"Structural Health Monitoring Sensor Development at NASA Langley Research Center"

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Summary

NASA is applying considerable effort on the development of sensor technology for structural health monitoring (SHM). This research is targeted toward increasing the safety and reliability of aerospace vehicles, while reducing operating and maintenance costs. Research programs are focused on applications to both aircraft and space vehicles. Sensor technologies under development span a wide range including fiber-optic sensing, active and passive acoustic sensors, electromagnetic sensors, wireless sensing systems, MEMS, and nanosensors. Because of their numerous advantages for aerospace applications, fiber-optic sensors are one of the leading candidates and are the major focus of this presentation. In addition, recent advances in active and passive acoustic sensing will also be discussed.

Introduction

The application of traditional NDE methods for on-ground inspection of aerospace vehicles contributes greatly to their safety and reliability. However, periodic inspections significantly increase operating expense and vehicle processing time. Further, the need to disassemble and reassemble structural components to allow inspections can lead to damage or degradation of the structure or auxiliary systems (e.g., electrical wiring and hydraulic lines). NASA is focusing on technology development for structural health monitoring (SHM) to address these issues, and to meet demanding goals in increasing aerospace vehicle safety and reliability while reducing operating costs. On-board, real-time SHM sensing systems are central to the larger programmatic goal of Integrated Vehicle Health Management (IVHM). Such sensing systems will minimize the need for periodic NDE inspections, or at least focus these inspections to specific vehicle areas where damage or degradation was indicated. SHM sensors must be able to withstand harsh aerospace operating environments, while having minimal size, weight, and power requirements. Several candidate SHM sensor technologies are discussed in this paper including fiber-optic sensors, and active and passive acoustic methods.

Fiber Optic Sensors

Considering the large acreage of aerospace vehicle structural components, it is a given that extremely large numbers of sensors will be required for on-board structural health monitoring. Fiber optic sensors have been identified as the leading candidate technology for meeting this requirement with minimal weight penalty. Numerous sensor sites can be multiplexed along a single optical fiber, mitigating the complexity and weight inherent with the wiring required for a large number of single ended sensors. Fiber optic sensors also provide other advantages such as the ability to measure many different structural parameters of interest, immunity to electromagnetic interference (EMI), and the ability to operate over very large temperature environments.

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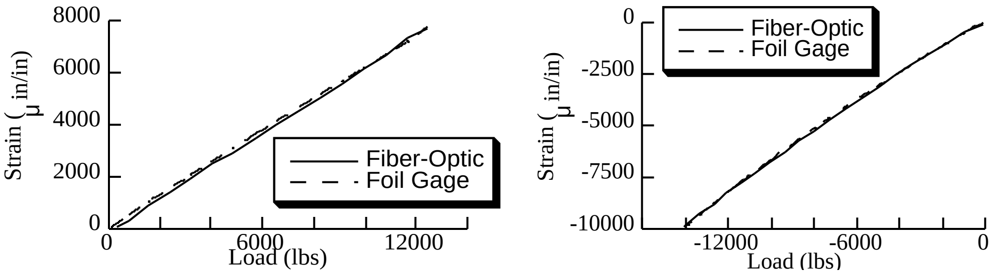
Fiber optic sensors can be separated into two classes for discrete strain and temperature measurement: cavity-based designs and grating-based designs [1]. Cavity-based designs utilize an interferometric cavity in the fiber to create the sensor. Examples include the extrinsic Fabry-Perot interferometer (EFPI), the intrinsic or fiber Fabry-Perot interferometer (IFPI or FFPI), and all other etalon-type devices. Although such sensor designs have been utilized in a wide variety of applications such as in high temperature and EMI environments, they do not allow for multiplexing capability in a single fiber, and thus may be limited for applications requiring large number of sensors.

