Supported by tetfund

DEVELOPMENT OF FIBRE BRAGG GRATING SENSOR MODEL FOR SIMULTANEOUS MONITORY OF STRAIN, STRESS AND APPLIED LOAD ON COMPOSITE STRUCTURES

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Received: August 07, 2020 **Accepted:** December 13, 2020

Abstract: This research work presents the development of fibre Bragg grating sensor model for simultaneous monitory of strain, stress and applied load on composite structures. The deployment of composite structures in harsh environment makes Structural Health Monitoring (SHM) system of great important. Point sensing is a process whereby a sensor senses physical parameter on a specific spot on the composite structure in which they are deployed. Most point sensors sense only one physical parameter which is subject to the nature of their encapsulation. Point sensors are generally classified into two broad areas they are the interferometric and the FBG sensors. In the distributed sensing the length of the fibre is the sensor or an array of sensor is inscribed in the length of the optical fibre. Distributed sensing is classified into Distributed Optical Fibre Sensor (DOFS) and Distributed Fibre Bragg Grating Sensor (DFBGS). In this work, with the aid of relationship model the measuring capacity of FBG point sensor is extended to simultaneously compute the values of strain, stress and load. By accounting for strain values and extending it to obtaining stress and applied load components on the structure, respectively. This in turn reduces the number of sensors deployed during monitoring, there for reducing cost of deployment and network complexity without depleting the sensors efficiency. Furthermore, the shift in Bragg wavelength for the enhanced FBG (*i*FBG) was plotted against that of the conventional FBG (FBG). The graphs show that the shift in Bragg wavelength for the enhanced FBG sensitivity is higher than that of the conventional FBG. It is due to the increase in Poisson's ratio and decrease in effective refractive index of the FBG sensor.

Keywords: Multi-physical parameter point sensing, distributed FBG sensors, distributed FOS

Introduction

The deployment of composite structures in harsh environment makes Structural Health Monitoring (SHM) system of great important. SHM technology is geared towards identification, localization, and quantification of damage in structures at an initial stage in order to avoid unexpected failure (Amafabia *et al.,* 2018). Most SHM methods are based on the identification of deviations from a standard condition of structures (Amafabia *et al.,* 2018). The main reason that enables the sensing features in optical fibres is that the environmental factors affect the constituent properties of the optical fibre media (Luca, 2017). Fibre Optics Sensor (FOS) sensors are classified basically into point sensors, Bragg grating sensors and distributed sensors respectively. In this work, a multi-physical parameter Fibre Bragg Grating (FBG) point sensor was developed for simultaneous monitoring of strain, stress and applied load on composite structure.

The following is an overview of some fundamental concepts of this study.

(A) Point Sensing

Point sensing is a process whereby a sensor senses physical parameter on a specific spot on the composite structure in which they are deployed. Most point sensors sense only one physical parameter, this is subject to the nature of their encapsulation. Point sensors are generally classified into two broad areas they are the interferometric sensors and the fibre Bragg grating sensors.

Iinterferometric Sensors: The interferometric sensors are made up of an intrinsic or extrinsic interferometric cavity along an optical path (Lee *et al.,* 2012). The obvious changes in the structures due to the presence of the physical parameters are reflected in the sensor by the modifications in the optical phase difference between two interference light waves and the optical path length difference (Guo *et al.,* 2011). The interferometric sensors are Fabry Perot Interferometer, Structural Monitoring by Fibre Optics, Mach Zehnder Interferometer, Michelson Interferometer and Sagnac Interferometer.

Fibre Bragg Grating (FBG) Sensor: The point sensing operation in this case is obtained when the FBG senses a specific (for instance strain) physical parameter on the spot or a known location on the composite structure. When broadband light propagates in the fibre medium it interacts with the FBG sensor and a narrow band light is reflected back to the source while the rest are transmitted as shown in Fig. 1. The reflected narrow band light is subject to the presence of the physical parameter exacted on the composite structure. The various types of FBG sensors are as follows; standard grating sensor, long period sensor, chirped grating sensor, tilted grating sensor and superstructure grating sensor.

