Measuring variable amplitude loading with fibre optic

Wahyu Kuntjoro1,2*, Ramzyan Ramly1,2 and Najmuddin Assanah2

1 Aviation Technology Research, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
2 Flight Technology and Test Centre (FTTC), Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

*wkuntjoro@yahoo.com

Abstract. Cyclic loading is known to be responsible for fatigue failure. The variable amplitude loading is a general type of fatigue load and the most common one in practice. Monitoring of fatigue loading such as variable amplitude loads is commonly conducted using strain gauges. The use of fibre optics like fibre Bragg gratings (FBG) is attractive because this type of sensor is not easily interfered by the electromagnetic fields. Its suitability for measuring accurately the cyclic loadings need to be investigated. This paper is reporting the experiments to investigate the suitability of FBG to measure variable amplitude loadings. FBG test setup using a standard fiber optic measurement system was prepared and the cyclic test was conducted using universal testing machine. The fatigue test specimens used were prepared according to the ASTM E606 standards. The obtained result shows that FBG is able to measure variable amplitude loads and this means that FBG can potentially be used for fatigue monitoring of structures.

1. Introduction
Fatigue of structures happens due to cyclic loads and this can lead to catastrophic failure. This type of failure is dangerous as it happens suddenly. A way to avoid fatigue failure is by continuous monitoring of the structure, hence the term structural health monitoring (SHM). The structural deterioration over time due to fatigue can be predicted to calculate the remaining life by analyzing the gathered history data through SHM program [1]. Development of a fatigue monitoring to fighter aircrafts was reported by Kuntjoro et al. (2009) [2]. The analysis was based on Low Cycle Fatigue (LCF) and the monitoring was based on the accelerometer and strain-gauges that were installed on the airplanes.

To perform fatigue analysis, fatigue parameters must be known. One important parameter is fatigue load, in the form of cyclic load spectrum [3]. To obtain the fatigue load spectrum, a good sensor shall be attached to the structure. A sensor must be sensitive to the measured parameters, does not influence the behavior of structure, durable and sensitive to small changes. Strain gauges are normally applied for this purpose. However, the use of fiber optics such as fiber Bragg gratings (FBG) is attractive as this type of sensor is not easily interfered by the electromagnetic fields. FBG sensor is sensitive to the change of physical parameters by responding in the form of a reflected light wavelength shift in a very narrow bandwidth (typically 0.1-0.5 nm) [4].

Tahir et al. (2008) performed a comparison study between FBG sensor and electrical strain gauge for strain measurement [5]. They stated that their obtained FBG sensor data correlates better with the theoretical calculation. They found that FBG is immune to electromagnetic interface, can measure very high strain (>10,000 μm/m) and have good corrosion resistance. In another study, Li and Jiang (2009)
also reported that FBG can be used to measure very high strain [6]. Guan et al. (2000) found that fiber optic sensor can be used to measure both strain and temperature simultaneously [7]. This was achieved by measuring the transmitted intensity and wavelength at one of the loss peaks. Li et al. (2004) reported that fiber optics application for SHM has begun to widespread in civil engineering applications [8]. The use of fiber optics for SHM was reported in buildings, piles, bridges, pipelines, tunnels and also dams. Moreover, a research on the application of optical FBG sensor for composite honeycomb sandwiched panel monitoring was reported by Ramly et al. (2012) [9]. The FBG was embedded inside the layup and the research was aimed to identify delamination on the face of the panel.

A research of studying the response of FBG under variable amplitude load is reported in this paper. The idea is to make use of the data further for fatigue analysis. In this research, a standard specimen (ASTM E606) was used. FBG sensors were attached to the specimen and test configuration was set up. Comparison with load cell reading (which comes from strain gauge sensor) was performed.

2. Fatigue loads
The fatigue load or fatigue stress is often in the form of a sinusoidal pattern. Figure 1 illustrates some of the various stress-time relations. Figure 1(a) illustrates a complete reversed cycle of stress where the mean stress for this case is zero. On the other hand, Figure 1(b) illustrates a cyclic stress in which the maximum stress, $\sigma_{\text{max}}$, and the minimum stress, $\sigma_{\text{min}}$, are not equal to each other, and both are in tension. Last but not least, Figure 1(c) illustrates a rather general stress cycle on a component that is subjected to periodic unpredictable loads.