Most of the research emphasis at NASA Langley has been on the development and application of Bragg grating-based fiber-optic sensors. Bragg gratings utilize a photo- or heat-induced periodicity in the fiber core refractive index to create a sensor whose reflected or transmitted wavelength is a function of this periodicity. The biggest advantage of Brag grating-based sensors (e.g., Bragg gratings) is that they can be easily multiplexed to enable multiple measurements along a single fiber. One approach for multiplexing Bragg gratings is to place gratings of different wavelength in a single fiber and utilize wavelength division multiplexing (WDM). However, the limited bandwidth of the source as well as that supported by the fiber, and the range over which the physical parameter of interest is being measured provide practical limitations on the number of gratings that can be multiplexed in a single fiber with WDM approaches.

A different grating measurement approach, developed at NASA Langley [2,3], provides a significantly increased ability to multiplex gratings. This system, based on the principle of optical frequency domain reflectometry (OFDR), enables the interrogation of hundreds or thousands of Bragg gratings in a single fiber. OFDR essentially eliminates the bandwidth limitations imposed by the WDM technique as all of the gratings are of nominally the same wavelength. Very low reflectivity gratings are utilized, which allow reflections from large numbers of gratings to be recorded and analyzed. By tracking wavelength changes in individual gratings, one is able to measure mechanical or thermal induced strain in the grating. In addition, by applying a coating to the fiber that strains in the presence of a chemical of interest, it is possible to use this Bragg grating measurement system to provide high density chemical sensing. NASA Langley has demonstrated this approach for the sensing of hydrogen using palladium coatings. A sensing system of this type was flight tested on the Space Shuttle [4].

Figure 1 shows measurements of mechanical strain in composite specimens taken from both Bragg gratings and conventional foil strain gages. Good agreement between the gages is observed. For these tests the specimens were at cryogenic temperatures of –320°F. Similar measurements have been made up to temperatures of 500°F, demonstrating the wide range of temperatures over which these sensors can be used.



a) IM7/977-2, Tensile, -320°F. b) IM7/977-2, Compressive, -320°F.

Figure 1. Comparison of strain measurements from Bragg gratings and foil strain gages.

One current limitation of the NASA Langley OFDR measurement system has to do with the speed at which measurements can be made. Currently because of the limited tuning speed of commercially available tunable lasers, the fastest acquisition rates possible are on the order of 1-3 Hz. Thus, the system provides only quasi-static measurements. To address this limitation, work is ongoing to develop high-speed fiber stretching mechanisms to provide high tuning rate tunable Erbium-doped optical fiber lasers. Such fiber lasers can be designed with excellent mode-hop free tuning characteristics needed for use with the OFDR system. Another potential advantage of these lasers is that they can be compact and lightweight, which is an essential consideration for aerospace applications. The fiber stretching mechanism under development utilizes a very lightweight piezoelectric device developed at NASA Langley [5]. This device is known as Thin Layer Composite Unimorph Ferroelectric Driver and Sensor (THUNDER) and is generally much lighter weight than conventional piezoelectric devices such as microstages. As a driver, THUNDER produces physical displacement and/or force in response to a varying applied controlled voltage. For this application, two actuators are used to pull at both ends of an optical fiber containing a Bragg grating as shown in Figure 2, in order to produce a shift in the reflected wavelength. For an actual laser device, this shift in the Bragg grating wavelength would be used to tune the fiber laser. Successful stretching of Bragg gratings has been demonstrated with this device, and further research effort is ongoing to develop tunable lasers.

