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Measurement of Temperature, Humidity and Strain Variation Using Bragg Sensor

Amira Zrelli, Tahar Ezzeddine

Abstract**—**Measurement and monitoring of temperature, humidity and strain variation are very requested in great fields and areas such as structural health monitoring (SHM) systems. Currently, the use of fiber Bragg grating sensors (FBGS) is very recommended in SHM systems due to the specifications of these sensors. In this paper, we present the theory of Bragg sensor, therefore we try to measure the efficient variation of strain, temperature and humidity (SV, ST, SH) using Bragg sensor. Thus, we can deduce the fundamental relation between these parameters and the wavelength of Bragg sensor.

Keywords**—**Optical fiber, strain, temperature, humidity, measurement, Bragg sensor, SHM.

I. Introduction

RECENTLY, the appearance of optical sensor has provided excellent choices for engineers to monitor the performance of many things. Optical sensors have several advantages such as small dimensions, good resolution, high accuracy, and excellent ability to transmit signals over long distances. Therefore, the development of FBGS technology has provided an excellent alternative in the domain of SHM. Civil engineers require the using of FBGS to monitor various parameters. Civil structures like tunnels, bridges and mines can be monitoring using these technologies. The monitoring of the safety of these structures is the aim of Wireless Structural Health Monitoring (WSHM). WSHM must be able to detect damage (fire, strain, shaking, etc.) and to localize the exact emplacement of the damage. As well, the smart optical sensor technologies have become one of the key technologies in WSHM. Optical sensors, especially FBGS, have small dimensions, good resolution; the error rate of temperature is usually between 0.2 and 0.5 °C [2]. Moreover, fidelity of strain variation in the optical fiber is under 5 με, as well as FBGS have an excellent ability to transmit signal at long distances. Therefore, optical fiber grating and FBG sensors specially, are robust against radio frequency interference [3]. Thus, FBGS have many advantages which facilitate supervision and control of civil structure. Monitoring of the structural condition of various civil structures is critical to the extent and safety of structures. In order to monitor anomalies in structures, more and more measures should be carried out in various strategic areas of the structure, indeed the use of FBGS are recommended by the work of Ezzedine et al. [6].

A.Zrelli is a Ph.D student at National engineering School of Tunis, 1068 University of Tunis El-Manar, Tunisia,(e-mail: amira.zrelli@enit.utm.tn).

T. Ezzedine is professor at the Department of TICn, National engineering School of Tunis,1068 University of Tunis El-Manar, Tunisia, (e-mail: tahar.ezzedine@enit.utm.tn).

Huynh et al. have used wireless vibration sensor nodes to monitor accelerations in Hwamyung Bridge [13]. Ezzedine et al. have proposed a SHM for concrete strength monitoring in tunnels and they designed the hardware and the software architecture of wireless node which can monitor each concrete structures [6]. In WSHM system, several parameters can derange hugely our daily life, like vibration, temperature, pressure, deformation, etc. SHM is considered as a data acquisition system from a civil structure, this structure receives internal or external stimuli. More importantly, SHM systems are used to quantify the change in state of the structure. Hence, we can deduce about the prognosis aspects such as capacity and remaining life. FBGS are extremely sensitive to changes of temperature and strain, and are an extremely useful candidate for measuring and monitoring of strain variation (SV), temperature change (TC) and humidity change (RH) in the civil structures [6]. Furthermore, SV, TC and RH are always considered as annoying settings which can affect human life.

FBGS are used to ensure reliable and continuous monitoring associated to optical fiber (OF) which is a new technology, sensitive to many kinds' parameters [1]. Thus, to assure security and safety of human life, simultaneous monitoring of SV, TC and RH are very important and must be controlled in real time. Specifically, to keep an adequate humidity, temperature and strain, FBGS have been used for vibration and humidity sensing [7], [14].

