Distributed Multi-Point Fiber Optic Acoustic Emission SHM System For Condition Management Of Aircraft Structures

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Abstract
Acoustic emission is the leading structural health monitoring technique use for the early warning detection of structural damage in advanced aircraft structures associated with impacts, fatigue, cracks, fractures, corrosion, and delaminations. This paper describes progress towards the development and qualification of a distributed fiber optic acoustic emission sensor (FAESense™) system based on the use of a novel adaptive and dynamic reconfigure two-wave mixing (TWM) interferometer produced on a photonic integrated circuit (PIC) microchip. The FAESense system uses a distributed array of miniature and minimally invasive fiber Bragg grating sensors, embedded or surface mounted on a composite or metal aircraft structure, used for the detection and localization of acoustic emission events associated with structural damage. The TWM interferometer interrogates the status of the array of FBG sensors and demodulates the small wavelength shifts of the FBG sensors associated with the detection of acoustic emission waves in the presence of quasi-static strain and temperature variation effects. The FAESense™ system represents a new, robust and reliable, technology that can be used for the remote structural health monitoring and prognostics of aircraft SHM applications.

1. Introduction

Acoustic emission (AE) is one of the proven methods used for the detection of cracks, fractures, delaminations, and prognostics indication of potential failure of a composite material structures. However, current AE systems based on electronic PZT transducers suffer from various limitations. Conventional electronic AE transducers are bulky and complex to operate with need of near proximity pre-amplifiers and signal conditioning units for each sensor that results in a bulky set-up and requires an extensive electrical wiring infrastructure that often hinders their use in practical avionics applications.

Recent advances in fiber optic Bragg grating (FBG) acoustic emission sensors have demonstrated capabilities to detect AE waves with comparable performance as electronic PZT transducers, but with the added advantages of using a minimally invasive micron size FBG transducer deployed over a single, EMI insensitive, fiber optic network incorporating a large array of sensors used for complete global and local coverage of the composite structure. Our group is expanding on its proven use of photonic integrated circuits (PIC) microchip technology for the development of miniature, lightweight, and low power FBG sensor interrogators, and expanded to integrate at the microchip level a new adaptive and dynamically reconfigured FBG sensor demodulation methodology.
based on photorefractive two-wave mixing (TWM) interferometry techniques previously
demonstrated by Professor Krishnaswami for the detection and discrimination of passive,
low frequency (DC) events (stress and temperature) to highly sensitive ultra-wide
frequency (DC to 1-MHz) vibration and acoustic emission events. [3]

1.1 Advanced Composites in Aircraft Structures

The extensive use of composite materials in modern commercial aircraft such as the
Boeing 787 and the AirBus A380, and military aircraft such as the Joint Strike Fighter F-
35 Lightning makes them some of the most advanced aircraft ever built. And while these
aircraft are approved for flight, safety officials are concerned about the long-term viability
of those materials, which are now being used in the aircraft's wings and fuselage.

Composite materials like carbon fiber and plastics have been used in aircraft components
for years now, but concerns have been raised—in a report published by the U.S.
Government Accountability Office—that the composite structures that make up the wings
and fuselage are being tested against safety standards designed for planes with metal
structures. Over time metal will bend, flex and stretch before failing, providing safety
inspectors with telltale signs that repairs are needed before there's a serious problem. But
composite materials behave differently, and officials are worried that inspectors simply
don't know what signs might allude to impending structural failure. Even the risk factors
of something as simple as a dent aren't fully understood at this point, and there are further
concerns that maintenance workers aren't properly equipped when it comes to repairing
these materials. As a result, it has become apparent to aircraft safety, structural health,
and maintenance engineers that a new generation of in-flight smart structural health
monitoring techniques are necessary to develop an advanced capability to detect, localize,
and classify damage in aircraft composite structures subject to representative loading and
environmental fly conditions to fulfill the operational structural safety requirement
objectives.

