Lamb wave-based damage detection of composite shells using high-speed fiber-optic sensing

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ABSTRACT

A Lamb wave-based damage identification method called damage imaging method for composite shells is presented. A damage index (DI) is generated from the delay matrix of the Lamb wave response signals, and it is used to indicate the location and approximate area of the damage. A piezoelectric actuator is employed to generate the Lamb waves that are subsequently captured by a fiber Bragg grating (FBG) sensor element array multiplexed in a single fiber connected to a high-speed fiber-optic sensor system. The high-speed sensing is enabled by an innovative parallel-architecture optical interrogation system. The viability of this method is demonstrated by analyzing the numerical and experimental Lamb wave response signals from laminated composite shells. The technique only requires the response signals from the plate after damage, and it is capable of performing near real-time damage identification. This study sheds some light on the application of a Lamb wave-based damage detection algorithm for curved plate/shell-type structures by using the relatively low frequency (around 100 kHz) Lamb wave response and the high-speed FBG sensor system.

Keywords: Damage detection; Lamb wave; composite shells; piezoelectric actuators; fiber optic sensors; optical interrogation; damage imaging.

1. INTRODUCTION

Vibration based techniques[1, 2], particularly Lamb wave based methods using piezoelectric actuators and sensors[3] are being increasingly used for damage detection, e.g., of delamination[4], in composite materials[5-7]. In this paper, we further discuss and given examples of the replacement of the piezoelectric sensors by fiber Bragg grating (FBG) sensors. While several groups have recognized the possibility of using fiber Bragg grating (FBG) acousto-ultrasonic sensors[7-10], the technology remains as yet under-exploited and a range of different methods based on the detection of Lamb waves may be used. For example, in Reference 11 for metallic structures, we adopted a spectral method analogous to electromechanical impedance methods. In this paper for composite structures with well-defined boundaries we found a time-of-flight approach to be appropriate. A key requirement for practical implementation is a high sampling rate FBG interrogator that provides simultaneous detection for multiple FBGs so as to determine relative phases.

In Sec. 2, we review previous work. In Sec. 3, we describe proof-of-concept flat composite plate testing. In Sec. 4, we describe curved composite plate testing. Conclusions are presented in Sec. 5.

2. REVIEW OF PREVIOUS WORK

Fiber Bragg grating (FBG) sensors have been extensively investigated for its application in structural health monitoring in the past decade. A typical FBG sensor has a gage length of 5-10 mm, a series of parallel gratings with 0.5 μm or so period printed in the core of an optical fiber. When a broadband light is illuminated into the fiber, a narrow wavelength range will be reflected due to the refractive index change induced by grating. The change of the reflected wavelength indicates the status of the FBG sensors such as strain[12] and temperature[13, 14].

FBGs have significant advantages over conventional electrical sensors, such as piezoelectric accelerometers and resistive strain gauges:

1. FBGs are immune to electromagnetic interference (EMI).
2. FBGs are lightweight and small in size, suitable for being embedded into or attached to a structure.

Smart Sensor Phenomena, Technology, Networks, and Systems Integration 2014, edited by Wolfgang Ecke,
Kara J. Peters, Norbert G. Meyendorf, Theodoros E. Matikas, Proc. of SPIE Vol. 9062, 906214 · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2058142

3. No additional wires are required to connect sensors to the data acquisition system since the fibers themselves act as both sensing and transmission element.
4. FBGs have excellent immunity to harsh environmental conditions, including weather, water and corrosion.
5. FBGs have attractive features such as multiplexing capacity and durability.
6. FBGs offer a self-referencing, absolute measurement scheme since FBGs provide wavelength information which is an absolute parameter.

FBGs have been successfully developed and employed in structural healthy monitoring in metal, concrete and composite structures. They can be configured to measure strain, temperature and moisture in different cases. Several review papers on recent application of FBGs are available[14-16].

For structural damage identification, the strain measurement ability is of the main interest. This review will mainly focus on the various applications of FBGs in damage identification using their strain sensing ability. These applications can be categorized into three categories:

1. FBG-based modal testing for damage identification
2. FBG-based ultrasonic non-destructive testing for damage identification
3. Other FBG-based damage identification techniques

2.1 FBG-based modal testing for damage identification

Modal analysis techniques have been extensively employed in structural damage identification for many years using conventional accelerometers or strain gauges. It is intuitive to apply FBGs to damage identification through modal testing due to its excellent performance in dynamic strain measurement.

Cusano et al.[17] used embedded FBGs and an impact hammer to perform an experimental modal analysis on an aircraft wing model. The experimental results confirmed that the FBGs can be successfully employed to measure the modal parameters of complex structures. Capoluongo et al.[18] used FBGs to conduct modal analysis and damage detection on a sample structure obtained by joining two steel bars. The result showed that FBGs can retrieve mode shapes up to frequency of 1.5 kHz. The difference of modal frequencies and FRF amplitudes can be used for detecting damage location and damage level.

