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# Determination of the calibration equation for FBG temperature sensors

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***Abstract*— This paper presents a brief introduction to FBG sensor technology and its applications. Then the procedure for determining the sensor calibration equations is presented. These equations are determined for each individual sensor and are necessary to perform the trans-oceanographic measurement of the FBG sensor's wavelength variation in the measured parameter**

***Keywords—component; formatting; style; styling; insert (key words)***

## I. Introduction

Thermocouples, thermoresistors or semiconductor temperature sensors are the main methods of temperature measurement in electric motors [1]. Although these systems have proven their qualities, in the particular case of monitoring electric motors or other equipment with a strong electromagnetic field they have the great disadvantage of being strongly influenced by these electromagnetic fields. This disadvantage of classical sensors is overcome when using FBG fiber optic sensors to measure the temperature of electric motors [2]. Due to their operating principle, these sensors are immune to disturbances induced in electrical systems by electromagnetic fields. FBG sensors have a number of advantages that make them underpin the development of a range of new applications in data acquisition. Thus, FBG sensors are widespread in the field of structure monitoring. The main advantages that make FBG sensors applicable in the field of building monitoring are multiplexing capability, small size, low weight, possibility of encapsulation, high sensitivity, and last but not least immunity to electromagnetic interference [3][4][5].

The FBG is a sensing element which can be used to determine temperature, strain and stress, displacement, and pressure [3].

Several industries have application where FBG sensors have proven their efficiency.

In the energy sector FBG sensors are used for monitoring wind turbines [6],[7],[8], power grids [9],[10], and also in renewable energies solar power [11]. In the civil and industrial constructions sectors FBG are widely used for buildings structural monitoring [12],[13],[14],[15], smart building applications [16],[17],[18].

## II. Fiber Bragg Grating Sensor Operation Principle and Sensor Fabrication

### A. *Operation principle of FBG sensors*

Although optical fibers have been a major step forward in the telecommunications industry where they have enabled the development of transmission systems with previously unheard-of parameters, optical fibers have not had significant applicability for sensors. This has changed with the development of techniques that allow the altering of fiber core index of refraction by optical absorption of UV light [19]. This allows the fabrication of phase structures in the core of fibers called the fiber Bragg grating (figure 1).

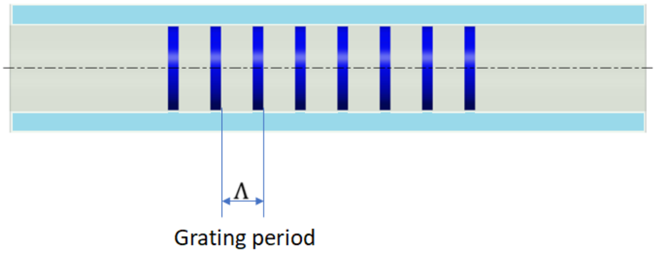



Fig. 1. Brag gratting in a optica fiber (phase structures)

At the end of the Bragg grating of the optic fiber, a broad spectrum light wave is applied via a device called an optical interrogator. Part of the applied light spectrum is reflected in the area of the Bragg gratings and the other part passes on. The wavelength that is reflected depends on the characteristics of the Bragg gratings. The planes on which the gratings are made and which are perpendicular to the longitudinal axis of the fiber are subject to changes caused by temperature or deformation [19].

