Autonomous Structural Monitoring Using Fiber Bragg Grating

[1]Reza Adhami and [2]Houssam Toutanji
[1]ECE Department, [2]CE Department
University of Alabama in Huntsville Huntsville, AL 35899, USA
adhamir@uah.edu & toutanh@uah.edu

Abstract— **An autonomous structural monitoring system (ASMS) is a functional unit capable of sensing and assessing the health of a structure and reporting the status to a maintenance center for appropriate action. In this paper, such a system is presented. The main components of an ASMA are: power meter, broadband optical source, twin-core fiber, spring, fiber Bragg grating (FBG), and a wired or wireless transmitter. It has been shown that FBG has applications in strain and temperature measurements. A newly developed sensing head has been built and tested which consists of a spring and FBG and is used to sense displacement or cracks in various structures such as buildings, bridges, pipelines, ships…, etc. Here, the new sensing head is adapted to integrate the functions of the sensing head FBG and spring with an optical coupler and twin-core fiber into a displacement sensor unit. The proposed ASMS can be tuned for different structures and specifications.**

Index Terms— **Autonomous structural monitoring, FBG application, Sensor.**

I. INTRODUCTION

Structural-integrity assessment is vital to public safety and prolonging the lifetime of a structure. When structures are small enough for human inspection, there is no need for a sophisticated ASMS. However, it is not always possible to manually inspect structures, such as when the structures are massive or inaccessible. Imagine a natural gas pipeline stretching from one country to another passing through rough terrain. How easy it is to manually inspect this pipeline for gas leaks or other faults? How about monitoring the walls of a sky scraper for cracks? What about inspecting an unmanned vehicle orbiting in space?

Over the past several years, many structural monitoring systems have been proposed. A wireless structural health monitoring system for bridges was   proposed, built, and deployed in [1]. The concept of using FBG for structural monitoring is given in [2]. Both papers indicated that the system can be used in harsh conditions for strain measurement with temperature compensation. A real-time structural health monitoring using fiber optics accelerometer is introduced in [3]. This system integrates the Moire fringes with fiber optics to achieve accuracy and reliable measurements. Other systems such as [4]-[10] use different sensors including FBG. Traditional structural monitoring systems use strain gauges for sensing strain and stress in complex structures. Reasons for using strain gauges are: relatively inexpensive, flexible, sensitive to minor changes, and able to be packaged for durability. However, there are some shortcomings associated with using these gauges. For different applications, strain gauges made of different materials are needed. The gauges cannot be removed after installation without damage. Strain gauges have been around for a long time. In 1856, William Thompson (known as Lord Kelvin) noticed that strain/stress on some materials causes a change in electrical resistance of the materials. No notable activities are recorded regarding strain gauges until the 1930s when Charles Kearns, Arthur Ruge and Edward Simmons discovered that structural surface strain could be measured by bonding electrical wires to the material surface. This very simple idea was first used by aircraft manufacturers during World War II. Figure 1. is a rough sketch of a strain gauge.
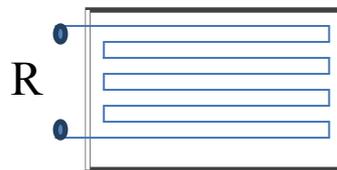

Figure 1 Strain Gauge

The strain applied to a wire is inversely proportional to the strain sensitivity of the wire, that is

$$\varepsilon = \frac{1}{S}\frac{dR}{R} . \qquad (1)$$

Where ε is the strain, R is the resistance of the wire at rest, and S is the strain gauge sensitivity factor.

Since $R = \rho\,\frac{L}{A}$, A and L are the cross section and length of the wire gauge, respectively, and ρ is the resistivity of the wire gauge material, the change in resistance is

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} \qquad (2)$$

If the radius of the wire is r, then $A = \pi r^2$ which implies $dA = 2\pi r dr$ and (2) becomes

$$\frac{dR}{R} = \frac{d\rho}{\rho} + (\frac{dL}{L} - 2\frac{dr}{r})$$

When the wire gauge is bonded to the surface of a structure, the deformation in the structure causes deformation in the wire gauge. The wire gauge strains in the longitudinal and radial directions are given by:

$$\varepsilon_L = \frac{dL}{L} \text{ and } \varepsilon_r = \frac{dr}{r} = -v\frac{dL}{L} = -v\varepsilon_L \qquad (3)$$

In (3), v is the Poisson's ratio. The change in the cross section is

$$\frac{dA}{A} = -2v\frac{dL}{L} \qquad (4)$$

Therefore,

$$\frac{dR}{R} = (1+2v)\varepsilon_L + \frac{d\rho}{\rho}. \qquad (5)$$

S, the strain gauge sensitivity factor is a number that depends on the wire gauge compound (approximately 2 for most metallic materials),

$$S = 1 + 2v + \frac{1}{\varepsilon_L}\frac{d\rho}{\rho} \qquad (6)$$

And since $S = \frac{1}{\varepsilon_L}\frac{dR}{R}$, we have

$$\varepsilon_L \approx \frac{1}{S}\frac{\Delta R}{R} \qquad (7)$$

The only unknown in (7) is $\frac{\Delta R}{R}$ which can be measured using the well-known Wheatstone Bridge.