Park et al.[19] applied the modal flexibility-based damage detection approach for damage detection and localization on a steel beam using FBG sensors. Their result demonstrated that the strain-flexibility approach using dynamic strain measurement from short-gage FBG sensors can only detect and localized multiple small damages near the sensors in a very limited range.

One important application of FBG-based technique is by considering the distributed long-gage fiber optical systems developed by Wu and Li[20-22]. The system is developed by extending the gage length of fiber Bragg grating (FBG) from 10 or 20 mm to several centimeters or more and then arranging the long-gage FBG sensors in series. The data provided by long-gage FBG is the so called “dynamic macro-strain”, which is in fact an average strain over the sensing area. Li and Wu[20, 21] proposed a two-level damage identification strategy based on dynamic macro-strain response. First, the modal macro-strain vector (MMSV) was extracted from dynamic macro-strain time-series response from distributed long-gage fiber optic sensors. A damage index similar to strain energy method by Stubbs is constructed using MMSV to locate damage with a spatial resolution of the gage lengths of FOS. Then, the finite element model updating technique was utilized to locate damage with a spatial resolution of the element sizes and to quantify damage based on the first few natural frequency changes. Furthermore, Li and Wu[23] proposed a model-free damage identification method for beam-like structures based on distributed long-gage fiber optic sensors. A normalized MMSV can be constructed from the modal macro-strains (MMS) in a certain mode. Then, a damage index vector is defined as the relative change of the normalized MMSV due to damage. The damage index can be directly used to locate damage. A polynomial curve representing the relation of the damage index versus damage extent was suggested for damage quantification. It was verified numerically and experimentally that the same polynomial curve can be applied regardless of damage locations, scenarios, sensor placement, reference sensor selection and structural model.

2.2 FBG-based ultrasonic non-destructive testing for damage identification

Ultrasonic non-destructive testing is one important method for structural damage identification. Traditional ultrasonic testing usually employs piezoelectric actuators and sensors to generate and capture the ultrasonic wave, respectively. Recent studies showed that FBGs can also be effectively used as ultrasonic sensors for ultrasonic testing.

De Waele et al.[24, 25] conducted strain monitoring and damage detection in filament wound pressure vessels using FBGs, an acoustic emission detector and a pressure transducer. They concluded that the optical fiber Bragg-sensors are effective in strain monitoring and much more reliable compared to traditionally-used electrical-resistance strain gauges.

Takeda et al.[26] developed a FBGs-based damage detection system using small-diameter optical fiber. In this system, Lamb waves in a CFRP laminate are generated by a piezo-ceramic actuator and received by FBGs. It is suggested that through the theoretical simulation, the gage length of FBG should be shorter than 1/7 of the ultrasonic wavelength to capture the Lamb wave mode. It showed that a new mode (accelerated mode) introduced by delamination appears between S0 (symmetric) and A0 (antisymmetric) mode. The delamination length can be evalutated from the changes in the amplitude ratio and the time of flight of the new mode. Furthermore, FBGs were embedded in a double-lap type coupon specimen for debonding detection. The debonding progress can be evaluated quantitively through the continuous wavelet transform of the received waveforms. The detail of the ultrasonic test for debonding detection and its further application to a skin/stringer structural element of airplanes were described in [27].

Tsuda et al.[28] used Lamb waves to detect impact damage in a cross-ply CFRP. Lamb waves in the CFRP laminate were generated by a piezo-ceramic actuator and received by FBGs. The frequency characteristics of the waveform received by FBGs were analyzed to evaluate the interaction between Lamb wave and damage. The results were further compared with those obtained by piezoceramic sensors. It showed that the FBG-based system is effective in impact damage detection of CFRP and comparable to piezoceramic-based system in ultrasonic damage detection. Tsuda [10] also compared two types of FBG ultrasonic sensing system using different light source: a broadband light source and a tunable laser source. It was shown that the system with a tunable laser source has higher sensitivity to ultrasonic wave than the broadband light source.

Lee et al.[29] applied the strain-free mobile FBG ultrasonic receiver to detect impact-induced delamination in a CFRP laminate. The mobile FBG sensors can slide over the target surface, together with the mobile PZT ultrasonic actuator. Their experiment showed that the mobile FBG sensor can be used for the acoustic characterization and the fast selection of optimal sensor locations for constructing a built-in SHM network using FBGs. Furthermore, the mobile FBGs can be also used for precise damage detection due to its high spatial resolution.

Lee et al.[30] investigated the birefringence effect in the two typical installation technique of FBG sesors in ultrasonic testing: surface-mounting and embedding configurations. It is shown that the glue-induced low-birefringence results in loss of sensitivity in ultrasonic measurement. Simple and effective solutions of two installation configurations for removing the birefringence effect were proposed.

Li et al.[31] investigated Lamb wave-based damage detection for composite laminates using two different fiber optical sensors: fiber Bragg gratings (FBG) and Doppler effect-based fiber optic (FOD) sensors. The Lamb waves were generated by a piezoelectric actuator in a quasi-isotropic CFRP laminate. Experimental results showed that both types of sensors can be applied in Lamb wave sensing and damage detection in CFRP laminates. The signal-to-noise ratio (SNR) captured by an FOD is relatively higher than that by an FBG. The FOD is sensitive to the damage-induced fundamental SH0 (horizontal-shear) wave; while FBG is not due to its direction-dependent characteristic.