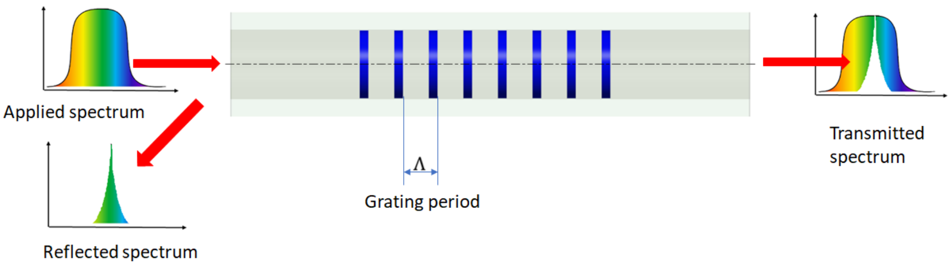



Fig. 2. Measurement principle of FBG sensors

The reflectivity characteristic of the Bragg grating in the case of an optical fiber is given by relation 1

$$\lambda_{Bragg} = 2n_{eff}\Lambda \qquad (1)$$

In equation 1, $\lambda_{Bragg}$ represents the wavelength that is reflected, also called Bragg wavelength, $n_{eff}$ is the effective refractive index which is a characteristic of the material of the optic fiber and Λ is the gratings period.

As far as the realization of FBG sensors is concerned, they are currently realized using several technological processes. The first widely used process is the interferometric process which is based on the interference of two UV light waves. Other methods involve the use of a photomask with the intended grating features [20].

### B. *Temperature measurement using FBG sensors*

The relative shift in the Bragg wavelength ($\Delta\lambda_B/\lambda_B$) due to an applied homogeneous and isotropic strain (Δε) and a change in temperature (ΔT) can be written as [21]

$$\frac{\Delta\lambda}{\lambda_0} = (1 - P_e)\varepsilon + [(1 - P_e)\alpha + \xi]\Delta T \qquad (2)$$

$\lambda_0$ is the Bragg wavelength of the FBG, $\Delta\lambda$ is the variation of the wavelength Δε is the change in strain experienced over the length of the FBG, α is the coefficient of thermal expansion of the fiber, Pe is the photo elastic constant of the fiber, ε is the strain induced on the fiber, α is the fiber thermal expansion coefficient and ζ is the fiber thermal-optic coefficient [21].

The temperature dependence of the FBG sensors is presented in equation 3[22].

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\Delta(n_{ef}\Lambda)}{n_{ef}\Lambda} = \left(\frac{1}{\Lambda}\frac{\Lambda}{\partial T} + \frac{1}{n_{ef}}\frac{\partial n_{ef}}{\partial T}\right)\Delta T = (\alpha + \xi)\Delta T \quad (3)$$

Where:

α – is the thermal expansion coefficient, ζ– id the thermo-optic coefficient (the influence of the index of refraction on temperature)[22]

## III. Calibration Procedure for the Temperature FBG Sensors

In the case of FBG sensor measurements, the information is encoded as a waveform variation. This determines some of the significant properties of these sensors such as immunity to electromagnetic disturbances. However, this involves determining the relationship between the wavelength variation and the measured parameter variation. In this paper we present the procedure to determine these relationships for a series of FBG sensors for temperature measurement.

FBG sensors were custom made at Box Optronics Technology Company located in Shenzhen China on the following wavelengths:

- 1520 nm – 2 pcs
- 1530 nm– 1 pc

- 1540 nm – 1 pc
- 1550 nm– 1 pc
- 1560 nm– 1 pc
- 1570 nm– 1 pc
- 

Preparation of the calibration stand involves reusing LabTech's EH20B heating plate(1), along with a NI PXIe-1071 optical interrogator from National Instruments (3) as well as Berzelius dishes that have been pre-prepared with ice water to establish a 0° start for FBG sensors (2). In addition, a computer was used on which the NI-OSI Explorer software was installed to identify and assign the location of each sensor.

Also on this computer we have installed the CONT ACQ&GRAPH signal recording software. The sett-up for the experimental stand is presented in figure 3.