II. FBG Sensor Head

A fiber Bragg grating wavelength shift is illustrated in Figure 2. In normal optical fiber, the refractive index remains uniform along the fiber length such that when light enters at one end it passes through the fiber with almost no reflection. However, this is not the case for FBG. In FBG, a periodic structure of indentation in the fiber core (grating) causes a small amount of light to reflect. That is, as light enters FBG, a narrow range of wavelength is reflected by the grating and the rest passes through the fiber. The Bragg wavelength is the center of this reflected wavelength. This phenomenon was first discovered by [Hill] in 1978.

A longitudinal strain in FBG causes a linear shift in the reflection wavelength of FBG. This characteristic of FBG can be utilized to sense small movements or strains such as cracks created on the surface of a structure.
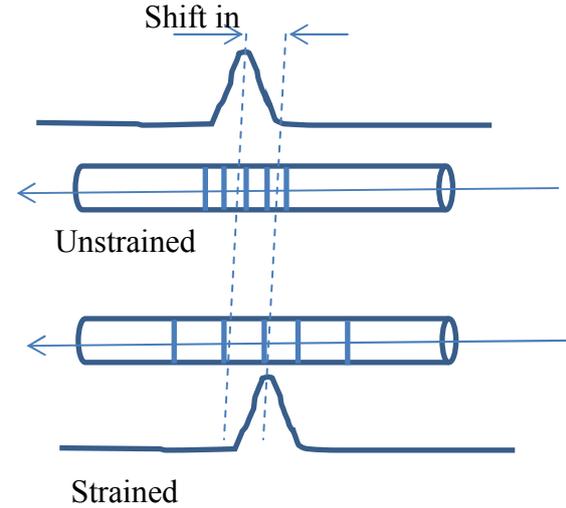

Figure 2. Illustration of wavelength shift in FBG.

The sensor which is developed by [11] consists of a spring and FBG, as shown in Figure 3. Most of the mathematical formulas mentioned here are from previous work of the author and his coauthors of [11].
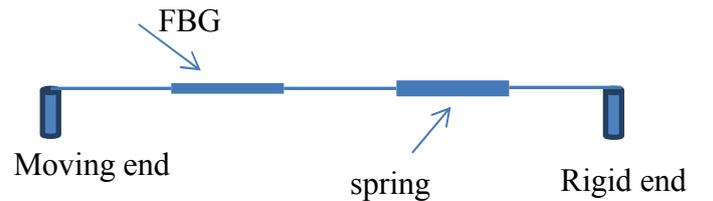

Figure 3. Sensing head using FBG

The Bragg wavelength is related to the effective refractive fiber index, n_{eff} and the period of the Bragg, Λ. That is

$$\lambda_B = 2n_{eff}\Lambda \qquad (7)$$

When the fiber is stretched, the Bragg period, Λ, changes which causes the reflected light's wavelength to shift. This shift provides enough information to detect the displacement.

It is shown,[11], that if the temperature is kept constant, then the shift of the Bragg wavelength is

$$\Delta\lambda_B = \{1 - \frac{1}{2}n^2_{eff}[P_{12} - \mu(P_{11} + P_{12})]\}\varepsilon_z\lambda_B \qquad (8)$$
$$= k_z\varepsilon_z\lambda_B$$

Where

$$k_z = 1 - \frac{1}{2}n^2_{eff}[P_{12} - \mu(P_{11} + P_{12})] \qquad (9)$$

is called the Bragg strain sensitivity and has an approximate value of 0.784. P_{11} and P_{12} are the Pockels coefficients (since these were first described by physicist Friedrich Pockels in 1906) and have values of 0.12 and 0.27, respectively. The parameter μ is called the Poisson coefficient, and is typically equal to 0.17.

Equation (7) shows that the relative shift of the Bragg wavelength is linearly related to the axial strain.

