Dynamic Response and Signal to Noise Ratio Investigation of NIR-FBG Dynamic Sensing System for Monitoring Thin-walled Composite Plate

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Abstract. Optical fiber systems for dynamic response measurement become an attractive study nowadays especially in the field of Structural Health Monitoring (SHM). This work presents the investigation of an optical fiber sensor system utilizing Near Infra-Red Fiber Bragg Grating (NIR-FBG) sensor for SHM of a thin-walled composite structure. In this study, a comparison between the experimental result and simulation study using finite element analysis has been presented. By comparing both results, the FBG dynamic sensing system was shown to have an excellent capability in acquiring dynamic response due to flexural wave propagations. In the meantime, a signal to noise ratio (SNR) study was also performed to several FBG dynamic sensor systems; particularly to see the comparison between NIR-FBG sensor and 1550 nm FBG sensor. Furthermore, with a proper configuration, an NIR-FBG system was proved to have better performance than the 1550 nm based FBG sensor.

1. Introduction
Optical-based sensor system has a huge potential nowadays. One of the significant benefits of using these optical sensors is the ability of utilizing the advanced technology of optical transmission systems. In other words, with the technology, distance becomes less concerned. It is an undeniable fact that these light-wave communication systems are very successful, especially in recent telecommunications applications. Besides having low transmission loss, this system also offers impressive advantages; small size and less weight of optical fiber cable, compared with conventional wiring cable.

An FBG in a dynamic sensor system usually involves a special interrogation system where wavelength variations; due to strain changes or temperature variations, can be converted into an electrical signal. The FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibers. The grating is the laser-inskiited region which has a periodically varying refractive index. This region reflects only a narrow band of light corresponding to the Bragg wavelength $\lambda_B$, which is related to the grating period $\Lambda_0$ [1],
where k is the order of the grating and \(n_0\) is the initial refractive index of the core material prior to any applied strain. Due to the applied strain, \(\varepsilon\), there is a change in the wavelength, \(\Delta \lambda_B\), for the isothermal condition,

\[
\frac{\Delta \lambda_B}{\lambda_B} = \varepsilon P_e
\]

where \(P_e\) is the strain optic coefficient and is calculated as 0.793.

Based on available literatures since early 20th centuries, the basic design of an FBG dynamic sensing system can be can be summarized as shown in figure 1. There are four major components in a basic FBG dynamic sensing as labelled by numbers in figure 1. In the third component; an FBG can be placed on the structures under monitoring by surface glue or embedding between layers. Meanwhile the fourth element is the most complex part; since it is the part where the optoelectronic conversion took place. The design of this part depends on the type of light sources used, either broadband or narrowband light sources. The use of photo detectors in this crucial part provides a lot of optical noises, thus need a proper digital or analog signal filtering. However, some systems have a complex arrangement. Although it may achieve the required results, yet, the more complicated systems may result in extra optical losses and relatively higher cost. There are two popular interrogation methods that are available for high frequency vibration signals with FBGs; that are edge filter detection and power detection methods [2].

![Figure 1](image-url)  
Figure 1. The basic schematic diagram of FBG dynamic sensing.

1.1. Noise in FBG dynamic system

The theory of the SNR has been explained in many texts [3, 4], as the ratio of signal power to the noise power. It should be noted that, the better the SNR of the system, the sensitivity to the higher frequency contents of wave propagations will also increase. There are many ways that have been investigated in order to improve the SNR of an FBG-based dynamic system; such as using smaller grating [5] and cantilever type FBG bonding [6]. However, one of the main criteria for having a sensitive system is the ability of providing higher optical power to the system. In terms of power, P, the SNR in decibel (dB) can be written as

\[
SNR_{dB} = 10 \log \frac{P_s}{P_n}
\]
where $P_s$ and $P_n$ indicate the average power of the signal and noise, respectively.

Optical noise is necessary to be considered when designing the FBG dynamic sensing. There are a lot of possible noises that can occur in an optical based system. Based on Figure 1, there are two parts that might contribute to the possibilities of optical noises: the light sources (in element 1) and the photodiodes (in element 2). The noises from light sources can be neglected if LEDs types of light source are used. If using lasers, possible optical noises can be from the mode partition noise, laser intensity noise and laser phase noise [7]. These noises are relatively small and usually attenuate before reaching the receiver part. However, if they are able to reach the photodiodes, the noise signals can appear in the resultant output signals. Usually the use of appropriate laser driver can eliminate any significant noises associated with the lasers.