Figure 1. Potential applications of fibre optic acoustic emission sensor (FAESense™) system for
real time early stage condition monitoring and inspection, and failure prevention of modern
composite aircraft structures.

2. Distributed Fiber Optic Acoustic Emission Sensor (FAESense™)
System
Redondo Optics Inc. (ROI) under the support of the U.S. Navy \cite{4,5} and with the collaboration of Professor Sridhar Krisnaswami from Northwestern University has been in the process of developing a smart in-flight fiber optic acoustic emission sensor (FAESense™) structural health monitoring system suitable for the onboard unattended detection, localization, and classification of damage in composite aircraft structures induced by shock events, impacts, fracture, cracks, voids, and delaminations that could potentially lead to catastrophic damage in new and aging aircraft infrastructures, as shown in Figure 2. ROI’s multi-channel wireless FAESense™ system is based on the innovative integration of proven state-of-the-art technologies that include: 1) the use of miniature in-line fiber Bragg grating (FBG) acoustic emission sensors unintrusively distributed at multiple locations of an entire aircraft structure; 2) the use of an innovative and highly integrated, adaptive and reconfigurable) photorefractive two-wave-mixing photonic integrated circuit (PIC) microchip used for the demodulation of dynamic acoustic emission signals in the presence of large quasi-static strain, temperature, and vibration gradients; 3) the use of a compact, aircraft ready, high speed data logger and communication optoelectronics transceiver unit used to transmit the FBG detected AE signals to the remote health and usage monitoring system (HUMS) command station of the aircraft; and 4) the use of “smart” adaptive neural network wavelet analysis algorithms, embedded within the microprocessor controller of the FAESenseTM interrogation transceiver electronics, used for data reduction, identification, localization, and classification of the type of structural damage identified of the aircraft composite structures.

At the heart of the FAESense™ system is a distributed array of miniature (250-µm diameter) FBG acoustic emission sensors that can be conveniently surface mounted or embedded at multiple locations of an entire aircraft composite structure. To interrogate the status of the AE sensors, the FAESense™ transceiver system uses ROI’s proprietary monolithic semiconductor photonic integrated circuit (PIC) microchip technology that integrates at the optical chip level all of the passive and active opto-electronic functionalities of the system, such as, light source, optical amplifier, phase-shifters, photodetector array, WDM demultiplexer, etc., and specifically a highly novel and ultra-sensitive two-wave-mixing (TWM) interferometer waveguide design that enables the broad-band frequency demodulation of FBG acoustic emission sensor signals in the presence of extreme strain, temperature, and vibration conditions. The adaptive TWM interferometer demodulation methodology allows the measurement of broad frequency (1-kHz to 500-kHz) acoustic emission events, while dynamically compensating for passive quasi-static strain, temperature, and vibration induced gradients.
2.1 Dynamically Reconfigurable and Adaptive Two-Wave-Mixing Interferometry Acoustic Emission Demodulation Solution

In the FAESense™ system, ROI has expanded on the use of its integrated optics microchip technology and incorporated a new dynamically reconfigured FBG sensor demodulation methodology based on the adaptive two-wave mixing (TWM) interferometry techniques. The adaptive TWM interferometer shown schematically in Figure 3, and whose concept was previously demonstrated by Professor Krishnaswami, [3] is a fast and effective method to demodulate the dynamic wavelength shifts of the peak reflectivity wavelength of the FBG sensors in the presence of passive quasi-static temperature and strain drifts. The reflected signals from the FBG sensor array are received by the PIC microchip as they traverse unequal path lengths in the interferometer prior to mixing in the photorefractive cavity (PRC) of the interferometer. Any wavelength shift of the light reflected from the FBG sensor array results in an equivalent “phase” shift between the pump and the sample signals because they travel unequal optical paths. The relationship between the wavelength shift ($\Delta \lambda_B$) of the FBG sensor and the relative phase shift ($\Delta \phi$) induced by the unbalanced interferometer is given by:

$$\Delta \lambda_B = \frac{\Delta \phi(t) \lambda_B^2}{2\pi d}$$  \hspace{1cm} (1)

where $\lambda_B$ is the peak center reflectivity wavelength of the FBG sensor, and $d$ is the optical path length difference (OPD) of a Mack-Zhender TWM interferometer. The expression shown in equation 1 shows that there is a direct linear relationship between the dynamic wavelength shift of the FBG sensor and the detected phase shift signal at the photoreceiver.
Here, the photoinduced interference grating generated within the PRC acts as a dynamic bandpass filter that enables only the transmission of the high frequency spectral shifts of the FBG sensor associated with AE events, while reflecting back all other passive, low frequency, spectral shifts of the FBG sensor associated with strain and temperature background variations. The photoinduced interference grating bandpass filter is dynamic such as it automatically reconfigures to the slow passive changes of the spectral signature of the FBG sensor. It also allows multiple interference gratings produced from the signal of each of the gratings in the FBG sensor array to be photogenerated simultaneously within the PRC resulting in a multi-dimensional high frequency FBG sensor demodulation device. The dynamically tunable PRC can be regarded as an adaptive high-pass optical filter that selectively transmits any high frequency events in the mixing signals and rejects the passive quasi-static changes in the FBG spectral signature, without the need of any external stabilization, hence enabling the real time detection of acoustic emission events, as shown in Figure 4.

3. Experimental Test Results

The performance of the FAESense™ fiber Bragg grating acoustic emission interrogation system has been extensively tested against standard electronic PZT AE transducers under a variety of laboratory AE experiments and ASTM standard pencil lead break tests. The experimental test set-up is shown in Figure 4. In this set-up, a distributed fiber sensor array incorporating five FBG sensors was surface mounted using standard strain gauge epoxy to a 2.5-ft long aluminum cantilever test plate. The separation between each of the FBG sensors progressively varied from 1-in, 3-in, 10-in, 1-ft, and 2ft along the cantilever plate. The cantilever test plate could be excited either by vibrating the plate, by using a power microphone positioned at the end of the beam. This type of excitation induces strain events on the FBG sensors mounted on the plate on the range of ± 1500-microstrains. The cantilever plate was also equipped with a broadband PZT AE excitation transducer used to excite acoustic emission signals in the range of 50-kHz to 500-kHz. In a typical experiment, the microphone positioned at the end of the plate and was used to excite strain and vibration events at low frequencies, i.e., 60-Hz, while the PZT AE transducer simultaneously excites high frequency AE events. This experimental protocol was used to demonstrate the capability of the FAESense™ system to detect AE events in
the presence of quasi-static strain changes induced by the microphone low frequency excitation.

Figure 4. Cantilever beam acoustic emission experimental test set-up for monitoring performance of FBG sensor array to detect acoustic emission events induced by a PZT transducer excitation, or by a pencil lead break test.

To monitor the generated AE signals by the PZT AE pulser, the cantilever plate was also equipped with a reference PZT AE receiver. In this way the signals detected and processed by the FAESense™ system could be compared and time synchronized to the reference AE PZT sensor. To synchronize the FBG sensor demodulated optical signals with the PZT reference signals, the system uses a signal generator connected to the PZT transducers, exciter and receiver, that connects to a monitoring oscilloscope. Similarly, the TWM PIC microchip test article connects to transimpedance amplifier (TIA), used to monitor the output of the photodetectors on the PIC microchip that connects to the monitoring oscilloscope. The TIA also connects to a fast data sampling (2-MHz) data acquisition card that connects to a computer for data acquisition. Using this experimental set-up, ROI was able to test several assembled TWM PIC microchips under a variety of test conditions to demonstrate the ability to detect acoustic emission events in the presence of strain and temperature variants. To validate the performance of the TWM PIC microchip, ROI also conducted similar tests at the laboratory facilities of Professor Krishnaswami at Northwestern University. The validation test confirm the results obtained at ROI that demonstrated the ability to detect high frequency (50-kHz to 500-kHz) AE events using a single channel photorefractive TWM PIC microchip.