Betz et al.[32] use the propagation of Lamb wave to detect damage location in plate-type structures. A tunable laser was used for interrogation of the FBGs. The directional responses of FBGs to Lamb waves were captured by mounting three of FBGs in a rosette configuration. Two suitably located rosettes were used to locate the damage. A genetic algorithm (GA) was then used to analyze the precise location of the damage and to account for any ambiguities for the Lamb wave measurement. The experimental results exhibited a good agreement with the actual position of the damage.

2.3 Other FBG-based damage identification techniques

There are also other FBG-based damage identification techniques available in literature. Most of them use FBG for strain monitoring and try to detect damage by comparing the reference signal in the intact state and the response signal in the damaged state.

Takeda et al.[33] used small-diameter FBGs for detection of the delamination in CFRP. The reflection spectra from FBGs were measured at various delamination lengths through four-point bending test. Experimental results showed that the intensity ratio in the spectrum is an effective indicator for the predication of the delamination length.

Minakuchi et al.[34] embedded a small-diameter FBG sensor into the adhesive layer of a honeycomb sandwich structures for debonding detection. During the curing process, the reflection spectrum was distorted because the formation of fillets induced non-uniform strain distribution in the adhesive layers between the core and the face sheet. The debonding process released this non-uniform strain to let the reflection spectrum recover to its original shape. Hence, debonding can be detected with high sensitivity in real time from the recovery in the shape of reflection spectrum.

Lin et al.[35] used FBG sensors to investigate the *in-situ* characteristics of the hydration process period and the curing process of highway concrete bridge construction. Montanini and D'Acquisto[36] used two coupled FBG sensors for simultaneous measurement of both the temperature and strain in a GFRP laminate. The temperature and strain can be obtained by decoupling the change of wavelength induced by temperature from that induced by strain.

3. PROOF-OF-CONCEPT FLAT COMPOSITE PLATE TESTING

3.1 Lamb wave-based Damage Imaging Method

To demonstrate the damage imaging method, two rectangular CFRP composite plates are investigated in this study, one with localized delamination, and the other as healthy. The dimensions of the plates and the delamination are shown in Figure 1. Both the plates are $[0/90]_4$ carbon/epoxy composite laminates with thickness of 1.78 mm, $E_{\text{carbon}} = 235.0$ GPa, $E_{\text{epoxy}} = 3.4$ GPa, $V_{\text{f}} = 55\%$. The bottom layer of the damaged plate is delmaminated in an area of 36 mm × 40 mm, as shown in Figure 1. A PZT actuator is installed at the center of the plate to generate the omni-directional Lamb wave, and four FBG or PZT sensors are installed at four corners to capture the Lamb wave signal. A tone burst signal with 3.5 cycles of 50 kHz sine wave is sent by the actuator to excite the A_0 mode lamb wave. The response is collected by four sensors. It should be noted that it is difficult to generate a pure single mode A_0 Lamb wave in a plate due to the multi-mode nature of Lamb wave. When the plate is excited at the frequency below the cutoff frequency of A_1 mode, the A_0 and S_0 mode lamb wave always co-exist inside a plate. However, using the frequency-tuning technique, it is possible to maximize the amplitude ratio between the A_0 and S_0 mode so that the S_0 mode Lamb wave can be negligible in response signal. This is the case in the low frequency Lamb wave since the A_0 mode will dominate in terms of amplitude at the low frequency range.

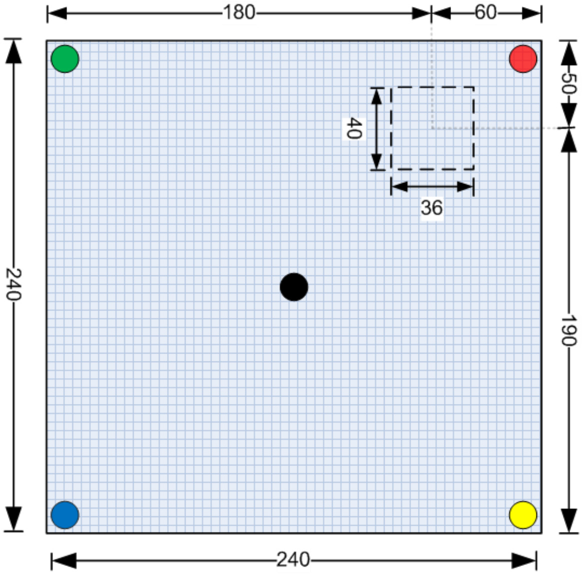

Figure 1. The dimensions of the plates and the delamination

When the FBG or PZT sensors are adopted as sensors, a pattern of multiple reflections of Lamb wave can be captured. The propagation path of the Lamb wave signal captured by four sensors can be analyzed using a mirror image containing 25 adjacent plates, as shown in Figure 2.