The biggest noises in an FBG dynamic sensing system are due to the photodiodes (PD) [1]. The use of PIN type of PD will reduce the amount of noise to only three kinds: thermal noise, quantum and dark current noise. However, the impact of the dark current noise is usually ignored; since its power is relatively so low [7]. Meanwhile, quantum noise is not to be a major concerned in PIN PD. However, the impact of the thermal noise cannot be neglected, since it is always visible in the signal viewer; even if optical signals are not present, as illustrates by figure 2.

![Figure 2](a) Output signal without any dynamic input and (b) Output signal due to a vibration.

The thermal noise is generated by the process of converting the photocurrent to voltage by the load resistor. The load resistor creates its own noise because of the random thermal motion of electrons [7]. Increasing the load resistor may reduce the noise and increase the receiver's sensitivity; however it will also affect the receiver bandwidth thus, causing limited bandwidth. In order to investigate the SNR of the FBG dynamic system; particularly in the thermal noise effect, an experiment with several types of FBG dynamic sensing systems was conducted. The case study will be explained in the next section.

1.2. NIR-FBG system

In this research, NIR-FBG sensor in FBG dynamic sensing system was also investigated. Through limited literatures available, an NIR-FBG sensor was shown to have a sufficient capability to perform as a static and dynamic sensor [8-11]. Meanwhile, [10] has successfully validated the capability of an NIR-FBG system to be applied in an SHM system. The NIR-FBG system was also revealed to have a relatively comparable performance with the conventional 1550nm-FBG sensor which has been widely used nowadays. Furthermore, in an NIR-FBG system, contain a relatively cheap silicon-based technology.

2. Experimentation

A thin glass / epoxy sample was prepared. The symmetric sample was manufactured with 8 plies of laminates; thickness 4 mm and has the orientation of $[0^\circ,90^\circ,-45^\circ,45^\circ,45^\circ,-45^\circ,90^\circ,0^\circ]$. Figure 3(a)
shows the detailed geometry of the sample. Two FBGs with different wavelengths, 830 nm (NIR) and 1550 nm, were surface-glued by using the epoxy resin and were placed near to each other as illustrated by figure 3(b). A shaker model number V201-M4-CE, from the LDS Test and Measurement Ltd; was attached approximately at the middle of the composite specimen.

![Figure 3. Thin plate specimen.](image)

Each FBGs (NIR and 1550 nm), was connected with two different kinds of arrangements in order to measure and compare the SNR from each system. All four configurations of FBG dynamic sensing systems can be summarized as in figures 4; whereby the systems were labeled as System A, B, C and D. For System A, C and D a common configuration has been used; whereby this type of arrangement has been reported in several research works [12, 13]. Note that in System A, the NIR-FBG sensor was utilized, instead of the usual 1550 nm FBG sensor. Meanwhile System C and System D were distinguished by the use of two different optical components: the optical coupler and optical circulator, as illustrated by the figure 6 and 7. For System B, only single FBG sensor was used; which is the NIR-FBG. Its configuration and detail sensing mechanism has been explained thoroughly in [10], and it was sufficient for detecting the location of an impact on a thin composite plate. The System B had its own advantages, where it only required a 'stand-alone' NIR-FBG sensor.

![Figure 4. NIR-FBG dynamic sensing with a fixed FBG filter (System A).](image)
Figure 5. NIR-FBG dynamic sensing with a single FBG (System B).

Figure 6. 1550-FBG dynamic sensing with a fixed FBG filters using optical coupler (System C).

Figure 7. 1550-FBG dynamic sensing with a fixed FBG filters using optical circulator (System D).

A sinusoidal excitation with constant amplitude and frequency was applied to the composite sample. The response due to the excitation was measured by the Systems A, B, C and D. Prior to the shaker excitation, an impact with an impact hammer was done to the sample. The FFT result of the impact signal revealed some of the sample's natural frequencies, as shown in the figure 8. Note the impact signal was acquired by using system A (figure 4). The resulting frequency values as labeled by letter ‘a’ to ‘g’ are presented in the table 1. One of the natural frequencies, approximately 1100 Hz (Peak ‘g’), was selected as the excitation frequency.

Figure 8. Frequency spectrums of the impact signal.
In the meantime, a free vibration analysis by Strand7 software was also done to the sample, for better understanding of its behaviour during the vibration. Strand7 is excellent finite element analysis (FEA) software that can provide a fully integrated visual environment, combined with powerful solvers. The software can be used for a variety of analysis such as linear and nonlinear static analysis; natural frequency, harmonic response and spectral response analysis; and steady-state and transient heat transfer analysis. For this study, Strand7 was used to determine the natural frequencies and mode shape of the composite specimen. Thus, the natural frequency solver was chosen, and set to calculate up to 40 mode shapes.

