Exploration of Ultrasonic Guided Wave Detection with Optical Fiber Sensors and Piezoelectric Transducers

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ABSTRACT

This paper presents a comparative study of ultrasonic guided wave detection with optical fiber sensors and piezoelectric transducers. In recent years, fiber Bragg gratings (FBG) have been investigated by several researchers as an alternative to piezoelectric sensors for the detection of ultrasonic waves. FBG have the advantage of being durable, lightweight, and easily embeddable into composite structures as well as being immune to electromagnetic interference and optically multiplexed. However, there is no turn-key commercially available product that uses this promising technology for the detection of ultrasonic guided waves because: (a) the frequency is high (hundreds of kHz and above); (b) the strains are very small (less than one microstrain); (c) the operational loads may also induce very large quasi-static strains (the detection of very small ultrasonic strains superposed on large quasi-static strain presents a quite challenge).

Although no turn-key optical system exists for ultrasonic guided wave detection, two commercially available FBG interrogation systems with various frequency ranges and strain resolutions (Micron Optics SM690 and Redondo Optics M200) are available and have been evaluated by us. This paper starts with a literature review of the state of the art in optical technologies for ultrasonic wave detection. Subsequently, this paper describes our comparative tests with several fiber optics systems. The measurement resolution and sampling speed were considered as the most important criteria in our test. In the final part, a commercially available tunable laser source from LUNA was customized for ultrasonic sensing. Parallel strain measurements were done with different systems including FBG and piezoelectric wafer active sensors (PWAS). The measurements were compared. Possible calibration and performance improvements for the optical interrogation system are also developed and discussed. The paper ends with conclusions and suggestions for further work.

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INTRODUCTION

Structural health monitoring (SHM) determines the health of a structure by monitoring over time a set of structural sensors and assessing the remaining useful life and the need for structural actions. Fiber optic sensors have been widely used for the measurement of strain, temperature, humidity, pressure, and other parameters [1]. Piezoelectric transducers have received considerable attention in the SHM community by monitoring the structures with ultrasonic guided wave both actively and passively [2]. Recently, Fiber Bragg grating (FBG) sensors have been applied for a variety of SHM application including spacecraft, aircraft, fiber reinforced polymer composite, etc. FBG sensors have many advantages for strain sensing including their small size, the potential to multiplex hundreds of sensors with a single fiber, their immunity to electromagnetic interference, and their corrosion resistance. In recent years, FBG sensors have been investigated by several researchers as an alternative to piezoelectric sensors for the detection of ultrasonic waves [3-7].

The purpose of the paper is to evaluate several commercially off-the-shelf (COTS) FBG interrogation systems for the ability to detect ultrasonic guided wave generated by a piezoelectric wafer active sensor (PWAS). The comparison is based on the FBG interrogation method, resolution, sampling frequency, etc. In the final part, a commercially available tunable laser source from LUNA was customized for ultrasonic sensing.

FBG INTERROGATION

Bragg gratings reflect light over a narrow wavelength range and transmit all other wavelength based on the principle of Bragg reflection. A FBG sensor consists of Bragg grating applied to an optical fiber. When a broad spectrum of wavelengths passes through the FBG, FBG acts as a “wavelength-dependent filter”. The central wavelength of reflection is referred to as the Bragg wavelength ($\lambda_B$). The Bragg wavelength varies based on the strain and temperature that are applied to the FBG. As axial strain is applied to the fiber, the FBG pitch is modified and the Bragg wavelength shifts to lower wavelengths (compression), or higher wavelengths (tension). The shift in Bragg wavelength is linearly related to the applied axial strain. Multiple gratings which are designed to reflect at different wavelengths can be spatially distributed along the length of the optical fiber. The strain and temperature sensitivities of an FBG with a Bragg wavelength of 1,550 nm are 14 pm/K and 1.2 pm/με, respectively [1].

FBG Interrogation Methods

The methods for FBG interrogation include wavelength division multiplexing (WDM), time division multiplexing (TDM), optical frequency domain reflectometry (OFDR), intensity based system which rely on various types of wavelength dependent filtering. Based on the light source used in the system, FBG system can be classified as two types: (1) broadband light source; (2) narrow linewidth scanning laser source. In broadband light source FBG systems, a wavelength detection subsystem is required to demodulate the FBG sensor signal.
In tunable laser source FBG systems, a laser is tuned to a wavelength positioned on the slope of the FBG reflective spectrum. A tunable laser source provides more capacity for multiplexing and less system noise than a broadband source; however, it is more expensive.

In recent years, many commercial off-the-shelf (COTS) FBG interrogators have come to market but typically, regardless of the demodulation approach, they tend to compromise between speed, multiplexing capability, and strain resolution. A summary of the available commercial FBG interrogators for dynamic sensing application are compared in ref [7]. From the comparison, it is apparent that most commercial FBG systems available in the past decade are based on WDM [7]. Most FBG interrogation system uses broadband light source because of the high cost of scanning laser source.