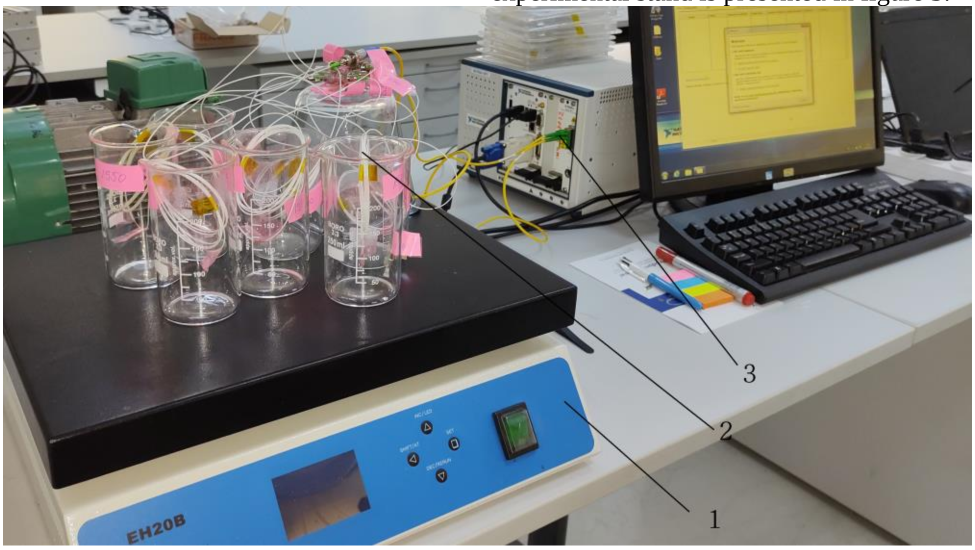
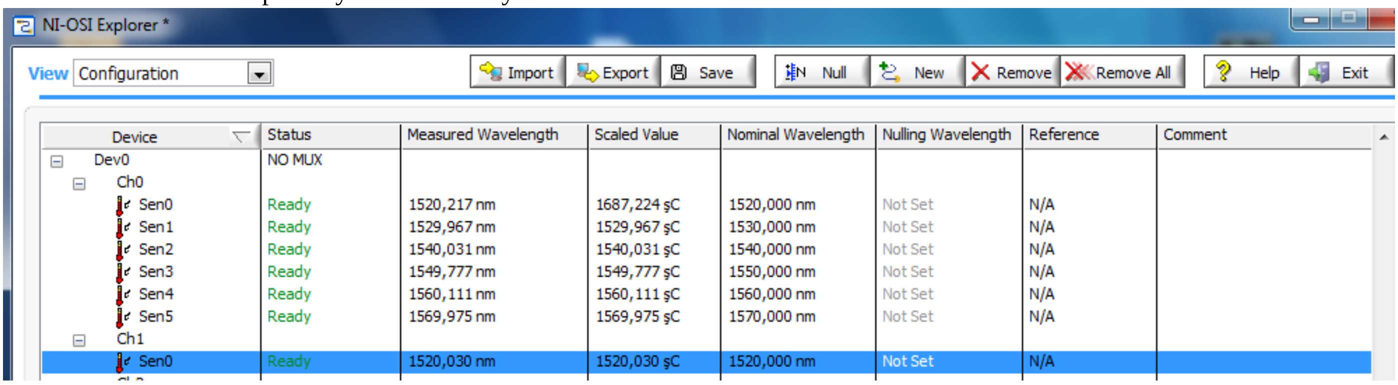



Fig. 3. Measurement principle of FBG sensors

The advantage of optical sensors is that it is not necessary to make a separate line for each sensor to capture and read the signal as well as to connect to the power supply. Sensors can be inserted and identified separately because they work on separate light wavelengths. In the figure below you can see how an identifier is assigned to wavelengths.




