High-temperature Ultrasonic/AE sensing System Using Fiber-optic Bragg Gratings

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Abstract

Heat-resistant composite materials, such as ceramic matrix composites, have been used as structural materials in aircraft engine parts to increase fuel efficiency. Development of the reliable composite materials requires the techniques of non-destructive testing (NDT) for evaluating damage progress during material testing. Furthermore, structural health monitoring (SHM) technology under harsh environment is also expected to be realized for the heat-resistant composite structures. To provide the potential solutions for the establishment of the technologies, this research proposed two kinds of techniques by applying fiber-optic Bragg grating (FBG) sensor to high-temperature acoustic emission (AE) measurement and ultrasonic detection. First, this research devised a novel remote AE measurement method. In this method, optical fiber was used as the waveguide to propagate the AE waves in the composites from a high-temperature environment to the room-temperature environment where the FBG was located. We conducted experiment to verify that the method was able to detect precise AE waveform with a stable performance even at elevated temperature over 1000 °C. Then, this research also developed a heat-resistant sensor using a regenerated FBG (RFBG) which was produced by a special annealing process. Due to its heat-resistance, the RFBG sensor achieved a stable in-situ ultrasonic detection at 1000 °C. We believe the two kinds of proposed techniques could contribute to establishing effective NDT and SHM technology for evaluating and monitoring microscopic damage in composites under engine-operating environments.

1. Introduction

Ceramic matrix composites (CMCs) have shown growth potential as new civil aviation engine materials owing to their weight-saving properties and great heat-resistance over 1000 °C. However, fracture process in CMCs results from accumulation of microscopic damages which are difficult to be experimentally observed and evaluated, especially, under high-temperature engine-operating environment. That poses a major safety risk to CMC-made engine systems. Hence, developing safe and reliable CMC requires non-destructive testing (NDT) technologies that are available to clarify the damage propagation behaviour at elevated temperature. In addition, in-situ structural health monitoring (SHM) technologies are also necessary for reducing the CMC-made engine maintenance cost in the future.

Guided wave-based ultrasonic detection and acoustic emission (AE) testing can potentially achieve the NDT and SHM technologies. However, common AE and ultrasonic sensors made from Pb(Zr,Ti)O3 (PZT) show degraded performance at temperatures higher than 200 °C. The conventional approach to the high-temperature
detection uses metal buffer rod to propagate AE or ultrasonic wave from the test environment to a room temperature environment where the PZT sensors are operable. However, the waveguide distorts the waveform and drastically damps the amplitude of the AE or ultrasonic signals. Although some special heat-resistant piezoelectric sensors have been developed for ultrasonic detection at elevated temperatures, the unstable crystal property and electrode problem still hindered their practical applications [1]. Because optical fiber sensors (OFSs) are induced in silica-glass fibers with large heat resistance exceeding 1000 °C, that kind of sensors are attractive for the alternative high-temperature sensing technology. As one type of OFSs, fiber Bragg gratings (FBGs) have been widely used for ultrasonic detection [2-4]. In particular, Wu and Okabe [5] promoted application of FBG-based sensor to AE detection by developing a highly sensitive ultrasonic sensing system using a phase-shifted FBG (PSFBG). PSFBG is produced by inserting a π-phase-shift into the middle of the grating area of an FBG. Because of the phase shift in the refractive index, a sharp notch with FWHM of 9.4 pm is generated in the reflection spectrum. When ultrasonic wave propagates through the PSFBG sensor, the ultrasonic wave excites dynamic strain along the gratings, which shifts the wavelength spectra. Demodulating the wavelength shift of the sharp peak could realize sensitive ultrasonic signals [5, 6]. In addition, the PSFBG sensor responds to ultrasonic wave in a very broad frequency bandwidth because the effective sensing length is very short, which is only in the vicinity of the phase-shifted point [6]. Taking advantage of the PSFBG sensor, this research attempted to achieve the high-temperature AE and ultrasonic detection with enhanced performance.