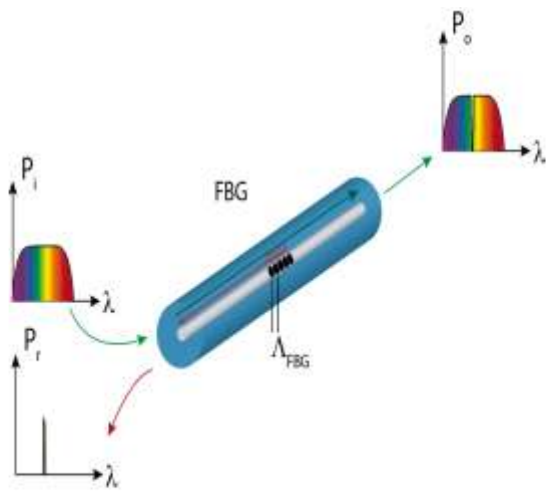

Fig. 1: FBG point sensor working principle (Garcia *et al.,* 2015)

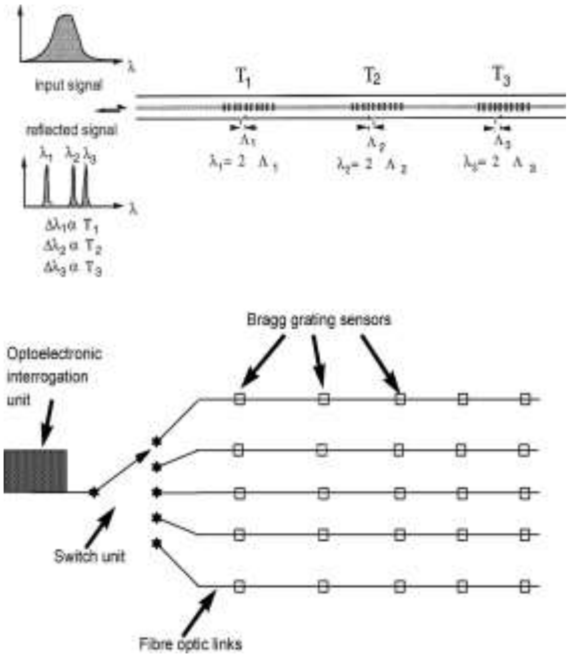

Fig. 2: FBG Sensor Array forLarge Scale Monitoring System (Brian & Alan, 2008)

(B) Distributed Sensing

Distributed sensing can be archived by Distributed Optical Fibre Sensor (DOFS) and Distributed Fibre Bragg GratingSensor (DFBGS).

Distributed Optical Fibre Sensors: In Distributed Optical Fibre Sensor (DOFS) the optical path length or the entire length of the fibre optics cable is the sensor. It spans over a very large area of deployment for sensing purpose. The operation of DOFS is based on the scattering process that occurs in an optical media when light propagates the fibre. The scattering mechanisms in the optical path are Rayleigh, Raman and Brillouin scattering. Rayleigh scattering is an elastic process resulting from local variations of refractive index due to heterogeneity and density fluctuation of the material (Luca, 2017). While Raman and Brillouin scattering are inelastic process that affect the intensity of the anti-Stokes and Stokes signal due to direct effect of the environmental conditions mainly strain and temperature (Guo *et al.,* 2011).

Distributed Fibre Bragg Grating Sensor: The Distributed Fibre Bragg Grating Sensor (DFBGS) is based on deploying an array of FBGsensors over a large area. The distributed sensing operation of an FBG sensor is actualized when many (some time over hundred) FBG sensors are inscribed in an optical fibre cable to uniquely (base on encapsulation) sense one physical parameter across the optical path length individually. The purpose of deploying DFBGS in structural health monitoring system is to achieve a wide area of monitoring coverageand a simultaneous monitoring of different physical parameters in the area as a distributed point sensor as shown in Fig. 2.