3. Results and discussion
All the 40 mode shapes were successfully calculated by the Strand7 software. However, only selected results were shown in this paper. Table 1 tabulated some of the natural frequencies by the theoretical results (Strand7) and its comparison to the experimental results (NIR-FBG dynamic sensor). Some of the selected mode shapes, specifically the ones which correspond to the peaks a – g, as shown in the figure 8, can be presented by the figures 9. The results reveal an important sensing characteristic of general FBG dynamic sensing, which has excellent response to the flexural type of wave propagations. However, this also as the result of the excitation of the shaker mainly excited the flexural waves all over the plate surface.

| Frequency peak | FEA (Hz) | NIR-FBG (Hz) | Error (%) |
|----------------|----------|--------------|-----------|
| a              | 131.6    | 131.0        | 0.46      |
| b              | 275.4    | 276.4        | 0.36      |
| c              | 366.0    | 368.1        | 0.57      |
| d              | 478.5    | 473.2        | 1.11      |
| e              | 591.4    | 591.6        | 0.03      |
| f              | 862.9    | 867.8        | 0.57      |
| g              | 1126.0   | 1195.71      | 6.20      |
Figure 9. Selected mode shapes which simulated by the Strand7 software.

Meanwhile, the figures 10 to 13 reveal the responses from all the FBG dynamic systems to the given 1100 Hz of excitation from shaker. In all figures, the plots can be divided to the signal with the vibration (a), signal without the vibration (b) and the FFT of the signal with the vibration (c), respectively. All the results are presented without signal filtering or denoising, in order to see the existence of noises. Although all systems were able to acquire the excitation frequency, 1100 Hz, however the noises from each system were noticeable. The system B and C have relatively weak responses among others. Although system B has a higher SNR than system C, yet, it was not able to show a stable response as obtained by using system C. Table 2 summarized the SNR values, for all systems. Note that, the SNR values of each system were determined by using equation (1).
Figure 10. Response of System A.

Figure 11. Response of System B.

Figure 12. Response of System C.
Table 2. SNR of the FBG dynamic sensing systems.

| System   | SNR (dB) |
|----------|----------|
| System A | 17.97    |
| System B | 6.15     |
| System C | 4.74     |
| System D | 19.41    |

In the meantime, the results comparison between the 1550 nm based FBG dynamic systems, C and D, reveals a significant difference between the usage of two optical components; the optical circulator and optical coupler. Both components are known to be able to transmit the reflected light from the FBG sensor to the photo diodes. Yet, the optical powers received by the PDs, using an optical circulator are much greater than the one with an optical coupler.

For an FBG dynamic system with 50:50 ratio optical couplers, the optical power received by the PD is only about a quarter of the original power from broadband light source. Meanwhile, the light power in the circulator-based FBG dynamic system will remain at the same level until it reaches the FBG filter. As a result, a small wavelength variation due to dynamic strain at the FBG sensor give a big changes to the optical power level, before being received by the PD. Therefore it increases the SNR, thus raises the sensitivity of the sensor system. Note that, the System A or the NIR-FBG dynamic sensing with a fixed FBG filter actually utilized an optical coupler. However, its SNR value was as the same as the System D. Therefore, it is expected that if an optical circulator is used in the System B, instead of the coupler, the SNR and sensitivity of the system will increase.

However, the coupler-based system has its own benefit; whereby it allows many connections to be made through the system. Besides, the coupler also can perform as an optical divider. Consequently, the system can have several series of parallel systems, such as combining with FBG static measurement, or dynamic measuring system with several channels and etc. These extra capabilities would not be achievable with the circulator-based system.

4. Conclusions
This study has revealed that an FBG dynamic sensing system have an excellent capability to capture the acoustic waves that are consistent with the flexural wave propagations. It is supported by the small percentage of errors between results from FEA analysis and experimental results; which is below 1% for frequency not more than 1000 Hz. Meanwhile, based on the observation through SNR comparison...
for NIR-FBG and 1550 nm based systems; the NIR-FBG system was shown to have significantly higher SNR value, and therefore able to give more accurate results with less effort on the denoising. The outcomes of this study lead for a relatively cheaper option of an FBG system for dynamic response measurements.

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