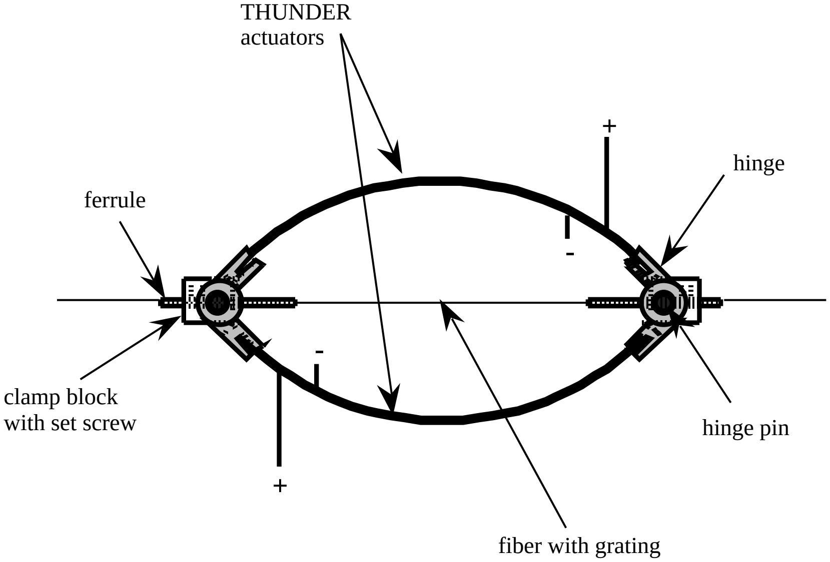


Figure 2. Diagram showing top view of fiber stretcher hardware assembly.

Similar to conventional foil strain gages, fiber-optic Bragg grating sensors respond to both mechanical and thermal strains. In current applications, either the strain or temperature is kept constant and changes in the other parameter are measured, or a separate temperature sensor is used to provide thermal compensation. However, it would be more desirable to be able to separate thermal and mechanical strain effects using only the Bragg grating sensors. To accomplish this, a new technique has been developed using dual-wavelength fiber-optic Bragg gratings.

Two Bragg gratings with different wavelengths are inscribed at the same location in an optical fiber to form a sensor, whose reflection spectrum is shown in Figure 3. By measuring the wavelength shifts that resulted from the fiber being subjected to different temperatures and strains, the wavelength-dependent thermo-optic coefficients and photoelastic coefficients of the fiber were determined. This enables the simultaneous measurement of temperature and strain. In this study, measurements were made over the temperature range from room temperature down to about 10 K, addressing much of the low temperature range of cryogenic tanks, which are an important aerospace application. In these measurements, a structure transition of the optical fiber during the temperature change was found. This transition caused peak splitting of the spectra characterizing the Bragg gratings, and the determination of wavelength shifts was consequently complicated. The effectiveness and sensitivities of these measurements in different temperature ranges are undergoing further study.

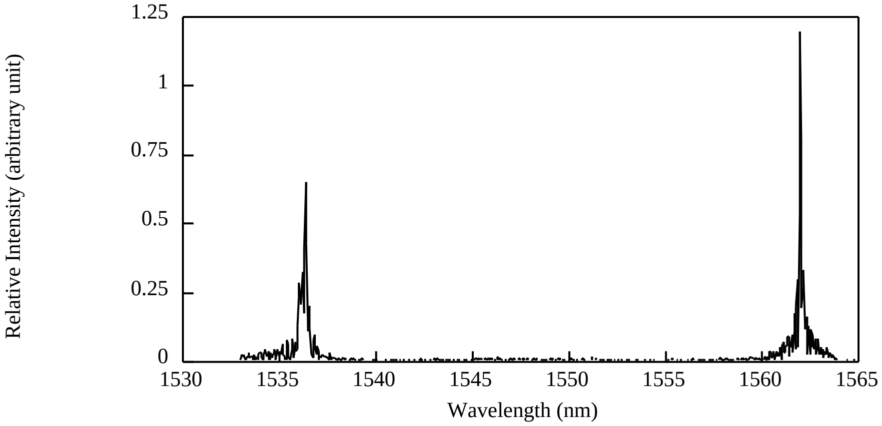


Figure 3. Wavelength spectrum of a dual wavelength Bragg grating sensor.

Another effort ongoing at NASA Langley is the development of photonic crystal fiber (PCF). PCF is constructed in a very different fashion than the usual optical fiber configuration, which has a single core surrounded by a cladding, and then a protective coating. The construction of PCF begins with a preform made from packed tubes arranged in a hexagonal pattern inside a thin outer tube. This preform is then drawn down to fiber dimensions in an optical fiber draw tower to produce fiber configurations such as that shown in Figure 4 [6]. The periodicity of glass and holes in such fiber provides unique light guiding characteristics. PCF has many potential applications including wavelength specific custom designed fibers, high power single mode light transmission, and wavelength converters. However, most interesting for SHM are potential applications of PCF to develop pressure, temperature, and chemical sensors.