However, the mainstream FBG-ultrasonic sensors (including PSFBG) are composed of ultraviolet (UV)-induced (type I) gratings with thermal instability. That nature results in the inability of applying the FBGs to in-situ measurements. Hence, this research proposed two novel techniques to solve the problem. First, this present paper introduced a new remote AE measurement configuration. The configuration was similar to the buffer rod-based detection method. However, instead of the metal rod, we used an optical fiber as a waveguide to provide an ideal system for elastic wave propagation with low damping and slight mode conversion. In addition to the heat-resistance of the optical fiber, the ADRM configuration achieved an exact AE detection without signal distortion at elevated temperature. Section 2 presented the sensing principle of PSFBG sensor in the ADRM configuration and the verification experiment on the high-temperature AE detection.

Then, we used a heat-resistant regenerated FBG (RFBG) to build a novel sensor for the in-situ ultrasonic detection. As shown in section 3 in details, that kind of RFBG was obtained by annealing the disappeared PSFBG caused by large thermal energy. Verification experiments showed that the fabricated RFBG sensor was heat-resistant and capable for a stable ultrasonic detection at a high temperature of 1000 °C.

2. Remote acoustic emission measurement

As mentioned above, large thermal energy destroys the FBG. Hence, as shown in Figure 1, we devised a new adhesive method for remote AE measurement (ADRM). In the configuration, an optical fiber was used as a waveguide to propagate AEs from the structural composite under a high-temperature environment to the PSFBG located in the room-temperature environment. That configuration could prevent the PSFBG sensor from exposure to high-temperature environments. Furthermore, because of the great
thermal stability of silica glass-made optical fiber, the waveguide system has a predictably stable performance under harsh environment as shown in section 3.2.

Figure 1: Adhesive method for remote measurement (ADRM)

In addition to the availability of high-temperature detection, the another primary issue was to show that our ADRM configuration was able to detect original AE signals without large damping and waveform distortion caused by wave propagation in the waveguide, but was completely different from the metal buffer-rod-based remote detection. Hence, this study elucidated elastic wave propagation in optical fiber-based ultrasonic waveguide and subsequently examines whether the characteristics of guided wave modes could be extracted precisely from the detected ultrasonic signal via the PS-FBG sensor in the ADRM configuration.

2.1 Sensing principle of FBG sensor in ADRM configuration

We conducted an ultrasonic detection experiment shown in Figure 2 to clarify the sensing principle of ADRM configuration. In the experiment, a piezoelectric type macrofiber composite (MFC) (M-8714-P2, Smart Material Corporation) was glued on the aluminum plate to excite ultrasonic waves. The waves were detected via the high sensitive PSFBG sensor (Fujikura Corporation) connected to the balanced sensing system [5]. The optical fiber was glued onto the aluminum plate by commercial Cyanoacrylate adhesives with a length of 5 mm. Figure 2(a) illustrates the position of
the adhesive point and the PS-FBG sensor in the ADRM configuration. The notation ADRM (D<sub>Sensor</sub>-D<sub>Adhesive</sub>) is used to indicate the different distance conditions between the adhesive point and the PS-FBG sensor, where D<sub>Adhesive</sub> (cm) indicates the distance between the MFC and the adhesive, and D<sub>Sensor</sub> (cm) indicates the distance from the MFC to the PS-FBG. In Figure 2(b), the notation AD (D<sub>Sensor</sub>) describes the normal adhesive method, where the PS-FBG sensor was directly glued on the plate surface at the position D<sub>Sensor</sub> (cm) away from the actuator.