When strain is applied to the sensor, the spring will be stretched accordingly. The stretch in the spring is then measured which represents the displacement in the sensor head. Hooke's Law defines the tensile force as

$$|F| = kx \qquad (10)$$

where x is the spring displacement, k is the Hooke's coefficient of the spring, and x is the displacement. Here we only use the condition $x \geq 0$, since the strain causes a stretch not compression. Therefore, we can relate x, the displacement, to the tensile force, that is the FBG axial stress [11]. A simulation measurement of the sensing head performance is presented in [11].

III. FBG STRAIN GAUGE SENSOR SYSTEM

One possible method for testing the FBG sensing head given in Figure 3 is to use the following arrangement of the sensor head, a twin-core fiber, a fiber coupler, and a broadband light source. Figure 4 is a drawing of the experimental setup.
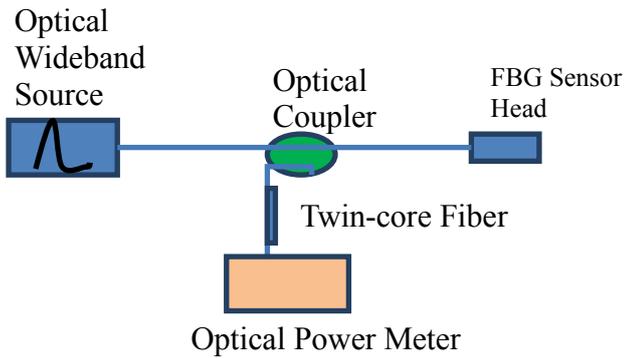

Figure 4. FBG Strain Gauge System

The function of this system is very straight forward. The wideband source emits light into the fiber which is reflected by the FBG in the sensor head. When there is a displacement, the wavelength of the reflected light will be shifted due to the property of the FBG. This reflected light carries displacement information. The reflected light enters the optical power meter through a twin-core fiber for the displacement measurement. In our experiment, we used an FBG with the central wavelength of 1556.990nm at the room temperature. The bandwidth of the reflected wave was 0.2nm. It was observed that for different displacements, the intensity of the reflected light remains linear. Figure 5 shows a plot of reflected intensity versus displacement.
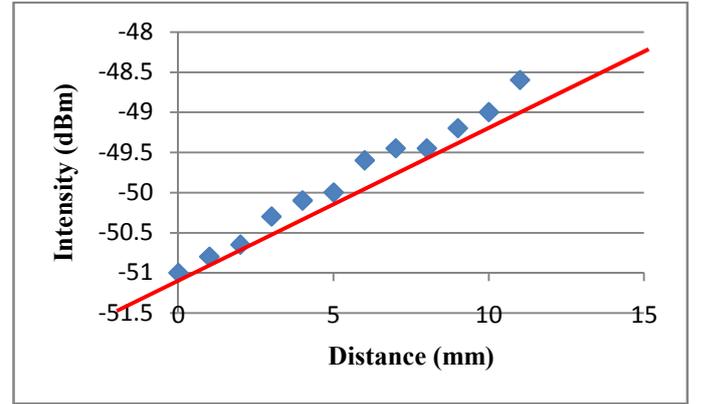

Figure 5. Reflected intensity versus displacement

IV. MULTICHANNEL FBG STRAIN GAUGE SENSOR SYSTEM

For monitoring large areas of a structure, a single FBG strain gauge sensor is not adequate. A mesh structured version of the system explained in section III could be easily developed to monitor large areas, see Figure 6.
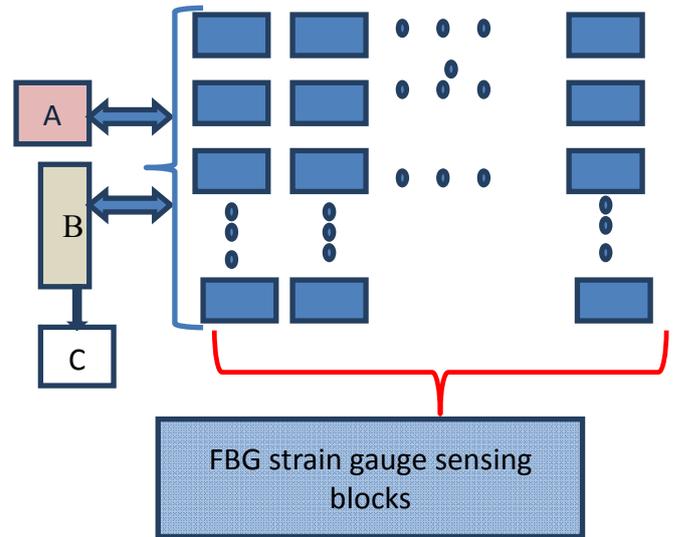