Acoustic Sensing

Ultrasonic sensing, applied in both active and passive modes, is another sensor technology area receiving considerable attention. Analysis of actively transmitted ultrasonic signals is a conventional NDE methodology that has long been used to detect and assess damage. However, such approaches use sensors that are scanned over the structure to provide a point-by-point representation of material properties and/or damage locations. Such scanning probe approaches are not currently feasible for continuous, on-board monitoring. Therefore, the use of arrays of permanently attached or embedded ultrasonic transducers, which act dually as transmitters and receivers, is being researched. Ultrasonic signals generated by one transducer are detected by neighboring transducers within an array. Damage along paths between the transducers can be detected, and with more complex analysis methods, material along secondary propagation paths that include reflections from structural boundaries can also be evaluated. The development of the Stanford Multi-Actuator Receiver Transduction (SMART) layer is an excellent example of recent efforts in this area [7]. NASA Langley is investigating the application of these SMART layers as well as working in the development of other sensor concepts based on the use of piezoelectric fibers. The schematic of a prototype piezoelectric fiber based sensor is shown in Figure 5. In addition, Langley is developing models to better understand and predict the propagation of guided mode acoustic waves in thin plate structures, which comprise many aerospace structures. Work is also underway to investigate neural based approaches for connecting these sensors to minimize the data acquisition hardware and efficiently process the data.

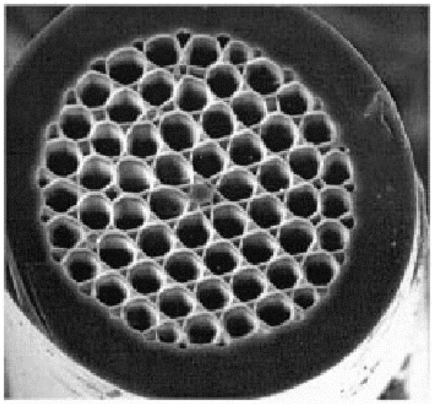


Figure 4. End view of a photonic crystal fiber [6].

Passive ultrasonic monitoring, also known as acoustic emission (AE), also utilizes an array of ultrasonic sensors. The sensor array is used to passively monitor acoustic signals generated by damage mechanisms such as crack growth and impact damage. AE is widely used as a conventional method for off-line structural assessment, and can also be implemented in-situ to monitor a structure while in service. This capability makes it well suited for structural health monitoring. However, considerably more research and development is required to make AE a more viable technology for aerospace vehicle applications. NASA Langley is working on the development of fiber-optic AE sensors [8] and AE multiplexing instrumentation to provide lighter weight measurement systems necessary for flight applications. Also, significant research effort is ongoing to develop propagation models [9] and Modal based AE analysis methods [10] to provide more accurate methods to locate and assess damage, and to discriminate and eliminate extraneous noise signals. Such models are also of benefit for characterization of AE transducers, optimization of sensor placement on a structure, and scaling of AE results from laboratory test coupons to full-scale structures.

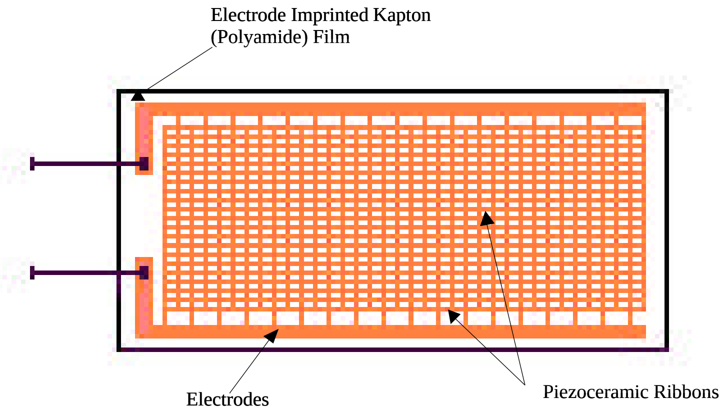


Figure 5. Schematic of a piezoelectric fiber based acoustic sensor.

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