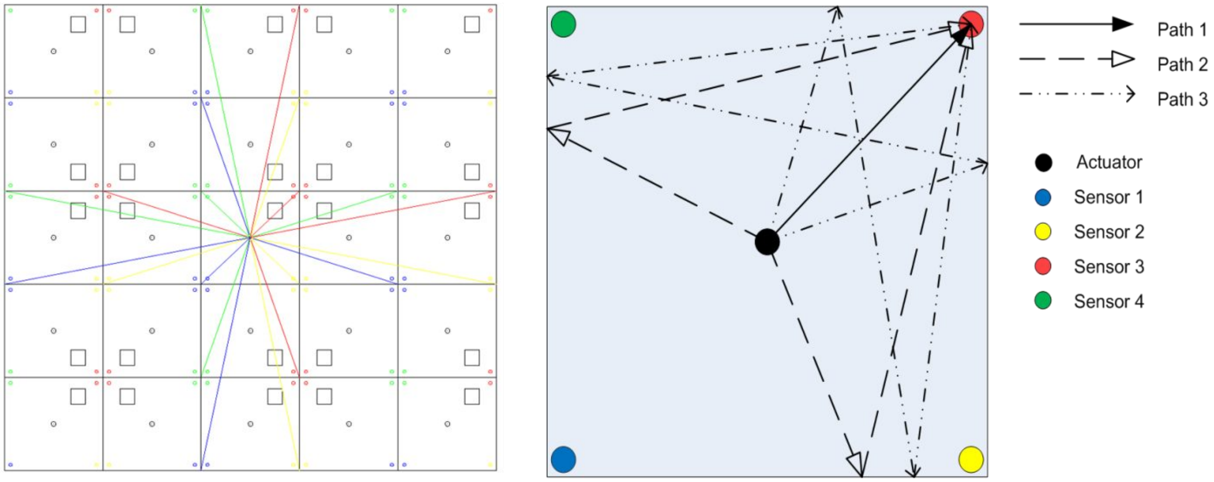

Figure 2. Lamb wave propagation paths in the CFRP composite plate: (a) Mirror image of the original plate; (b) The first three propagation paths of the response signal captured by sensor 3.

3.2 Experimental Demonstration

An FBG/piezo array sensor-actuator system for structural health monitoring of advanced composite structures was developed as shown in Figure 3. Initially, rather than a large array operating intermediate speed (tens of FBGs operating at kHz), for first proof-of-concept, we focused on a panel with 3 FBGs operating at ultra-high speed (up to 500 kHz).

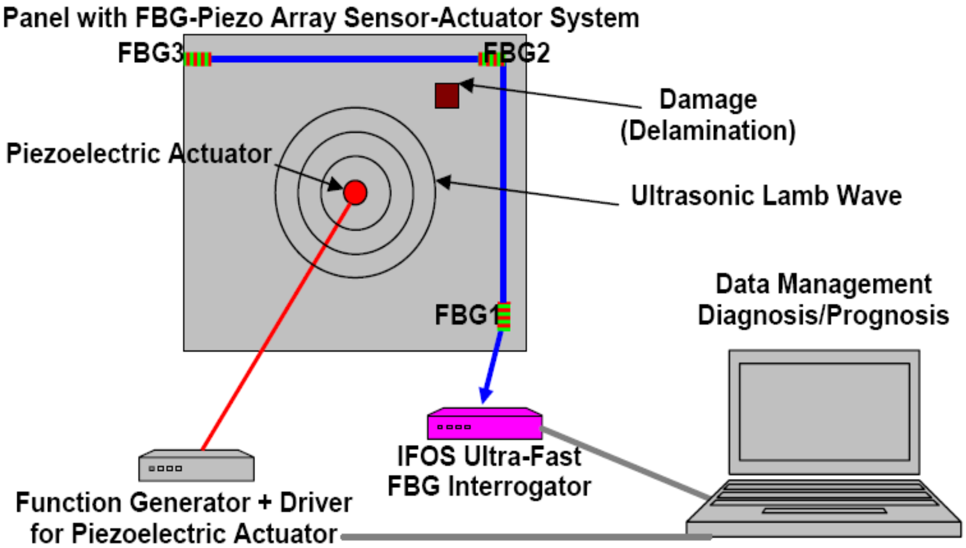

Figure 3. FBG-piezo array sensor-actuator system as proof-of-concept demonstration for structural health monitoring damage wave imaging technique for damage identification of composite plates using Lamb wave-based approach.