The MFC was used to generate a three-cycle sinusoidal wave excitation with a hammering window. In the ADRM configurations, the adhesive point was located 20 cm away from the MFC, and the sensor position was located 40 and 60 cm away from the MFC, resulting in ADRM(40-20) and ADRM(60-20) configurations, respectively. In addition, normal adhesive methods with distances of 20 cm between the MFC and PS-FBG were also used as references. It resulted in AD(20) configuration. We note that these three experimental setups had the same adhesive position but with different sensor positions. Consequently, comparison between the corresponding results could clarify the influence on ultrasonic detection caused by the optical fiber-based waveguide between the adhesive point and PS-FBG sensor.

Figure 3: Received waveforms obtained by experiments and numerical simulations with FEM

Figure 3(a) to 3(c) show the responses to an input signal with a central frequency of 300 kHz. On the basis of the calculated theoretical dispersive curve of Lamb wave in the aluminium plate, the S<sub>0</sub> mode and the A<sub>0</sub> mode were separated as shown in Figures 3(a) corresponding to the direct adhesive configuration (AD(20)). And then, referring to the result, we found that the wave components having the same characteristics as that of the S<sub>0</sub> and A<sub>0</sub> modes also appeared in the ADRM configurations’ detections shown in Figures 3(b) and 3(c). In particular, a further comparison between the three results revealed that the wave propagation in the fiber evidently resulted in an arrival time delay with a linear relation to the increased distance between the adhesive point and PSFBG sensor. In addition, the propagating wave components corresponding to the S<sub>0</sub>
mode and the $A_0$ mode had the same velocity in the fiber. As a result, waveform detected using the PSFBG sensor in the ADRM configuration enable us to obtain accurate physical characteristics of the modes included in the wave propagating through the adhesive point.

Three dimensional finite element method simulation was also carried out to validate the experimental results. As a result, the behaviour of $S_0$ and $A_0$ modes in the simulated results (Figure 3 (d), 3(e) and 3(f)) agreed with that in the experimental results. Hence, on the basis of the simulation model, we clarified sensing characteristics of the ADRM configuration which was shown in the Figure 4.

Figure 4: Detection property of PS-FBG sensor in the ADRM configuration.

AE propagated in the structural plate as a Lamb wave, including the $S_0$ and $A_0$ modes, until its arrival at the adhesive point. However, when the Lamb wave was propagated from the plate to the fiber through the adhesive, it was transformed into the other type of wave, including longitudinal and transverse modes, which propagated in the optical fiber-ultrasonic waveguide. Then, the two modes continued to propagate along the optical fiber without any mode transformation due to a relatively ideal wave propagation system provided by the thin optical fiber with a small diameter (125 µm). The PS-FBG was produced in the core of the glass fiber; that is, the PS-FBG was in the neutral axis of a thin fiber. Also, the PS-FBG could only detect the axial strain, and therefore, only the longitudinal wave mode was detected. This implied that the detected wave components corresponding to the $S_0$ and $A_0$ modes propagated at the same velocity as that of the longitudinal wave. Hence, the $S_0$ mode or the $A_0$ mode in the detection results showed a linear delay change following the linearly changing distance between the PS-FBG sensor and the adhesive point. As a result, the PS-FBG sensor in the ADRM configuration demonstrated accurate remote sensing for the Lamb wave modes included in AE signals that propagated from the generation sources to the adhesive point.

2.2 AE detection at 1000 °C using ADRM configuration

In this section, we conducted a verification experiment to show the great performance of ADRM configuration in high-temperature AE detection.

In the experiment, the optical fiber was bonded on the surface of a heat-resistant alumina plate by a high-temperature carbon paste (G7716, Ted Pella, Inc.). The cement used here shows high heat-resistance over 1500 °C. As shown in Figure 5, the adhesive point was placed in the furnace. The optical fiber extended across the high-temperature
environment to room temperature environment, where the PSFBG sensor was located and was used to remotely detect pencil lead break (PLB)-simulated AE signals. The edge condition in the reflection spectrum of the PSFBG determines the performance of the sensor in AE detection [5]. Hence, while raising the temperature at elevated temperatures up to 1000 °C, we first confirmed the spectrum by sweeping tunable laser from 1550 to 1550.5 nm with a tuning speed of 500 pm/s. Because the balanced sensing system was used to demodulate the dynamic strain [5], the spectra of the PSFBG shown in Figure 6 were also detected in the balanced conditions. The results show that the rising temperature in high-temperature furnace did not deform the shapes of the spectra. This result indicated that the ADRM configuration protected the PSFBG sensor from the degradation by heating.

