Interrogation (MOFIS™) System for the In-Flight Real Time Detection, Localization, and Classification of Fatigue Damage in Helicopter Rotor Blades.

The MOFIS™ SHM system is based on the integration of proven state-of-the-art technologies: 1) monolithic integration of all the MOFIS™ system's passive and active opto-electronic components within a miniature (1-cm^2) photonic integrated circuit (PIC) microchip, 2) the use of a broad-band WDM/TDM demodulator architecture used for the accurate wavelength tracking of a high density array of FBG sensors (>15-FBGs) each with a spectral dynamic range of ±10,000-microstrains, 3) the use of advanced ultra-low power signal processing electronics equipped with embedded neural network algorithms used for the real-time, dynamic (≥20-kHz), and accurate (<0.1-pm) peak-wavelength measurement of the spectral signature of each of the FBG sensors inscribed within the fiber sensor array, and 4) the use of optical switching to provide simultaneous real time measurements of an array of 8- to 12-sensor fibers installed in each of the blades of the helicopter rotor structure.

Compared to conventional FBG sensor interrogation technologies for rotorcraft applications, the MOFIS™ system has many advantages. These include:

- Compact miniature package (0.5-in x 1-in x 2-in), lightweight (<250-gr), ultra-low power (<1-W), and autonomous operation for applications where weight, size, and power are critical for operation;
- Multi-Channel, ultra-wide bandwidth, high resolution, demodulation of a high-density array of FBG sensors (≥ 15-FBGs) inscribed over a single sensor fiber with a wide dynamic range response (±10,000-µstrains/FBG sensor), high accuracy (≤ 0.1-micro-strains), and fast sampling frequencies (DC to 20-kHz).
- Ultra-low power MOFIS™ smart optoelectronics with micro-processor-controlled power management of the interrogator light source, battery power, and capability of using the rotorcraft energy harvested power;
- Reliable and accurate wireless data transmission from a MOFIS™ transceiver unit located in the moving frame of the rotor to a nearby MOFIS™ data-logger receiver located in the

stationary frame of the rotor using low power wireless communication protocols (Wi-Fi, ZigBee, or Bluetooth);

- Low cost automated manufacturing common in the semiconductor IC and telecommunications components industries translates into a low-cost device allowing the ability to permanently integrate the MOFIS™ system into each of the blades of a rotorcraft helicopter.

When developed and airborne qualified the light weight (<300-g), compact (≤ 200-cm^3), ultra-low power (≤ 1-W) MOFIS™ SHM system will use available energy harvested power from the helicopter rotor and will wirelessly transmit the acquired and processed sensor structural health data from the rotating frame of the rotor to a remote wireless data-logger receiver/gateway system located in the non-rotating frame of the rotor assembly providing a new and innovative structural health management solution for helicopter rotor blades.

Testing Operational Performance of MOFIS™ SHM Laboratory Prototype

To test the performance of the packaged stand-alone MOFIS SHM laboratory prototype ROI assemble a simulated helicopter rotor test blade that incorporates a high-density (≥15-FBGs) array of FBG sensors for monitoring load, vibration, impact, and potential damage of the blade structure. The composite article test blade was mounted on a high power and speed rotor motor to simulate the high load and vibration condition of the simulated helicopter blade. For these tests, ROI acquired a composite material helicopter blade test article of 100-cm length and instrumented the test article with the MOFIS SHM FBG sensor interrogator, as shown in Figure 4 below.