| Device | Status | Measured Wavelength | Scaled Value | Nominal Wavelength | Nulling Wavelength | Reference | Comment |
|---|---|---|---|---|---|---|---|
| Dev0 | NO MUX | | | | | | |
| Ch0 | | | | | | | |
| Sen0 | Ready | 1520,217 nm | 1687,224 şC | 1520,000 nm | Not Set | N/A | |
| Sen1 | Ready | 1529,967 nm | 1529,967 şC | 1530,000 nm | Not Set | N/A | |
| Sen2 | Ready | 1540,031 nm | 1540,031 şC | 1540,000 nm | Not Set | N/A | |
| Sen3 | Ready | 1549,777 nm | 1549,777 şC | 1550,000 nm | Not Set | N/A | |
| Sen4 | Ready | 1560,111 nm | 1560,111 şC | 1560,000 nm | Not Set | N/A | |
| Sen5 | Ready | 1569,975 nm | 1569,975 şC | 1570,000 nm | Not Set | N/A | |
| Ch1 | | | | | | | |
| Sen0 | Ready | 1520,030 nm | 1520,030 şC | 1520,000 nm | Not Set | N/A | |

Fig.4 Configuration of the NI OSI for the measurement of temperature

For each measurement point (0 ºC, 21.5 ºC, 24 ºC, 30 ºC, 35 ºC,40 ºC,45 ºC,50 ºC,55 ºC , 60 ºC,65 ºC ,70 ºC ,75 ºC) the NI system generates a file that can be exported in Microsoft Excel format. The file contains the measured wavelength for each sensor. A minimum of 330 values with a frequency of 10 Hz were acquired for each to the temperature sensor.

To process the data, a series of applications were developed in Matlab©. The first step of the calibration is to read the variables from the excel file containing the wavelength values afferent to each temperature and to store these values in files with the *.mat ending. Once the *.mat files have been generated, they are imported into the Fit application also created in Matlab©.

This application takes the data from each file and using the respective polyfit function determines the characteristic equation for each sensor. The polyfit function in Matlab© returns the coefficients for a polynomial p(x) of degree n that is a best fit (in a least-squares sense) for the data in y. The coefficients in p are in descending powers, and the length of p is n+1[23].

The polyfit function uses the method of least squares and is used to solve with approximate linear and nonlinear systems in which the number of equations is greater than the number of unknowns. Given a set of data z ( $x_z$, $y_z$) were $y_z$ is $f(x_z)$ an approximation function $r(x_r\ y_r)$ is determined so that $r(x_r)$ is proximately equal to $y_z$ .The approximation function is sought so that the condition in relation 4 is met.

$$\|g(x) - f(x)\| \text{ is minimal} \quad (4)$$

Method of smallest square is searching for the r function so that the condition (5) is met.

$$E = \sum_{z=0}^{m}(f(x_z) - (x_r))^2 \quad \text{is minimal} \quad (5)$$

By running the MAtlab program a series of equations were obtained for each fibre.

The generated equations are polynomial equations of degree 2 having the form:

$$f(x) = p_1x^2 + p_2x + p_3 \quad (6)$$

TABLE I. VALUES OF THE COEFICIENTS FOR EACH POLINOMIAL FUCTION CORRESPONDING TO EACH SENSOR

| Chanel | Wavelength | p1 | p2 | p3 |
|---|---|---|---|---|
| Dev0Ch0Sen0 | 1520 | -4.3386808e+01 | 1.3201097e+05 | -1.0041579e+08 |
| Dev0Ch0Sen1 | 1530 | -4.9240916e+01 | 1.5077641e+05 | -1.1541982e+08 |
| Dev0Ch0Sen2 | 1540 | -3.8731961e+01 | 1.1938720e+05 | -9.1999546e+07 |
| Dev0Ch0Sen3 | 1550 | 3.7985243e+01 | -1.1765611e+05 | 9.1107470e+07 |
| Dev0Ch0Sen4 | 1560 | -4.6953361e+01 | 1.466133918632e+05 | -1.1445117768644e +08 |
| Dev0Ch0Sen5 | 1570 | -5.1889363e+01 | 1.6303369e+05 | -1.2806077e+08 |
| Dev0Ch1Sen0 | 1520 | -5.7239001e+01 | 1.7411795e+05 | -1.3241427e+08 |

Use In order to visualize the correspondence between the measured data and the graph of the function obtained using the method of least squares, in matlab using the polival function which performs an error evaluation between the function obtained and the input sides, the characteristic curve of each sensor was plotted according to the determined formula. The results are shown in the following figures.

