Towards Use of Fiber Bragg Grating Sensors for Structural Health Monitoring of (aero)Space Structures

Mihai Tudose, Daniela Enciu, and Ioan Ursu

***Abstract*—In the present paper is made a state-of-the-art of Fiber Brag Grating sensors in R&D domain. Moreover, a test protocol and experimental measurements using optical fibers are developed. First of all, free FBG (not bonded on the substrate) were studied to determine the sensitivity to temperature variations. It has been found that the Bragg wavelength has a linear variation with temperature. This variation is due both to the strain generated as a result of the expansion of the optical fiber component (glass) and to the change in the refractive index of the glass with the temperature. Next, the measurements were done with sensors bonded to the aluminium substrate and subjected to different scenarios of temperature and/or mechanical deformations. The results show the variation of the Bragg wavelength of the optical fiber with respect to the applied load and the temperature of the substrate to which it was bonded. These experimental researches have been made as a first step for Structural Health Monitoring applications in the field of (aero)space structures.**

***Index Terms*—Structural health monitoring, fiber bragg grating, space and aerospace applications, optical fibers.**

I. Introduction

Optical Fiber Bragg Grating (FBG) have emerged as key candidates for the development of SHM systems. The latest trends in structural health monitoring for aircraft structures based on FBG sensors include detection in situ of structural mechanical stresses, but also the detection of other parameters related to the structures [1], [2]. So far, many technologies based on FBG sensors have been developed and some of them are already commercially available. Generally, fiber-optic sensors can be categorized into three categories: interferometric sensors (Fabry-Perot sensors), distributed sensors (Rayleigh scattering based distributed sensors, Raman scattering sensors, Brillouin scattering sensors) and grating-based sensors (Fiber Bragg Gratings sensors - FBG) [3]-[5]. Each category targets different types of measurements and applications.

Optical fibers are already present in structural health monitoring in the fields of civil engineering, infrastructures, telecommunications, and are becoming more and more attractive for aerospace and even space applications [6] - [11]. A first step to convert optical fibers into sensors to monitor the health of structures is to achieve with their help a high-accuracy response based on a sensitive variation in wavelength to a very low deformation of the structure. An algorithm processing the data measured with FBG, capable of sub-micron identification of the deformations is proposed in paper [9]. An innovative approach to identifying and localizing defects using fiber optics without other ultrasonic waves is based on a method used in statistics and form recognition [12].

Characteristics that recommend optical fibers for applications (measurements) are: immunity to electromagnetic interference, very low weight (few grams), the ability to cover a large area of monitoring, small size, broadband wavelength, low loss of information, high sensitivity, corrosion and water resistance, serial or parallel multiplexing, excellent resolution, etc. The disadvantage is given by the high costs for the purchase of the instrumentation (optical interrogator etc.). With optical fibers, the following parameters can be monitored: deformation (strain), tension (stress), vibration, temperature, pressure, concentration and leakage of gases.

Bragg fiber optic sensors have been investigated as an alternative to piezoelectric sensors for ultrasonic wave detection [6], [9], [12]. FBGs have a number of advantages in terms of durability, lightweight, ease of incorporation into composite structures, immunity to electromagnetic interference as well as ease of optical multiplexing.

Permanently installed (embedded) sensors can examine the structures at any time, throughout their lifetime, ensure the superiority of SHM technology versus the conventional ones, portable, non-destructive ultrasonic testing technologies. Combined with appropriate data analysis algorithms, SHM technologies can continue to provide information at all times about structural integrity, health status assessment, and diagnosis of important components concerning structural safety. The need to identify structural damage and monitor their evolution has been stimulated by the development of SHM systems and methodologies in recent years.

II. FBG Sensing Principle

The FBG sensor is characterized by a permanent change in the core of the fiber, taking into account the special techniques with which it is made. It reflects a portion of the input light, a certain wavelength, called the Bragg wavelength, and lets the rest of the input light pass without changing its properties. Bragg wavelength is defined by the refractive index of the fiber and the grid step, which are affected by changes in the external environment, such as temperature, strain, vibrations and other parameters. All these changes result in a change in Bragg wavelength, Fig. 1.

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The Bragg wavelength varies depending on the mechanical stress (strain) and the temperature at which the FBG is subjected.

When an axial stress is applied to the fiber, the fiber grating length changes and the Bragg wavelength moves to smaller Bragg wavelengths (at compression), or longer Bragg wavelengths (at traction). The change of Bragg wavelength is linear with respect to the applied axial mechanical stress. Multiple Bragg gratings that are designed to operate at different wavelengths can be spatially distributed over the length of the optical fiber.

Therefore, by monitoring the Bragg wavelength, several parameters can be monitored by FBG sensors. Current technology makes it possible to multiplex tens or hundreds of FBG sensors in a single optical fiber and to be monitored remotely. With the rapid development of recent years, FBG sensors have been selected as the major leader in comparison to other technologies competing with optical fiber sensors. In addition to the wavelength multiplexing capability, FBG sensors have a number of advantages such as low cost, compact size and good linearity. The length of the grating is usually in the order of 10 mm. The wavelength resolution depends on the interrogator and is currently up to 1 pm corresponding to 1 με measurement of strain and 0.1°C for temperature measurement.