The following presents a review of some works that are related to this study.

Michelle (2014) proposed an approach for damage identification in composite materials by means of piezoelectric actuators and sensors for SHM. The composite panels are made using the Vacuum Assisted Resin Transfer Molding (VARM) method. The materials are cut into small coupons (254 x 25.4 mm) to test different characteristics of the composite materials. The piezoelectric actuators are mounted on the surface of composite specimen to produce Lamb waves. The other end of the surface is being mounted by a piezoelectric sensor which quantifies the response of the transmitted wave. The piezoelectric actuator and piezoelectric sensor were surface mounted to the coupon using double sided tape. Different excitations of Lamb waves were varied using LabVIEW software to set input parameters and for synchronization of data acquisition. Data were obtained from an undamaged composite specimen under observation, and the process is also carried out for the damaged coupon. The damage component was obtained by equating the response of the damaged coupon and the undamaged one. The drawback of the technique was the dispersive nature of the composite panels which limits the travel distance leading to deployment of more sensors which makes the network complex.

Fabio *et al*. (2015) proposed an Electrical Strain Gauge (ESG) measurements approach as a method for sensing and identification of damage. Due to their high sensitivity to damage localization. The technique uses strain related estimations like mode curvature strain frequency response function and strain energy as the engineering indices for recognizing damage. The numerical and experimental models were done to assess the performance of the strain gauge measurements. The experimental results consequences of the ground vibration testing of a F-16 airplane shows how the visual interpretation of the strain modes were harder to be done, when contrasted with the displacement modes. In addition, the high sensitivity of the strain modes was evident, as the modes were able to show clearly the areas of with high strain concentration which are not clear when compared with the displacement modes. However, the deployment of this technique was complex because large numbers ESG sensors deployed with many connecting cables which leads to network complexity and sensors are also susceptible to electromagnetic interference.

Margherita *et al.* (2017) proposed a non-destructive assessment algorithm for the recognition of defects on composite airplane structures following High Energy Wide Area Blunt Impact (HEWABI) procedure for ground service equipment. The work employed the waveguide geometry of these structures by using ultrasonic guided waves and a line scan method. The contact model and a non-contact model were created and tried on realistic test boards panels subjected to impact in the test bed. Two laboratory models for line checking were created, one utilizing contact piezoelectric transducers with a differential methodology and utilizing non-contact (air-coupled) transducers in a pitch–catch approach. The review utilized a statistical analysis that compensates every quantification of the normal (baseline) variation during the scan, in this manner increasing the true detection and reducing false detection. The results were presented in terms of receiver operating characteristic curves. The curve shows great probability of detection with low false alarm for identifying areas in panel skin and stringers. However, the high energy for wide area coverage is needed and the wave scattering sources such as rivets, fasteners, stiffeners, and joints, limit the effectiveness of the technique which may lead to the deployment of more sensors therefore, making the network complex.

Ejiko & Olakolegun (2018) designed and constructed indigenous Electrical Strain Gauge (ESG) equipment for measuring strain and applied load for Structural Health Monitoring (SHM). The developed indigenous strain gauge has a height of 1.22 m and could accommodate samples of 5 to 10 mm diameters with a gauge length of 200 mm; coupled to it is a transducer to magnify the strain signal for efficient strain calibration. The construction was designed to withstand a load of 1000N. The ratio of deformation (Strain) with reference to load increment correlates with the theoretical strain gauge model. The rigidity of the design is dependable and the equipment performance is effective. The strain measured with the equipment was directly proportional to the theoretical strain. However, the limitations of the work are bulky size, complex sensor network and a high susceptibility to electromagnetic interference.

Materials and Methods

The proposed model for simultaneous monitoring of strain, stress and load was achieve by determining the relationship model and multi-parameter point sensing model as expressed below.