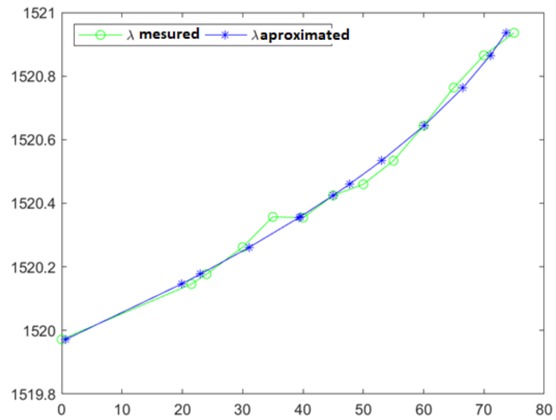



Fig.5 Approximate curve comparing measured values for Dev0Ch0Sen0

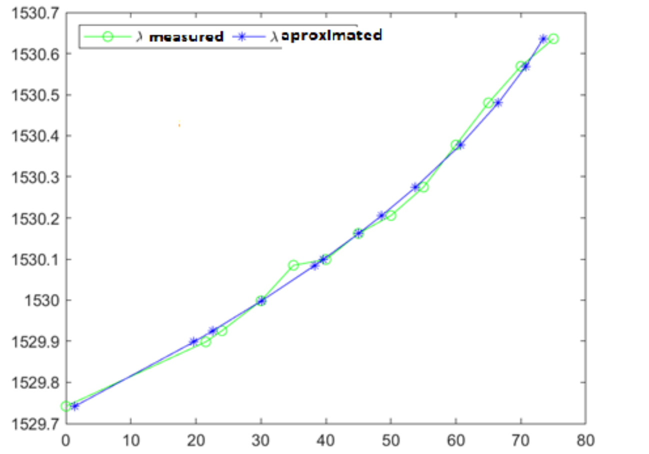



Fig.6 Approximate curve comparing measured values for Dev0Ch0Sen1

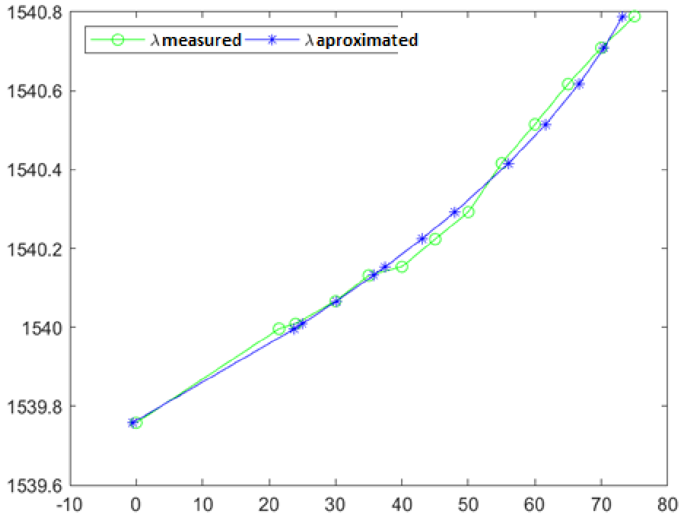


Fig.7 Approximate curve comparing measured values for Dev0Ch0Sen2

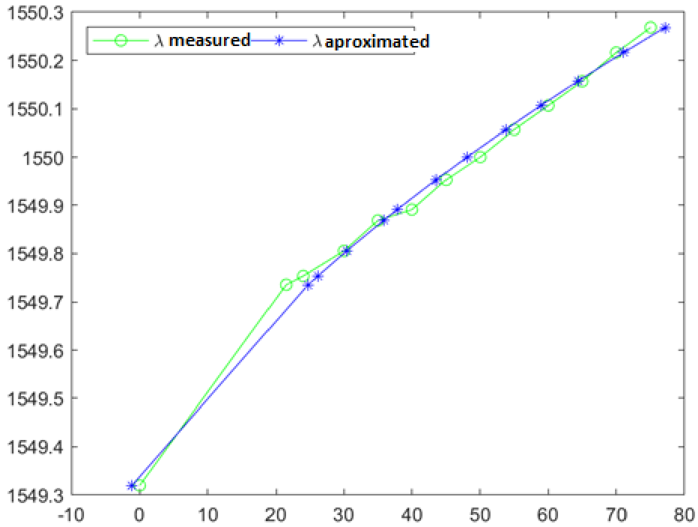



Fig.8 Approximate curve comparing measured values for Dev0Ch0Sen3