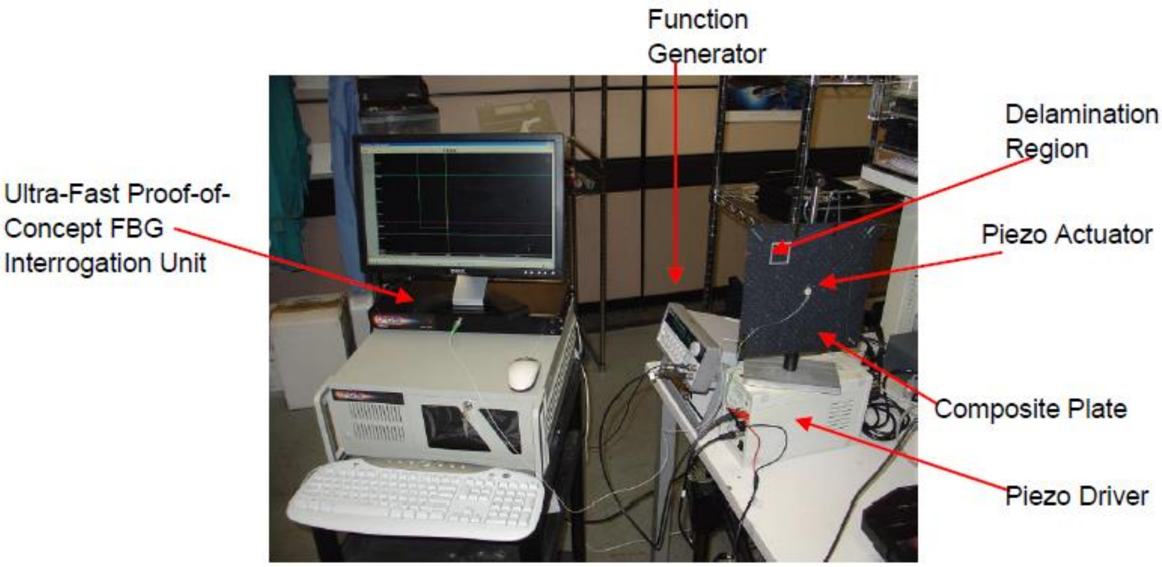

Figure 4. Photograph of experimental set-up corresponding to previous figure.

Figure 5 shows the three electrical (voltage) signals obtained from the reflected optical signals of the three FBG sensors. The new proof-fo-concept IFOS wavelength interrogator performed the optical signal detection, the optical-to-electrical signal conversion, and the electrical signal acquisition at 500 kHz sampling rate. The voltage signals shown above are filtered (DC component was filtered out) and their amplitudes are normalized. The two spikes are parts of the signals modulated by the Lamb waves which are excited at burst frequency of 10 Hz (0.1 s). As one can see, the spikes are separated in time by sub-millisecond intervals. This indicates that their Time-Of-Flights (TOFs) are slightly different. When excited Lamb waves travel through the damaged area of the plate, they are slowed down and, therefore, they reach some sensors sooner than the others. Consequently, the TOFs are different. The three signals further processed in a MATLAB-based program and the color map of the plate showing (approximate) size and location of the damage is obtained as shown in Figure 6. The square near the upper right corner in Figure 6 shows the region where damage (embedded delamination) was introduced and the color map shows the damage index deduced from the piezo-actuator excited FBG measurements.

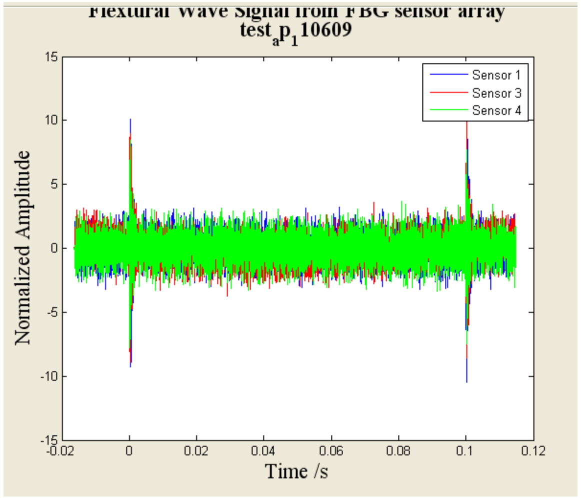

Figure 5: Filtered FBG Signals – The spikes on the left and right show the triggering between which the 3 sensor signals were measured for the damage index determination of the next figure.