(a) Strain, stress and applied load relationship model

The modulus of elasticity *(E)* is the material characteristics, that expresses its stiffness and it is an important property of solid materials (David, 2008). Stress is the force exacted on a structure per unit area. Strain is the elongation (contraction) per unit length when a material is strain elastically (David, 2008). The amount of deformation on the materials depends on the size. Strain and stress are related by Hooke´s Law as shown in equation (1). From the Hook's modulus of elasticity which is the ratio of stress to strain on the structure is expressed by equation (2) (David, 2008);

$$\sigma = E \times \varepsilon \qquad (1)$$
$$E = \sigma/\varepsilon \qquad (2)$$

Where σ is stress and ε is strain. For equation (3), (4) and (5), F is the applied load and A is the area. They express the relationship between stress, strain and applied load on the composite structures (David, 2008).

$$\sigma = F/A \qquad (3)$$
$$\varepsilon = F/E \times A \qquad (4)$$
$$F = \varepsilon \times E \times A \qquad (5)$$

In this research the modulus of elasticity of the composite material is 135GPa it was adopted from the Technical Data Sheet No.CFA-005 of the Toray Carbon Fibres America (TORAYCA Data Sheet, 2019). The induced strain on the composite structure is related to the strain in the FBG sensor as described in equation (6) (Limin *et al.*, 2012);

$$\Delta\lambda_B/\lambda_B = (1\text{-}p_e) \times \Delta\varepsilon \qquad (6)$$

Where $\Delta\varepsilon$ is the change in the applied local strain on the composite structure and (1-p_e) is the Gauge Factor of the FBG sensor also represented as k_{GF} (Florian *et al.*, 2013). The FBG relationship model for the strain in the FBG sensor for stress and applied load are obtained as shown in equation (7) and (8), respectively (David, 2008) and (Limin *et al.*, 2012);

$$\Delta\lambda_B/\lambda_B = k_{GF} \times \sigma \qquad (7)$$
$$\Delta\lambda_B/\lambda_B = k_{GF} \times F \qquad (8)$$

Where σ and F are the stress and applied load on the composite structure, respectively.

(b) Extended measurement capacity of FBG as a multi-physical parameter point sensing model

The FBG sensor has the advantage to operate as a point sensor as well as a distributed point sensor asa Fibre Optics Strain Sensor (FOSS). The distributed point sensing operation of an FBG sensor is actualized when more than one (sometime over hundred) FBG are inscribed in an optical fibre cable to uniquely (base on encapsulation) sense one physical parameter across the optical path length individually. The point sensing operation is obtained when the FBG senses a physical parameter at a spot. When a load is applied on a composite structure, the applied load induces stress and strain on the structure. This implies that stress and applied load component can be quantified alongside with the induced strain on the structure. In order words, the FBG sensor can measure more than one physical parameters (strain, stress and applied load) compared with the conventional FBG sensor (state of the art sensors) that measures only one physical parameter as a point sense. This is archived by the stress, strain and applied load relationship model which can further extend the capability of the FBG operating as a point sensor in measuring more than one physical parameters. By substituting the value of the stress and applied load in equations (3) and (5) into equation (6). To extend the FBG sensor capability to sense more than one physical parameter, multiplying equation (7) and (8) by the Bragg wavelength (λ_B) to obtain equation (9) and (10). The FBG capacity is extended to measure more physical quantities as a multi-parameter point sensor which outperform state-of-the-art method is shown in equation (9) and (10), respectively:

$$\Delta\lambda_B = \lambda_B \times k_{GF} \times \sigma \qquad (9)$$
$$\Delta\lambda_B = \lambda_B \times k_{GF} \times F \qquad (10)$$

Where $\Delta\lambda_B$ is the FBG sensitivity, λ_B is the Bragg wavelength, σ is the applied stress,
F is the applied load and k_{GF} is the proportionality constant of the effective strain optics coefficient of the FBG sensor. To obtain the simplified values of stress applied load component, substituting equation (1) into (6) and (9) into (10) to obtain equation (11) and (12) is the simplified expression for the extend measurement for the FBG sensor as shown below:

$$\Delta\lambda_B = \lambda_B \times k_{GF} \times E.\times \varepsilon \qquad (11)$$
$$\Delta\lambda_B = \lambda_B \times k_{GF} \times \varepsilon \times E \times A \qquad (12)$$

Where A is the sensing area of the FBG sensor, E is the modulus of elasticity of the composite material and ε is the induced strain on the composite structure.
The Flow chart of the proposed model is shown in Fig. 3.