**Ultrasonic Measurement Requirement**

In order to assess the suitability of the COTS systems to provide a measurement of dynamic strain from a series of FBG arrays, it was first necessary to develop the required system specifications for ultrasonic wave sensing, i.e. define the minimum strain resolution and frequency range required. For ultrasonic optical sensing applications, the ultrasonic sensing modules and baseline optical sensors should meet the following performance specifications:

- Optical sensing for ultrasonic guided waves in hundreds of kHz range
- High sampling frequency demodulation (> 2 MHz) for each channel to permit good capture of ultrasonic waves in hundreds of kHz range
- Typical ultrasonic guided wave wavelength ~ 4 – 100 mm
- Typical ultrasonic guided wave signal frequency: up to 700 kHz
- Typical wave strain: 1 \( \mu \varepsilon \) or lower
- High sensitivity for small strain (0.01 \( \mu \varepsilon \))
- Large dynamic range
- DC strain compensation
- Multi-channel system with multiple fibers detected simultaneously
- Multiple multiplexed FBGs on a single fiber are desired if available

However, there is no commercially available product that uses this FBG technology for the detection of ultrasonic guided waves with the above specification because: (a) the frequency is high (hundreds of kHz); (b) the strains are very small; (c) the operational loads may also induce very large quasi-static strains (the detection of very small ultrasonic strains supposed on large quasi-static strain presents a quite challenge).

### Table 1. Comparison of COTS systems

<table>
<thead>
<tr>
<th>Property</th>
<th>Micron Optics SM690</th>
<th>Redondo Optics M200</th>
</tr>
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<tbody>
<tr>
<td>Channels</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>FBGs/Ch.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Scan Freq.</td>
<td>DC to 2 MHz</td>
<td>DC to 40 kHz</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>50 nm</td>
<td>5 nm (1540 nm, 1550 nm)</td>
</tr>
<tr>
<td>Data output</td>
<td>LabVIEW</td>
<td>USB</td>
</tr>
<tr>
<td>External Trigger</td>
<td>Hardware</td>
<td>N/A</td>
</tr>
<tr>
<td>Typical noise level (p-p)</td>
<td>100 pm</td>
<td>20 pm (1540 nm), 10 pm (1550 nm)</td>
</tr>
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ASSESSMENT OF COMMERCIALLY AVAILABLE SYSTEM

Although there is no COTS FBG interrogation system for ultrasonic SHM, we evaluated two commercially available FBG interrogation systems (Micron Optics SM690 and Redondo Optics M200) with various frequency ranges and strain resolutions. The comparison of these two COTS FBG systems is shown in Table 1.

Micron Optics SM690

The Micron Optics sm690 is a high speed optical sensing interrogator capable of performing fast measurements – such as strains and mechanical vibrations – using optical FBG sensors on up to four simultaneous channels with a continuous acquisition rate of 2 MHz. The sm690 is not a stand-alone instrument but rather a dual-slot 3U PXI Express (PXIe) high-speed data acquisition module. The sm690 module is designed to work with the National Instruments PXIe system platform. A PXIe main chassis and controller is required for the operation of the sm690. Multiple sm690 modules can be integrated into the same chassis with other PXIe type modules to perform other data acquisition and control functions.

An integration NI PXIe platform including PXIe-1082 chassis, PXIe-8135 controller and sm690 was used for evaluation. The sm690 is integrated in the second slot of the system (Figure 1). The sm690 uses broadband light source. It is an intensity based system using a linear attenuation filtering for wavelength detection. The interrogation method of the Micron Optics sm690 is shown in Figure 2. The light from the broadband optical source goes through a circulator into the FBG. Circulator is a passive device in which the optical signal entering at one port is only transmitted to the next port coming up in rotation. The reflected spectrum with the representation of FBG wavelength under load is channeled from the same circulator to the 50/50 coupler. Two power detectors are used to measure (a) the intensity of the power through a linear attenuation filter (LAF) and (b) the intensity of the reference signal. The intensity difference between the reference and active signals depends on the wavelength due to the filter’s reduction of the intensity. The relation between attenuation and wavelength of the filter is a predefined linear relation. The ratio of the intensity of active (through LAF) and reference signal is used to determine the FBG wavelength using a lookup table. The change of wavelength under strain is converted to strain reading. The wavelength range of sm690 is 1520 nm - 1570 nm (50 nm corresponds to 40000 με). The sm690 uses a built-in FPGA to perform a 16-bit AD conversion and the theoretical wavelength resolution is 0.76 pm (0.6 με).

The noise level of sm690 varies with sampling frequency, as shown in Table 2. This hardware is promising for SHM application. However, sm690 is still in the early stage of product development. Micron Optics provides basic software with limited functionality. The initial official release SMABLN version 0.83-7 only provides short time monitoring to display live signals (500 points), FFT of the signal and simple data acquisition to file.

<table>
<thead>
<tr>
<th>Table 2. MO sm690 noise level at various sampling frequency</th>
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<tr>
<td>Sampling (kHz)</td>
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<tr>
<td>Noise level (pm)</td>
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The initial software from Micron optics used a low voltage level for external trigger. However, the function generator outputs edge trigger. For this reason, a synchronize signal box was built to trigger both signal generator and sm690 simultaneously. Using the software development kit released by the Micron Optics, several software improvements were added by us to the initial software. The effort was focused on the data collection, including modified trigger mode, added time averaging function to reduce the noise, optimized data processing to collect the data in real time, and improved saving function.