![Figure 5. Experimental setup for detecting the simulated AE signals generated using PLB](image)

![Figure 6. Spectra obtained by PSFBG in a high-temperature environment](image)

Finally, while raising temperature in the furnace from 100 °C to 1000 °C, we detected the simulated AE signals at every 100 °C. The obtained waveforms are presented in Figure 7 and show that the PSFBG sensor in the remote measurement configuration is suitable for AE detection at high temperatures. In particular, comparison of the results at different temperatures indicated that the rising temperature did not change the signal strength largely. Although wave dispersion in the plate may have added some fluctuations to the detected waveform at the elevated temperatures, the $S_0$ and $A_0$ modes could still be separated clearly in the results. These phenomena indicated that the remote AE measurement using the PSFBG sensor was very stable in a high-temperature environment.
3. Regenerated FBG-based ultrasonic sensing system

The above remote measurement method is highly sensitive and stable for high-temperature AE detection, thus is expectably applied to NDT at the stage of developing reliable CMC. However, this method is difficult for in-situ SHM technology, since the sensing parts have to be located in room temperature. Therefore, this section proposed a new type of FBG-based ultrasonic sensor to expectably achieve the in-situ SHM technology.

As mentioned repeatedly, UV-induced type I grating completely vanish at 900 °C. However, the researchers [8, 9] recently reported that annealing the disappeared one at a higher temperature could regenerate new heat-resistant gratings. Canning [10] explained that annealing stabilizes the periodic variation of stress at the clad–core interface of UV-induced FBGs, and the reconstructed stress distribution contributes to the regenerated FBG (RFBG). This annealing mechanism enables the RFBG to withstand ultra-high temperatures. As a result, RFBG sensing systems have been established for practical application, including strain and temperature detection [11, 12], flow measurement [13], and evaluation of the viscosity of silica optical fiber at high temperature over 1000 °C [14]. To our knowledge, no RFBG-based ultrasonic sensing system for use in high-temperature environment has been conducted. Hence, the current research verified that RFBGs could perform the ultrasonic detection.

3.1 Annealing process for RFBG

Commonly, normal FBG was annealed to obtain the RFBG. In this research, to enhance the sensitivity and broad bandwidth of the RFBG sensor for ultrasonic detection, we used the PSFBG as the seed grating to fabricate the RFBG.

Figure 8(a) shows the history of the annealing process. During the process, a spectrum analyzer monitored the peak reflectivity at different temperatures to observe the change in the reflection intensity of the PSFBG. The results indicated that the reflectivity began...
to rapidly decrease at 600 °C. Then, the PSFBG disappeared at 900 °C. However, by continuous heating at a trigger temperature of 920 °C, the vanished grating began to gradually regenerate. After approximately 30 min, the reflective strength returned to -12 dB and then retained a constant value, which indicated that an RFBG had been formed. After the annealing, we validated the heat resistance of the RFBG by reheating from room temperature to 1100 °C. From the measured peak reflectivity shown in Figure 8(b), we found that the RFBG did not disappear even at a temperature of 1100 °C. This result indicates that the RFBG exhibits heat resistance over 1000 °C.