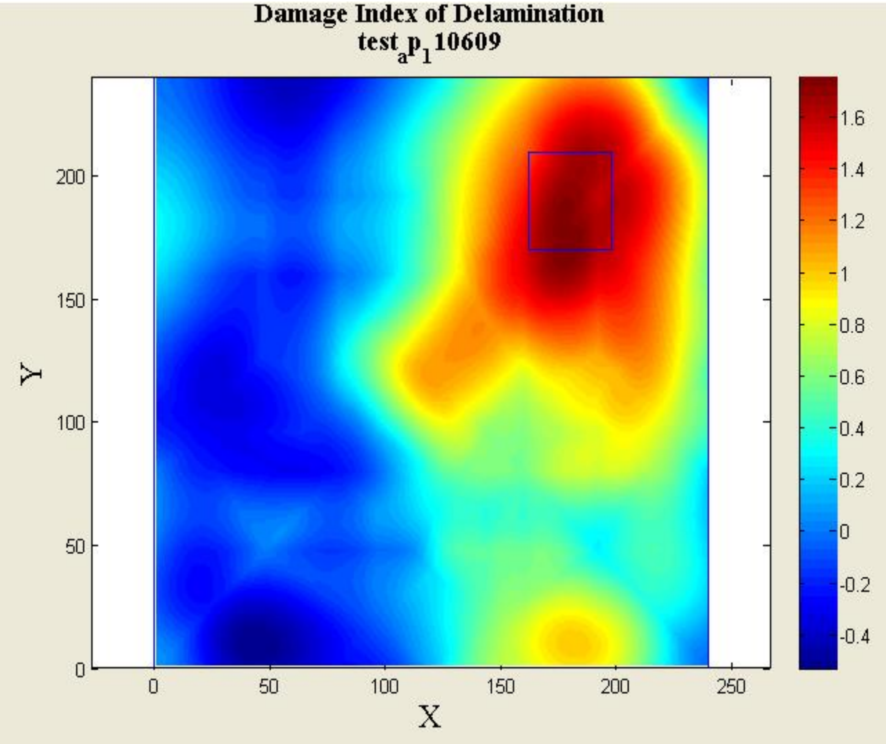

Figure 6. Damage index determined in flat plate using only three FBG sensors.

4. CURVED COMPOSITE PLATE TESTING

Figure 7 shows a schematic of the experimental design for damage detection in a curved plate.

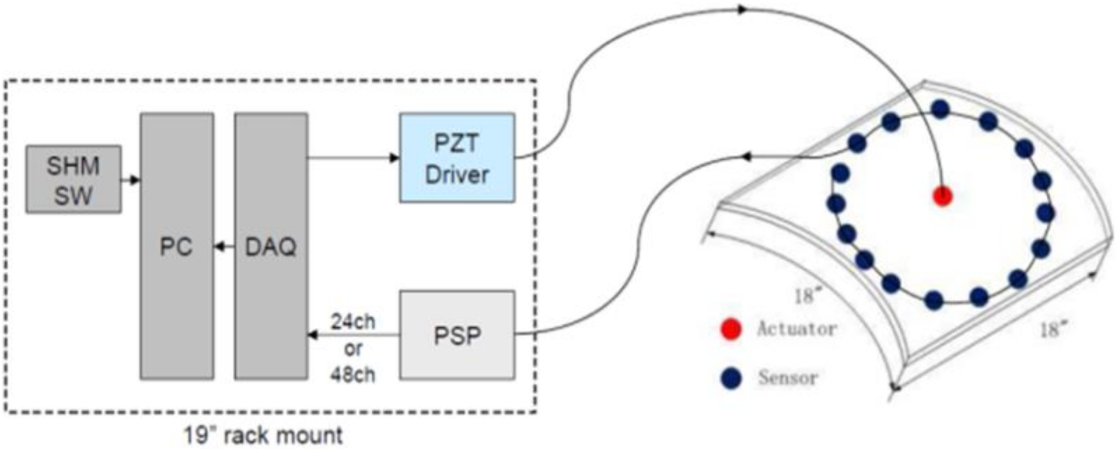

Figure 7. Schematic for damage identification in a curved plate.

As a demonstration, we implemented the system with four FBG sensors (see Figure 8). IFOS' Piezomaster and function generator are integrated into a PC, and the test setup with the fully integrated SHM system with FBG sensors is shown in Figure 9.

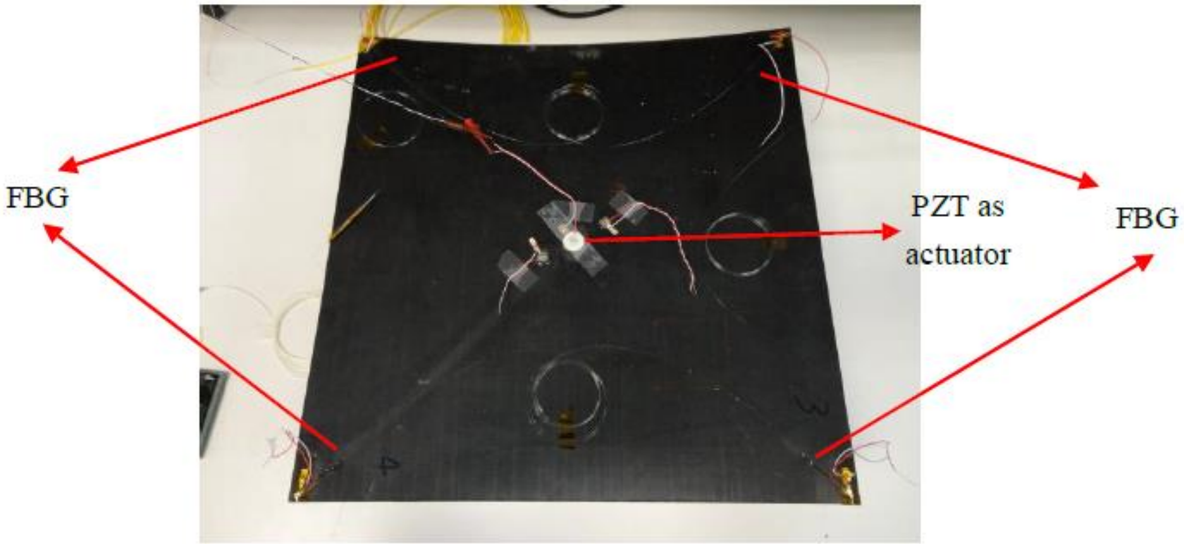

Figure 8. Photograph of composite shell bonded with FBG sensor/PZT actuator array