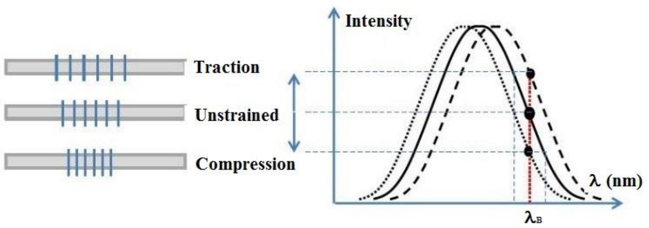


Fig. 1. The operating principle of an FBG interrogator.

The wavelength of the FBG changes with the strain or temperature according to the equation

$$\frac{\Delta\lambda}{\lambda_0} = K * \varepsilon + a_g * \Delta T \quad (1)$$

where $\Delta\lambda$ - wavelength shift, λ_0 - initial wavelength, $K = 1 - p$ $K = 0.78$, p - strain-optic coefficient $p = 0.22$, ε - strain, ΔT - temperature variation $[K]$, a_g - thermo-optic coefficient

$$\varepsilon = \varepsilon_m + \varepsilon_T \quad (2)$$

$$\varepsilon_T = \alpha_{sp} \cdot \Delta T \quad (3)$$

ε_m - strain induced by mechanical factors, ε_T - strain induced by temperature, α_{sp} - thermal expansion coefficient

$$\frac{\Delta\lambda}{\lambda_0} = K\left(\varepsilon_m + \alpha_{sp}\Delta T\right) + \alpha_g \cdot \Delta T$$

$$\frac{\Delta\lambda}{\lambda_0} = K\varepsilon_m + \left(K\alpha_{sp} + \alpha_g\right)\Delta T \quad (4)$$

The equation for measuring strain is given by

$$\varepsilon_m = \frac{1}{K}\frac{\Delta\lambda}{\lambda_0} - \left(\alpha_{sp} + \frac{\alpha_g}{K}\right)\Delta T \quad (5)$$

For a FBG sensor measuring only the temperature sensor, and the equation (4) becomes

$$\frac{\Delta\lambda}{\lambda_0} = \left(K\alpha_{sp} + \alpha_g\right)\Delta T \quad (6)$$

The equation giving the temperature is

$$\Delta T = \frac{1}{K\alpha_{sp} + \alpha_g} \cdot \frac{\Delta\lambda}{\lambda_0} \quad (7)$$

For FBG sensors that measure the strain a temperature compensation procedure is required to be applied to remove the effect of this factor.

III. Experimental Setup and Results

Initially, within INCAS Mechatronics Laboratory were performed measurements on FBG sensors not bonded on the substrate to highlight the influence of ambient temperature on the spectral characteristic of the sensor and to confirm its operation under extreme temperature conditions. For calibration at room temperature, the sensor was inserted into a TECHNE thermostatic bath and the measurements were made via a Labview interface. Different kind of FBG sensors were subjected to tests. In Fig. 2 are the results for OS 1100 Micron Optics (MO) FBG sensor with nominal wavelength of 1552 nm. The temperature ranges from +30 °C to +120 °C with steps of 10 °C using the FD 115 Binder thermostated oven.

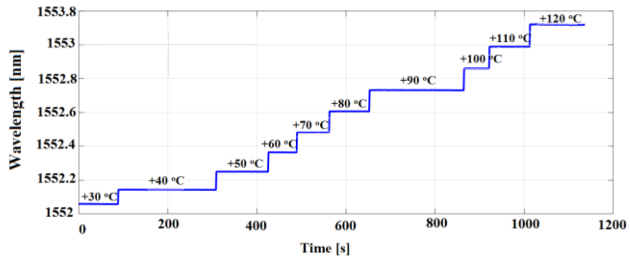


Fig. 2. Bragg wavelength variation of the OS110-MO sensor with nominal λ = 1552nm.

The average wavelengths measured on each temperature range were calculated and the variation graph of Bragg wavelengths according to ambient temperature was plotted. This graph is shown in Fig. 3, along with the line which approximates the measured curve.

The average wavelengths measured on each temperature range were calculated and the variation graph of Bragg wavelengths according to ambient temperature was plotted in the temperature range from + 30 ℃ to + 120 ℃. This graph is shown in Fig. 3, along with the straight line which approximates the measured curve. This graph shows that the variation with the temperature of the Bragg wavelength is linear and that the wavelength sensitivity of the FBG sensor OS1100-MO is about 12 pm/°C.