Figure 6. Multi channel FBG Strain Gauge System

Where A is the signal source and
      B is the power meter
      C= Transmitter

The blocks on the right side are identical. The interconnection for each block is given in Figure 7.
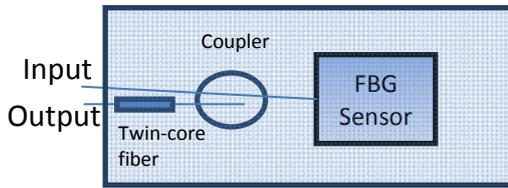

Figure 7. Sensing block

Each module in Figure 6 consists of an FBG strain gauge displacement sensor, an optical coupler, and a twin core fiber. There are two connectors, Input and Output. The Input connector is connected to the optical source and the Output, which is simply the reflected wave from the FBG sensor, carries the displacement information. The Output connector is connected to power meter B. The transmitter communicates displacement provided by the power meter to a central unit either through a wireless or wired channel.

V. CONCLUSIONS

In this paper, a new autonomous structural monitoring system (ASMS) is proposed. The system's strain gauge sensor is a modified version of a strain gauge sensor which was recently developed [11]. A theoretical analysis of the sensor and the system were discussed. This system may be utilized to detect and broadcast cracks in structures such as buildings, bridges, pipelines, ships…, etc. Depending on the types of springs and FBG length, the system can be utilized for different crack sizes. We have tested the system for cracks ranging from 1 to 10 mm. The results are shown in Figure 5. A system's sensitivity can be tuned according to the desired specification. The major parts of the system, which are fiber optics-based, can be fabricated in one piece. The system's components are relatively inexpensive and, therefore, the system can be fabricated cheaply. The only mechanical part of the system is the spring which could lose its sensitivity in the long run. The system is not as sensitive to temperature as is the traditional resistive strain gauge mentioned in the introduction section.

References
1. Alvaro Araujo, Jaime García-Palacios,et al, "Wireless Measurement System for Structural Health Monitoring With High Time-Synchronization Accuracy", IEEE transactions on Instrumentation and Measurement, Vol. 61, No 3, March 2012.
2. M. R. Mokhtar, K. Owens, et al., "Fiber-Optic Strain Sensor System With Temperature Compensation for Arch Bridge Condition Monitoring", IEEE Sensors Journal, Vol. 12, NO 5, May 2012.
3. Dae-Hyun Kim and Maria Q. Feng, "Real-Time Structural Health Monitoring Using a Novel Fiber-Optic Accelerometer System", IEEE Sensor Journal, Vol. 7, No. 4, April 2012.
4. Baofu Lu, Belle R. Upadhyaya, Senior Member, IEEE, and Rafael B. Perez, "Structural Integrity Monitoring of Steam Generator Tubing Using Transient Acoustic Signal Analysis", IEEE Transaction on Nuclear Science, Vol. 52, No. 1, February 2005.
5. D.M. Peairs, G. Park, D.J. Inman," Improving Accessibility of the Impedance-Based Structural Health Monitoring Method, Journal of Intelligent Material Systems and Structures", vol. 15, pp. 129-139, February 2004.
6. Lalande, F., Childs, B., Chaudhry, Z., and Rogers, "High-Frequency Impedance Analysis for NDE of Complex Precision Parts", Proceedings of SPIE Conference on Smart Structures and Materials, SPIE Publishing, V. C.A. 1996, pp.237-245.
7. Yuan-Feng Duan and Yi Li, "Strain-Temperature Correlation Analysis of a Tied Arch Bridge Using Monitoring Data", Multimedia technology (ICMT), 2011 International Conference on Digital Object Identifier, pp 6025-6-28.
8. A. D. Kersey, M. A. Davis et al., Fiber grating sensors", IEEE J. Lightwave Technol., Vol. 15, No.8, pp. 1442-1463, 1997.
9. N. E. Fisher, P. J. Henderson and D. A. Jackson, "The interrogation of a conventional current transformer using an in-fibre Bragg grating", Meas.Sci. Technol., Vol. 8, No. 10, pp. 1080–1084, 1997.
10. A. M. Wahbeh, J.P. Caffrey, and S. F. Masri. "A vision-based approach for the direct measurement of displacements in vibrating systems. Smart Materials and Structures", 12:785-794, 2003.
11. Yi Zou, X. Dong, G. Lin, and R. Adhami, Wide Range FBG Displacement Sensor Based on Twin-Core Fiber Filter, Journal of Lighwave Technology, Vol. 30, February 1, 2012.