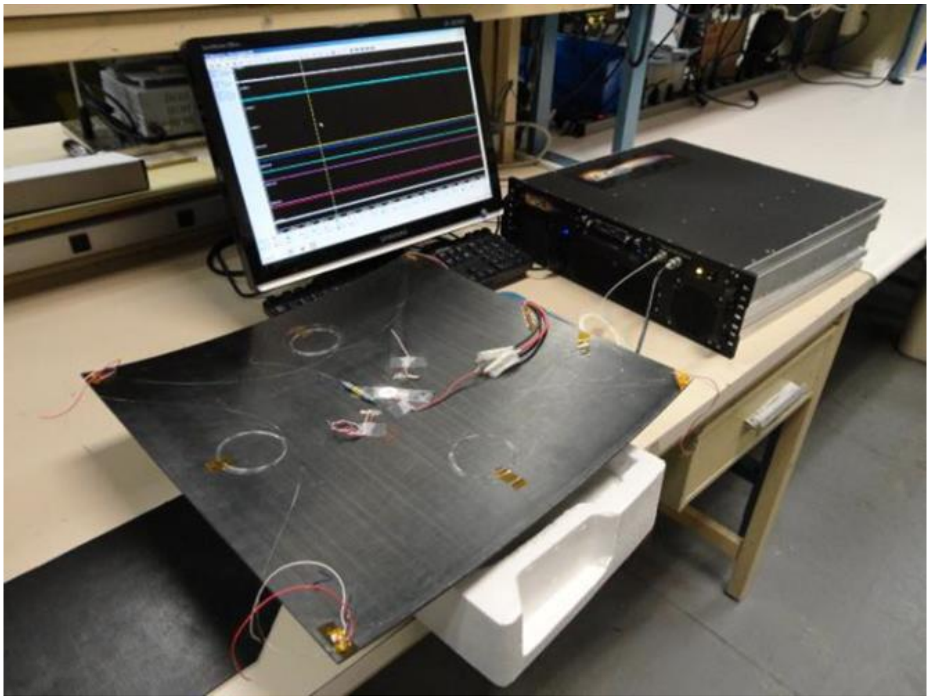

Figure 9 Photograph of experimental setup of the fully integrated SHM system with FBG sensors

In the experimental test, a tone burst signal with 3.5 cycles sine wave was sent by the actuator, which is located at the center of the shell, to excite the A0 mode lamb wave. Four different excitation frequencies 25 kHz, 30 kHz, 45 kHz and

40 kHz are conducted separately to identify a better input one such that a clearer damage index can be generated from the provided algorithm. A typical response signals for the composite shells from the four FBG sensors with excitation frequency of 30 kHz is shown in Figure 10(a). It shows that the reading signals from FBG were considerably interfered by the noise. Therefore, certain filter has to be designed to remove or suppress the interfering signals. The filtered signals are shown in Figure 10 (b). Based on the filtered signal, the damage index of the composite shell from the developed algorithm is shown in Figure 11.

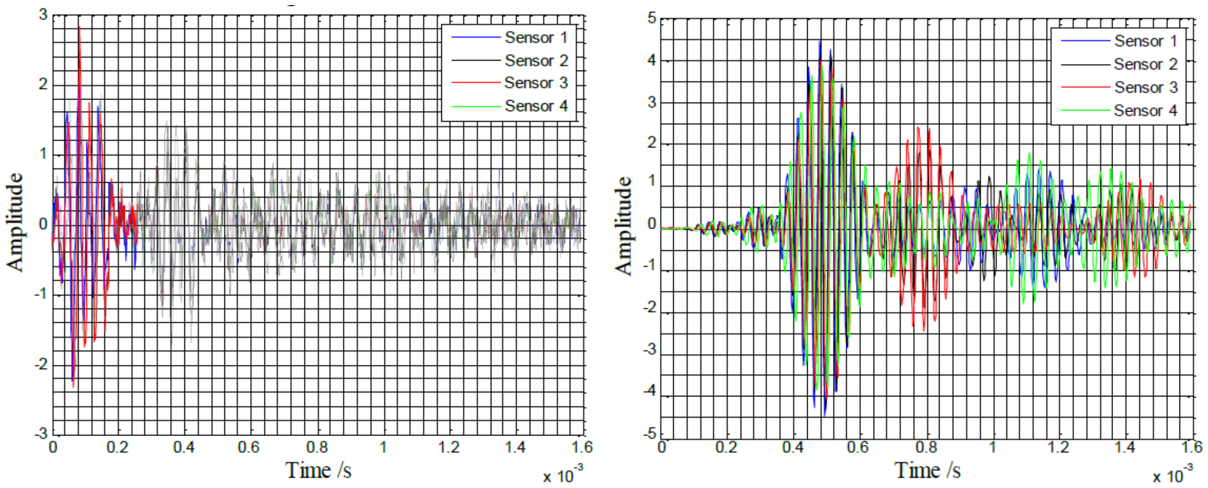

Figure 10. Response signals from the 4-FBG sensors with excitation frequency of 30 kHz (a) Flexural Wave Signal in Shell from FBG (b) Flexural Wave Signal in Shell after filtered