![Figure 1. Cyclic stress](image)

3. Fiber Bragg Grating (FBG)
Schematic diagram of FBG is shown in Figure 2. When light travels between the medium of different refractive indices, it may reflect and refract at the interface. Periodic perturbation of the core refractive index along the fibre length gives FBG the ability to work as a wavelength selective mirror. Bragg’s wavelength, $\lambda_B$, is defined at a condition when the reflectivity of the grating is maximum and is given as Eqn. 1, where $n_{\text{eff}}$ is the effective index of the grating in the fibre core and $\Lambda$ is the grating period.

$$\lambda_B = 2n_{\text{eff}}\Lambda$$ (1)
Under extension or compression, the grating spacing of FBG is changed and therefore causes a shift of the Bragg wavelength. The wavelength shift due to the strain is defined as given in Eqn. 2, where \( \varepsilon \) is the strain.

\[
\Delta \lambda = (1 - p_e) \lambda_B \varepsilon
\]  

(2)

The photoelastic coefficient, \( p_e \), is defined by Eqn. 3, where the \( p_{1i} \) coefficients are called the Pockel’s coefficient of the strain-optic tensor and \( v \) is the Poisson’s ratio [4].

\[
p_e = \left( \frac{n_{eff}^2}{2} [p_{12} - v(p_{11} + p_{12})] \right)
\]  

(3)

4. Cyclic load experiment

The test setup is shown in Figure 3. The equipment consists of FBG scanner, a notebook computer and the FBG itself as the sensor. The FBG was attached to the specimen. Variable loading was applied to the standard specimen (ASTM 606) to study the response from FBG sensor.

The specimen was tested using Universal Testing Machine available in the Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia. The setup was based on the variable
amplitude loading, involving some sequences of constant amplitude cycles. The variable loading input command is reflected in the load cell readings. Three specimens with FBG sensors were manufactured but only one specimen produced the proper results. The FBG sensors of the other two specimens were damaged during testing. The results are shown in Figure 4 and Figure 5.

![Load (kN) vs Time (s)](image1)

**Figure 4.** Variable loading applied to the standard specimen (load cell reading)

![Shifting WV (nm) vs Time (s)](image2)

**Figure 5.** Response from FBG sensor
Figure 4 is constructed based on load cell reading whereas Figure 5 is plotted based on the FBG wavelength shift. From both Figures 4 and 5, it is clear that not only the shape of the graphs is similar but both graphs also have the same proportion. It means that response from FBG sensor is consistent with the variation loading applied. Strain analysis of the FBG output can be obtained from equations 1-3 and a study is being done for that purpose. Nevertheless, there is no conclusive result as yet. It is noteworthy that the strain is potentially better to be found based on a direct proportion/scaling between the load cell reading and the FBG wavelength shift.

5. Conclusion
An investigation of FBG suitability for reading/sensing variable amplitude loading has been done. A fatigue specimen was prepared in accordance with ASTM 606. FBG fibre optics were attached to the specimens. A standard fibre optic test setup was prepared and the specimen was loaded under variable amplitude cycles using a Universal Testing Machine. The results show that response from FBG sensor is consistent with the variation loading applied. Hence it can be concluded that FBG is able to measure variable amplitude loads. There is a big FBG potential for application in aerospace engineering. It is especially attractive for application where the strain gauge is difficult or impossible to be used such as for sandwiched panel. However, this study also found out that FBG is fragile and needs to be carefully handled. The FBG sensor is better to be protected during tests by a kind of jacket, similar to jacket for cables.

References
[1] Balageas D. Structural health monitoring. ISTE Ltd 1st South Asian Edition, 2007
[2] Kuntjoro W, Ashari M S, Ahmad M, Mydin A M. Development of fatigue life monitoring of RMAF fighter airplanes. Book Chapter in ICAF 2009 – Bridging the Gap between Theory and Operational Practice, Springer.
[3] Budynas R G, Nisbett J K. Fatigue failure resulting from variable loading. Shigley’s Mechanical Engineering Design Book, McGraw Hill, 2008
[4] Fernando G F. Fiber optic sensor systems for monitoring composite structure. RP Asia 2005 Conference, 2005
[5] Tahir B A, Saktioto J, Fadhal M, Rahman R A, Ahmed A. A study of FBG sensor and electrical strain gauge for strain measurements. Journal of Optoelectronics and Advanced Materials 2008; 10(10): 2564 – 2568
[6] Li S, Jiang D. Structural large strain monitoring based on FBG sensor. Symposium on Photonics and Optoelectronics, 2009
[7] Guan B O, Tam H Y, Tao X M, Dong X Y. Simultaneous strain and temperature measurement using a superstructure Fiber Bragg Grating. IEEE Photonics Technology Letters 2000; 12(6): 675- 677.
[8] Li H N, Li D S, Song D B. Recent applications of fiber optic sensors to health monitoring in civil engineering. Engineering Structures 2004; 26(11): 1647-1657
[9] Ramly R, Kuntjoro W, Abd Rahman M K. Using embedded Fiber Bragg Grating (FBG) sensors in smart aircraft structure materials. Procedia Engineering 2012; 41: 600-606