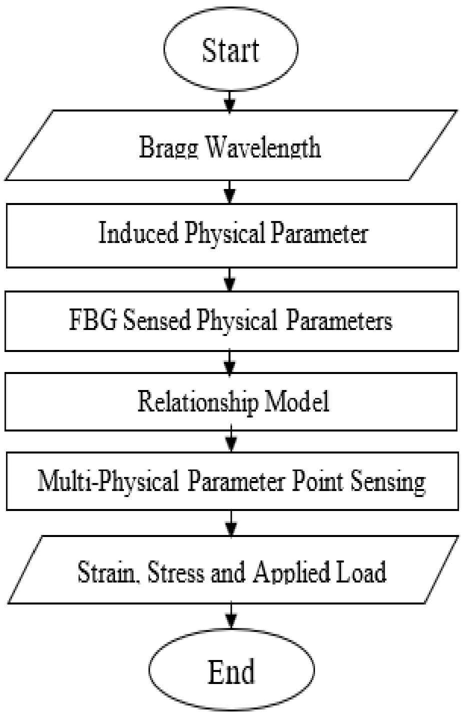

Fig. 3: Flow chart of the developed work

Results and Discussion

The results obtained from the simulation in this research work are discussed in this section. The following results are based on the Shift in Bragg Wavelength to induced strain, stress and applied load on the composite structure are discussed below.
In Fig. 4, the shifts in Bragg wavelength were plotted against the induced strains on composite structure. The plot was obtained from the simulation values in Table 1. Table 1 was obtained from equations (6). From the plot, it is observed that the shift in Bragg wavelength due to induced strain on the structure is higher for the improved FBG model (*i*FBG) when compared with the conventional FBG model. This is due to

the increase in Poisson's ratio and decrease in effective refractive index of the FBG sensor.

Table 1: Induced strain and sensitivity of the fibre Bragg grating sensor

Strain (με)	*i*FBG (pm)	FBG (pm)
0	0	0
50	66.050	50.03
100	132.10	100.01
150	198.15	150.01
200	264.20	200.01
250	330.25	250.02

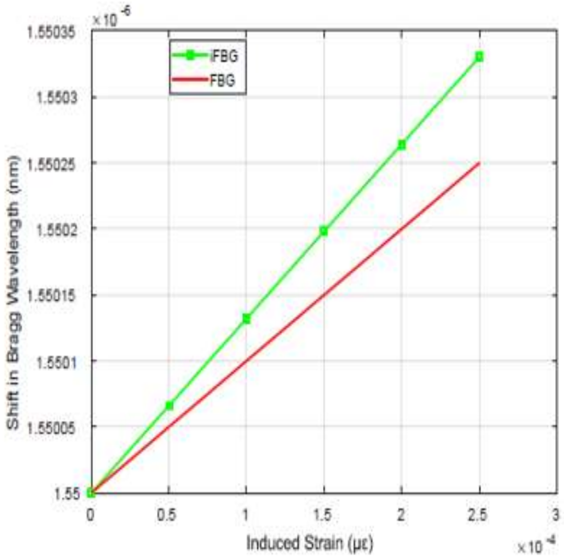

Fig. 4: Plot of the Shift in Bragg Wavelength against Induced Strain on the composite structure