![Figure 8](image)

Figure 8. (a) Temperature history of the annealing process and peak reflection during Bragg grating regeneration. (b) Reflection intensity of the RFBG during reheating

### 3.2 RFBG-ultrasonic sensor

Next, we built an RFBG sensing system for ultrasonic detection. In the system shown in Figure 9, RFBG was used as a sensor to receive dynamic strain caused by an ultrasonic wave that propagated through the grating area. The change in the strain shifted the spectrum of the RFBG. The current research employed an edge filter method [15] to monitor the spectra. This method requires a narrow-band laser source to filter the strain-induced edge shift. Hence, a tunable laser source (TLS, Agilent, 81682A) with a 100-kHz line width and 0.1-pm tunable resolution was used to adjust the laser in the linear region of the RFBG spectrum. The RFBG was connected to the TLS through a circulator. Then, the reflected light was led to a photo detector (PD, New Focus, 2117). Because the wavelength shift of the spectrum will result in modulation of the reflected optical power, ultrasonic signal can be acquired after the PD converts the optical power into an electric voltage.

![Figure 9](image)

Figure 9 Schematic diagram of the RFBG sensing systems
In ultrasonic detections using FBG-based sensors, the edge condition in the reflection spectrum is critical for sensitivity, i.e., a steeper slope in the spectrum edge leads to a higher sensitivity. Hence, after the annealing, we observed the spectrum shape of the RFBG at room temperature and compared it with that of the seed PSFBG. The comparison in Figure 10 shows that the annealing transformed the narrow sharp peak in the PSFBG spectrum into a broad peak with a gentle slope. This phenomenon could be interpreted as a change in the original UV-induced π phase shift in the regeneration because the annealing process restructured the stress at the interface between the core and cladding to generate the RFBG. However, this restructured stress around the π phase-shift point in the gauge did not keep the original phase but converted it to another angle. As a result, the changed phase led to a gentle peak. However, the linear region marked with red line in the RFBG spectrum exhibited a slope of 0.79 nm\(^{-1}\), which is larger than that of general FBG sensors. This result indicates that the sensitivity of the RFBG sensor for ultrasonic detection might be better than that of the FBG sensor.

Subsequently, we investigated the ultrasonic detection performance using the RFBG sensing system at 1000 °C. In the experiment shown in Figure 11, the RFBG sensor was remotely bonded on an aluminum plate to receive the ultrasonic wave excited using the MFC actuator. To protect actuator and plate from the exposure to thermal energy, only RFBG sensor was located in the harsh environment. The ultrasonic signal is a Hamming-windowed three-cycle sine-tone burst with central frequencies of 300, 600, 900, and 1200 kHz. The measured results in Figure 12 show that the RFBG sensor can
detect ultrasonic waves at a high temperature of 1000 °C. In particular, the Fourier transform results of the received waves show that the energy distribution shifts to higher frequencies with an increase in the central frequency of the input wave. These results indicate that the RFBG sensor has the same characteristics of broad bandwidth as that of the seed PSFBG with an extremely short gauge length [17] because the effective sensing region of the RFBG remained around the phase-shift point, although the phase-shift value differed from $\pi$ during the regeneration process.

![Figure 12 Ultrasonic waves received by the RFBG sensor at 1000 °C and their Fourier transform results](image)

4. **Conclusion**

By taking advantage of the sensing characteristics of the PSFBG sensor in the ADRM configuration, the present work successfully achieved stable AE measurements with high sensitivity at high temperatures of 1000 °C. That good performance was mainly due to the use of an optical fiber-based waveguide that was able to yield a stable system for propagating ultrasonic waves even under the temperatures exceeding 1000 °C. On the other hand, having to locate the PSFBG at room-temperature limited the application of ADRM configuration for the in-suit SHM technology. To solve the problem, we developed the RFBG sensor. Owing to its heat-resistant characteristics, we achieved stable ultrasonic detection at a high temperature of 1000 °C. In addition, because PSFBG was used as the seed grating, the RFBG sensor possessed very short effective sensing gauge length that resulted in a broad bandwidth response to ultrasonic wave over 1 MHz.

Because of the enhanced performance, we believe that ADRM configuration and RFBG sensor will contribute to establishing effective NDT and SHM technology for evaluating and monitoring microscopic damage under the engine-operating environments.
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