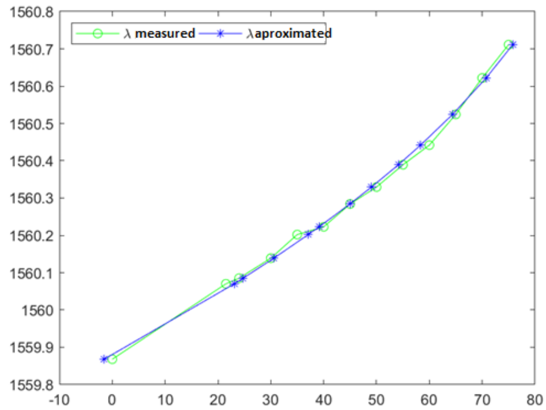



Fig.9 Approximate curve comparing measured values for Dev0Ch0Sen4

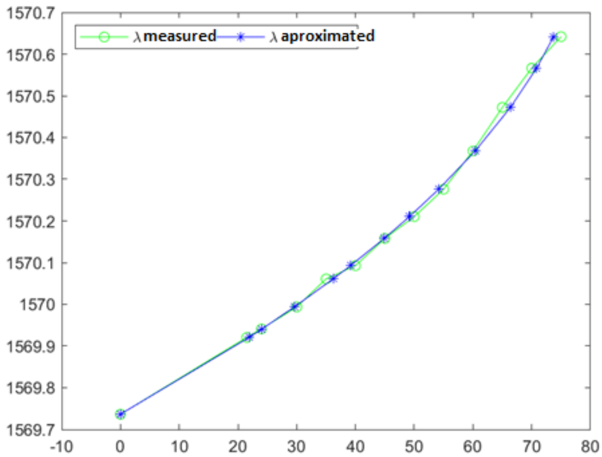



Fig.10 Approximate curve comparing measured values for Dev0Ch0Sen5

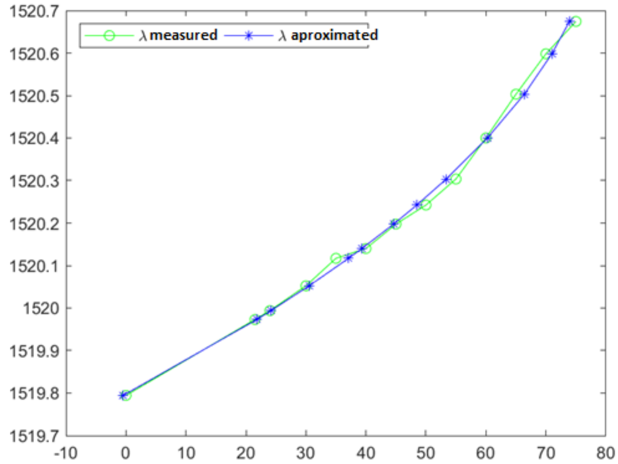



Fig.11 Approximate curve comparing measured values for Dev0Ch1Sen0

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