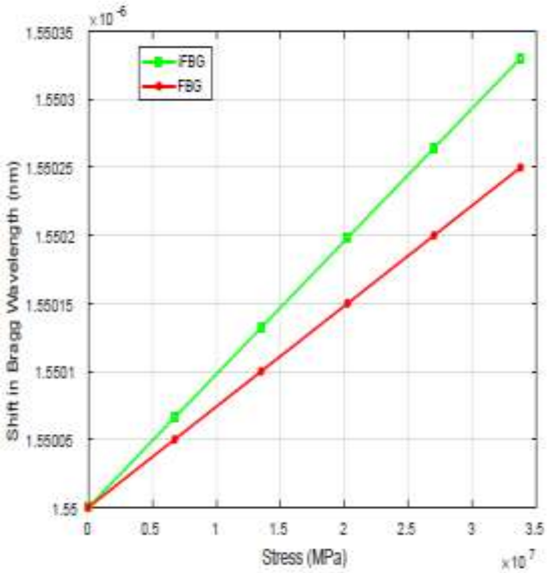

Fig. 5: A Plot of shift in Bragg wavelength against stress on the structure

In Fig. 5, the shift in Bragg wavelength was plotted against the stresson the composite structure. The plot was obtained from the simulation values in Table 2. Table 2 was generated using equation (11). From the plot, it is observed that the shift in Bragg wavelength due to stress for the enhanced FBG sensitivity (*i*FBG) is higher than that of the conventional FBG sensitivity (FBG). It is due to the increase in Poisson's ratio and decrease in effective refractive index of the FBG sensor.

Table 2: Induced stress on the composite structure and fibre Bragg grading sensitivity

Stress (MPa)	*i*FBG (pm)	FBG (pm)
0	0	0
6.7500	66.050	50.03
13.500	132.10	100.01
20.250	198.15	150.01
27.00	264.20	200.01
33.75	330.25	250.02

Table 3: Applied load on the structure and FBG sensitivity

Load (N)	*i*FBG (pm)	FBG (pm)
0	0	0
3375000	66.050	50.03
6750000	132.10	100.01
10125000	198.15	150.01
13500000	264.20	200.01
16875000	330.25	250.02

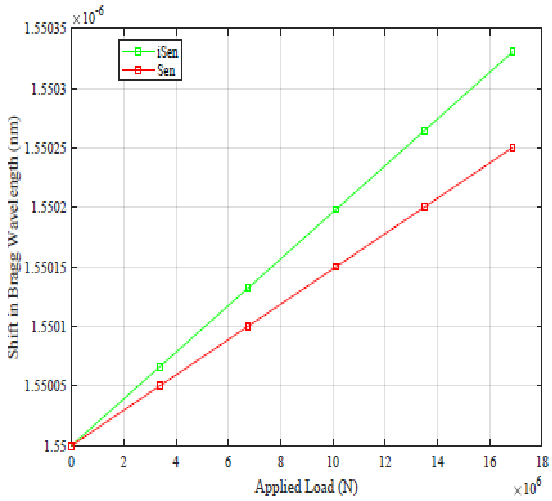

Fig. 6: A plot of shift in Bragg wavelength against applied load on the structure

In Fig. 6, the shift in Bragg wavelength was plotted against the applied load on the composite structure. The plot was obtained from the simulation values in Table 3. Table 3 was generated using equation (12). From the plot, it was observed that the shift in Bragg wavelength due to applied load on the structure for the enhanced FBG sensitivity (*i*FBG) is higher than that of the conventional FBG sensitivity (FBG). It is due to the increase in Poisson's ratio and decrease in effective refractive index of the FBG sensor.

Conclusions

In this research work, the development of fibre Bragg grating sensor model for simultaneous monitory of strain, stress and applied load on composite structure was presented. Point sensing is a process whereby a sensor senses physical parameter on a specific spot on the composite structure in which they are deployed. Most point sensors sense only one physical parameter which is subject to the nature of their encapsulation. With the aid of relationship model the measured strain value on the composite structure is extended to account for stress and applied load measurement. This in turn reduces the number of sensors deployed during monitoring, reducing cost in deployment and network complexity without compromising the sensor efficiency.

Conflict of Interest

The authors declare that there is no conflict of interest related to this study.

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