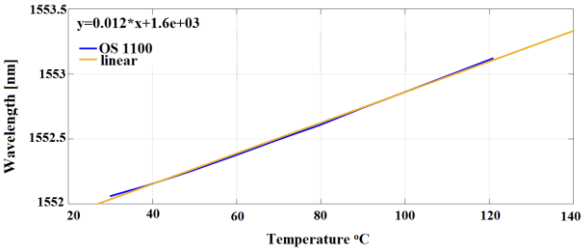
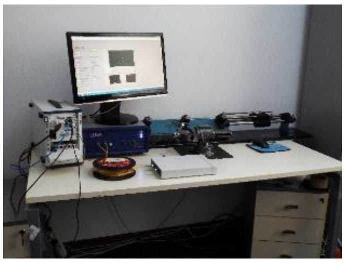


Fig. 3. The line that approximates the measured wavelengths for the OS1100-MO sensor with nominal λ_B = 1552 nm.

After highlighting the influence of temperature on the free FBG sensors, measurements for determining the characteristics of the FBG sensor mounted on the aluminum bar at the variation in ambient temperature are made. On a rectangular aluminum AW-6060 AlMgSi alloy bar with a length of 250 mm, a width of 20 mm and a thickness of 2 mm, an optical fiber was bonded, Fig. 4. The bonding procedure is standard: degreasing the surface with specific products, cleaning the surface with abrasive paper, cleaning the surface and the fiber with cleaning reagents, applying the adhesive, positioning the fiber, pressing the fiber until drying the adhesive. Finally, the area where the sensors is located is fixed to the surface by means of fixing reagents. On the same bar, along with the fiber is attached a tensometric mark to compare the results. The bar was tested on temperature variations and mechanical stress.



(a)

(b)

Fig. 4. Experimental Setup for FBG calibration (a) overview, (b) zoom on the aluminum bar and the clamping mechanism.

The measurements were carried out in the temperature range from −36 ℃ to + 120 ℃, the minimum temperature being the one that could be achieved with the FBCAL12D calibration bath and the maximum temperature of 120 ℃ being the maximum operating temperature of the FBG sensor type OS1100-MO. Fig. 5 presents the variation of the Bragg wavelength spectrum with the temperature.

Fig. 6 shows the variation of the Bragg wavelength with the temperature. It is noticeable that this variation is approximately linear. Based on this observation, the equation of the straight line which best approximates the curve made with the measured wavelengths was calculated and represented on the same graph. Thus, an average sensitivity of the wavelength with the temperature of about 37 pm/°C is highlighted, which is equivalent to a sensitivity of 23.04 με/°C, representing the coefficient of thermal expansion of the aluminum $\alpha_T = 23{,}6 \times 10^{-6}/^{o}C$.

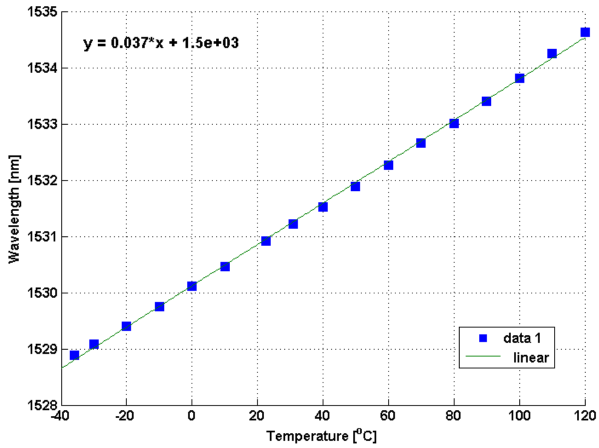


Fig. 6. Nominal wavelength variation with temperature.

In order to induce and measure the strain in the aluminum bar, a digital linear displacement device, which performs high precision controlled displacements, is used. The T90X-100D, manufactured by MPositioning Co., Ltd. China, was used for applications requiring precise movement control. To increase the reading accuracy of the movement a LK-H152 laser distance sensor, manufactured by Keyence Japan, was used.

The tunable PH 1400 laser manufactured by Luna Inc. is used under PC control to measure the spectrum of the FBG sensors. The controller performs the setting of the lower limit and the upper limit of the wavelength range to be scanned by the PH 1400 optical tunable laser, the laser emission power, trigger type, trigger thresholds, sweep rate and sampling rate. After the entire range of set wavelengths has been scanned, the acquired data is sent to the controller where it is stored and then processed to be displayed graphically or saved to for future processing. The results are shown in Table I.

TABLE I: RESULTS FOR STRAIN TESTS

deflection [cm]	strain [με]	force [N]
0.3	100.65	0.981
0.5	201.30	1.962
0.8	301.95	2.943
1.1	402.60	3.924
1.3	503.25	4.905
1.6	603.90	5.886
1.9	704.55	6.867
2.1	805.20	7.848
2.4	905.85	8.829
2.7	1006.50	9.81
3.0	1107.15	10.791
3.2	1207.80	11.772
3.5	1308.45	12.753
3.8	1409.10	13.734
4.0	1509.75	14.715

IV. CONCLUSION

On free FBG sensors (not bonded on the substrate) wavelength measurements were made to determine their sensitivity to temperature variations. The analysis shows that the variation with the temperature of the Bragg wavelength is linear and that the wavelength sensitivity of the FBG sensor type OS1100-MO is approximately 37 pm/^{o}C. The next step of the measurements was done with bonded sensors to the aluminium substrate and subjected to various strain and temperature demands.

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