To evaluate the performance of sm690, FBG (os1190 from Micron Optics) was bonded to a stacked PZT transducer (Figure 1b). We used a HP 33120A function generator with Krohn Hite 7602 wideband amplifier as the power source. The PZT transducer is excited with a voltage of 25 V_{pp} and +13 V offset. The harmonic excitation frequency ranged from f = 100 Hz to f = 1 kHz. A 200 Hz harmonic excitation with 125 kHz sampling frequency is shown in Figure 3. The signal collected with the Micron Optics original software was quite noise (Figure 3a). Our additional averaging function improved the signal to noise ratio quite a lot (Figure 3b). The peak to peak strain in this setup is around 50 με. It will require more power from power supply to excite the stacked PZT transducer at higher frequency. From this test, we can see the sm690 has the potential to detect ultrasonic strains provided their amplitude is large enough (> 10 με).

Figure 1. (a) Micron Optics sm690; (b) test specimen

Figure 2. Schematic diagram of the interrogation method from the Micron Optics Sensing Module sm690 to measure the wavelength
Figure 3. Comparison of sm690 measurement at 200 Hz (a) using manufacturer provided software; (b) using the improved software by USC

Redondo Optics FBGT-M200

Redondo Optics Inc. (ROI) miniature FBG-transceiver FBGT-M200 is a fully integrated FBG interrogation device capable of monitoring two FBG sensors distributed along a single optical fiber with a built-in intensity reference monitor based on ROI’s patented hybrid planar lightwave circuit technology. It uses a broadband light source and two individual intensity demodulation channels for strain measurements.

The device integrated USB communication, heat sink and two measurement channels in a small box. In contrast to the Micron Optic Sensing Module sm690, the FBG Transceiver Model M200 uses two different demodulators on two wavelengths: 1540 nm and 1550 nm. Redondo Optics employs a patented hybrid planar lightwave circuit system. The sampling rate is 40 kHz with a 10 pm resolution.

For the evaluation of the system, a cantilever steel beam with two half-bridge strain gauges, two PWAS and two FBG sensors has been prepared. The steel beam uses commercially available stainless steel 304 and the dimension of the beam is 609 mm x 18 mm x 2.5 mm (Figure 5).

The wavelength measurement is drawn in Figure 4a. The amplitude decreases in time due to free vibration which is excited only one time at the beginning. The steel beam was freely vibrating in its resonance frequency. The FFT is shown in Figure 4b. The resonance is measured at f = 7.29 Hz. Moreover, the second harmonic frequency at f = 14.23 Hz was also detected (Figure 4b).

Figure 4. Cantilever beam resonance measurement by Redondo Optics M200
FWHM METHOD WITH LUNA PHOENIX P1402

The broadband light source method does not seem suitable for high frequency low strain ultrasonic wave sensing. The intensity based interrogation is adopted which involves tuning narrow line-width tunable laser source (TLS) to interrogate the grating to a wavelength corresponding to the midpoint of the leading or trailing slope of the FBG (full-width half maximum, FWHM point) [4,7]. When a strain is applied to the grating, the grating spectrum will shift causing the transmittance at the tuned wavelength increase of decrease. The slope of the FBG spectrum works as an intensity filter and it is approximately linear. This method is also called FWHM method. The magnitude of strain that can be measured is limited only by the shape of the FBG spectrum. The frequency can be very high and is limited by the response characteristics of the strain transfer to the fiber, the power meter, and the sampling instrument. The flow chart of this method is shown in Figure 6.

There is no commercially available product that uses this FWHM method for ultrasonic sensing. However, there are a lot of tunable laser source on the market. We selected LUNA P1402 tunable laser source because it is a low-noise narrowband tunable laser (tuning wavelength range 1520-1570 nm) with a built-in two-channel power meter sampling at 5 MHz. After customization with LUNA, P1402 accepts an external trigger. The complete experimental setup is shown in Figure 7a. The only additional device required in the setup is a circulator. A comparison of PWAS and FBG is performed on the same experimental setup shown in Figure 5 with our own developed software. The pitch-catch setup consists with one transmitter PWAS excited with 20 Vpp, 300 kHz, three-count tone-burst signal, and a receiver PWAS and a receiver FBG located at 200 mm from the excitation PWAS. The measurement result is shown in Figure 7b and Figure 7c. Both measurements showed the capability of ultrasonic wave sensing. FBG did not show the electromagnetic (EMI) coupling as PWAS did.
CONCLUSION

Several commercially available FBG interrogation systems (Micron Optics SM690 and Redondo Optics M200) were evaluated for SHM application. The evaluation focused on the frequency ranges and strain resolutions. A tunable laser source LUNA P1402 was finally adopted to use with the FWHM method to be able to detect the high frequency and low strain ultrasonic guided waves excited by PWAS. The comparative tests with fiber optics systems on parallel strain measurements were performed with different systems including FBG and PWAS. Calibration and performance improvements were also developed and discussed.

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REFERENCE