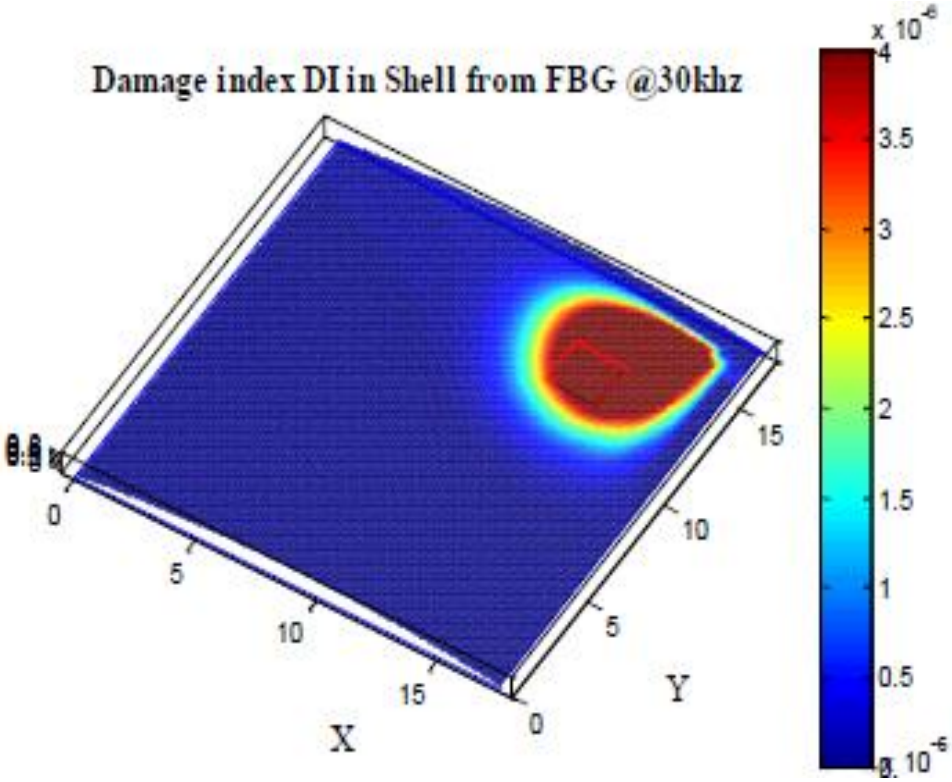

Figure 11. Damage index determined in curved plate from the fully integrated SHM System with four FBG sensors.

5. CONCLUSIONS

The FBG sensor matrices, which are light-weight, EMI-immune and highly multiplexable (many sensors on a single fiber), together with IFOS' broadband (DC to MHz) interrogation provide considerable promise for composite structure SHM. Testing of CFRP shells with integrated system was conducted, and the effect of environment on the system investigated. Results demonstrated that the integrated SHM system is capable of detecting delamination in composite shells and that the operating environment does not have much influence on the system. This integrated miniature-size SHM system has the potential to be implemented for real time and on-board SHM of aircraft structures.

The Lamb wave-based damage wave imaging method using FBG sensor/PZT actuator array and integrated system are studied to detect delamination in composite shells. A damage index (DI) is generated from the delay matrix of the Lamb wave response signals to indicate the location and approximate area of the damage. The validity and effectiveness of the proposed FBG/PZT array and its corresponding damage imaging method are demonstrated by both the numerical and experimental tests. Testing of CFRP shells with integrated system is conducted, and the effects of environment, such as vibration/machinery excitation and acoustic noise excited by running machines on the SHM system are investigated. It demonstrates that the integrated SHM system is capable of detecting the delamination in composite shells and the operating environment does not have much influence on the system.

The proposed method is a response-based, reference-free damage, and near real time detection technique which only requires the response signals from the plate after damage. The integrated FBG sensor and PZT actuator system tested in this study demonstrates its advantages and viability for high speed and near real time damage identification with only a limited number of sensors. This integrated miniature-size SHM system has the potential to be implemented for real time and on-board SHM of aircraft structures.

ACKNOWLEDGEMENTS

This work was performed as part of a NASA Phase 2 STTR Contract NNX10CB58C "Structural Health Monitoring with FBG and Piezo Arrays", awarded to Intelligent Fiber Optic systems Corporation (IFOS), with Washington State University as STTR Partner. The authors are grateful for the guidance and suggestions made by Mr. Shedrick Bessent and Dr. Hon Chan of NASA Dryden Flight Research Center during the program.

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