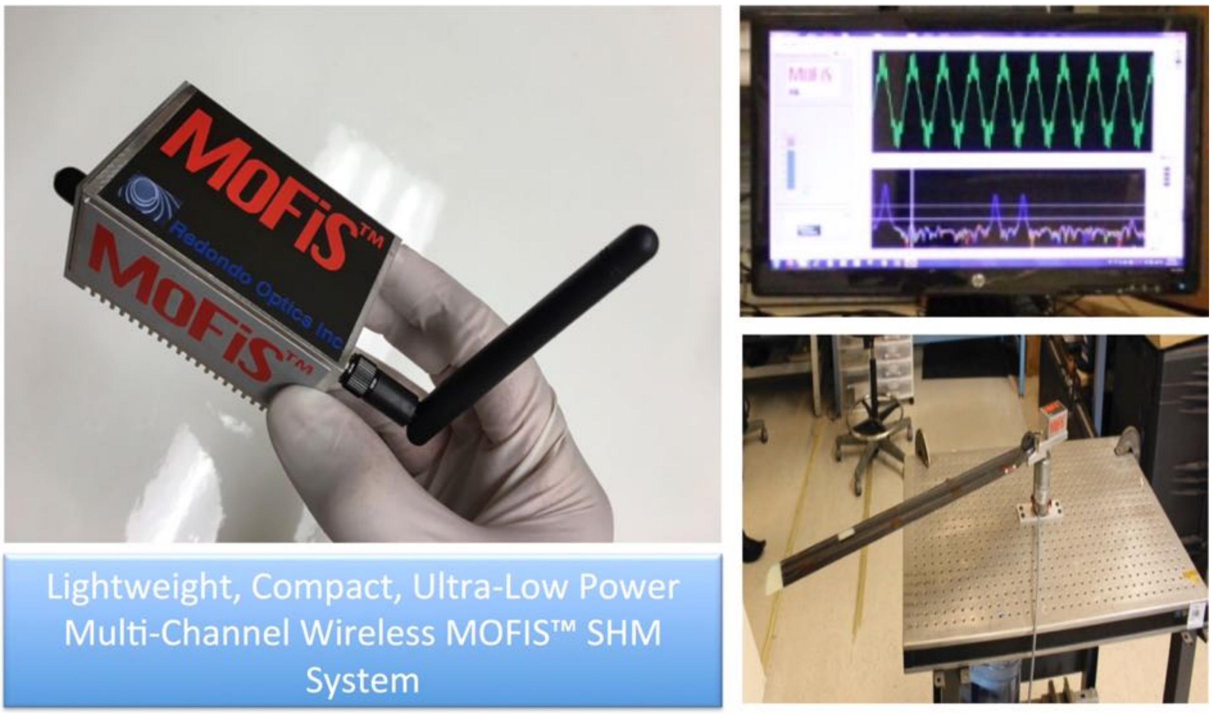

Fig. 4: Performance Testing of MOFIS™ System on a 1-meter Long Simulated Downscale Helicopter Composite Blade.

The MOFIS™ SHM laboratory prototype mounted on the vibrating helicopter blade test article was used to test the status of the FBG sensors surface mounted in the blade test article and use to collect and transmit the process FBG sensor data to a remote MOFIS™ receiver station using a Wi-Fi local area network. The WiFOS™ signal processing board integrates a low power (≤50-mA) Wi-Fi Tx/Rx transceiver to wirelessly transmit the process FBG sensor data through a wireless network architecture to remote PC computers and portable devices connected to the network at sampling rates of 20-kHz/Ch for a four FBG sensor demodulation system integrated with a 1-12 optical switch capable of supporting a 48-FBG point sensor network installed in multiple helicopter blades. Our target is 16-FBG sensor points in each helicopter blade resulting with the capability to monitor three helicopter blades with a single MOFIS-M400 system prototype. The power consumption of the MOFIS M400 system is under 300-mA at 3.7-V.

Summary

The results presented in this paper described on going work towards the development of an innovative light weight, high-speed, and self-powered wireless multi-channel fiber optic sensor (MOFIS™) SHM system suitable for the onboard and in-flight unattended detection, localization, and classification of load, fatigue, and structural damage in advanced composite materials commonly used in avionics and aerospace systems. The MOFIS™ SHM system is based on ROI’s advancements on monolithic photonic integrated circuit microchip technology, integrated with smart power management, on-board data processing, wireless data transmission optoelectronics, and self-power using energy harvesting tools.

ACKNOWLEDGMENTS

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