The results of the AE tests have demonstrated that the surface mounted FBG AE sensors show comparable detection to AE waveform signatures as the PZT AE transducer. Figure 5 shows typical experimental results when exciting the cantilever beam using a 100-kHz and a 500-kHz acoustic emission signal. The time domain plot shows the time trace of the PZT actuator (exciter), the PZT AE receiver, and the signal from the FBG sensor. From the plot it can be noticed that the time domain response of the FBG sensor is comparable to that of the PZT AE transducer, with the main difference related to the signal-to-noise difference between the two. Preliminary testing has shown that the FBG sensor exhibits a 10-x higher SNR than the PZT AE sensor. This results where obtained
using a plain FBG sensor fiber (250-µm diameter) glued to the surface of the cantilever beam. It is expected that custom packaging of the FBG sensor, as well as custom design of the FBG periodic structure, may improve the SNR of the FBG AE sensor system to compare levels as the PZT AE transducer. ROI is currently investigating custom packaging techniques that can be used to enhance the acoustic emission sensitivity of the FBG sensor.

Figure 5. Dynamic and adaptive TWM demodulation of acoustic emission signatures using FAESense™ system compared to a reference PZT AE transducer.

ROI also proceeded to test and demonstrate the performance of a multi-channel FAESense™ system to measure the simultaneous response of the distributed array of FBG sensor transducers mounted on the cantilever plate when excited by the PZT transducer. Figure 5 shows the response of the multichannel FAESense™ system to a 100-kHz acoustic emission signal excitation. As shown in this figure, all of the FBG sensors detected the AE signal excitation with comparable frequency response to that of the reference PZT AE transducer. Variations in the shape profile of the detected 100-kHz AE signal were related to the distance in between the FBG sensor and the PZT AE exciter. The results of this tests demonstrated the multi-channel deistiebuted detection capability of the FAESense™ system demodulator.
We also conducted a series of impact events in a graphite composite material test panel to compare the dynamic response of the FAESense system distributed FBG-AE sensors versus the response of standard PZT AE transducers, as shown in Figure 6. The results in this plot shows the response of the various sensors elements along with the corresponding time-of-flight delay response of the order of micro-seconds in between sensor elements due to the distance variation of the sensing element position on the test plate from the location of the impact source.
of pencil lead break tests to observe the response of the FAESense system to a pencil lead break excitation. Figure 6 shows the response of the multi-channel FAESense system when the cantilever beam plate was excited by a pencil beak event. As shown in the Figure, the multi-channel FAESense system readily respond to the pencil lead acoustic emission impulse with the expected characteristic AE signatures, with maximum frequencies observed at 210-kHz.

Figure 7. Demonstration of TWM PIC Microchip AE Detection Performance for a single FBG sensor array mounted on PZT Cantilever Plate and excited by a standard “Pencil Lead Break Test “on PZT cantilever beam.
The results of the conducted AE tests shown that the FAESense™ system is suitable for the multi-point detection of AE events using a distributed array of FBG sensors representing a next generation fiber optic sensing technology that is environmentally robust, reliable, and suitable for use in structural health monitoring and prognostics of new and aging commercial infrastructures. The current low cost of FBG sensors production, the availability of high-quality FBG demodulation system, and practical sensor embedding and packaging techniques are the cores for the FAESense system to be widely popularized for real time monitoring of new and aging infrastructures.

4. Conclusions

At the conclusion of these tests results it was demonstrated that the developed multichannel FAESense™ system TWM PIC microchip concept is suitable for the demodulation of FBG sensor signal and for the detection of acoustic emission events induced by a PZT AE exciter with comparable performance as a standard AE PZT transducer, or by the standard pencil lead break test, in the presence of quasi-static strain induced variants on the detected FBG sensor signals.

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References and footnotes