Leandro et al. presented a novel sensor system for simultaneous measurement of strain and temperature using a unique combination of a long period grating (LPG) and a one fiber laser based on a FBG. They demonstrate that vibration and temperature variation can be obtained by using a unique emission line [4]. Wu et al. have studied simultaneous temperature and strain sensing by dual wavelength FBG for cryogenic applications. They use low reflectivity FBGS for strain/temperature discrimination, also linear thermal responses of FBGS were found in the higher temperature range [15].

In this paper, at the first section, we present the methodology of measurement through Bragg sensor. Therefore, at the second section, we investigate the basic concept of temperature, humidity and SV measurement using Bragg sensor. We finish by presenting a diagram of simultaneous variation monitoring of temperature, vibration and humidity which have a big impact in civil structures. We will focus on the relationship between these parameters.

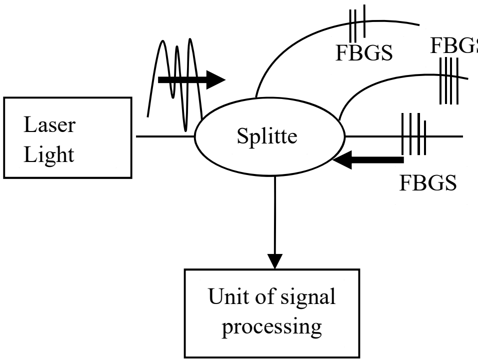

Fig. 1 Measurement of temperature, humidity and strain using Bragg scattering

II. Methodology of Measurement using FBGS

The fiber sensors are component to monitor the variation of humidity, temperature and strain over different wavelengths (λ_0). Frequently, RH is referred to the water vapor content in air or other gases and its measurements can be stated in a variety of terms and units [7]. TC presents the temperature variation at real time in the structure. SV refers in our study to variation detected of strain in the OF. In this paper, we present a simulation model to measure simultaneous temperature, strain and humidity through MATLAB codes. FBGS are used to measure and detect the shift in the Bragg wavelength which is proportional to TC, SV and RH. The variation of humidity, temperature and strain is translated into grating modulation which have a periodic refractive index modulation in the core of an OF. Fiber grating is a sensitive optical device, when UV irradiates, the refractive index of fiber core varies periodically along the axis leading to variation in its spectral characteristics [7].

The FBG Bragg wavelength under no load is defined by:

$$\lambda_B = 2\eta\Lambda \tag{1}$$

η is the refractive index of fiber core; Λ is the grating pitch given by $\Lambda=\Lambda_0(1+\varepsilon_z)$ where $\varepsilon_z = \frac{N\lambda_B}{2\eta_{eff}L}$, L is the fiber length under strain and N the Number of fringes) [7] [2].

A. Basic of Bragg Sensor

Bragg sensors are described as local sensors which are able to measure changes at specified local points in a civil structure. Interferometric FOSs are also by far the most commonly used local sensors since they offer the best sensitivity [5]. This sensing technique is based at the first on detecting the optical phase change induced in the light as it propagates along OF [8]. The basic principle of FBGS lies in the monitoring of the shift in wavelength of the reflected signal [7], [9], [1]. Fiber grating is an OF which is a cylindrical dielectric waveguide (no-conducting waveguide) which transmits light and waves along its axis. Operation of FBGS sensor is based on pump laser emission, this pump light will propagate along fiber. The pump is backscattering so it will be measured by the TV, RH and SV detection. Then, when we measure the wavelength of the light backscattering, we can easily detect TV, RH and SV.

B. Measurement Based on Bragg Sensor

The measurement of temperature, humidity and strain is detected by monitoring the variation of wavelength $\Delta\lambda_0$. In the following section we explain more the method used to monitor SV, RH and TV. FBGS provide the opportunity to monitor systems based on reflected signals which are used usually on demodulation. Therefore, through the spectrum of reflected signal we can detect variation of different parameters. Almost, reflected signals in FBGS offer exacted information about TC and SV, from TC we can deduce about humidity. The resolution and range of FBG give a very good spectrum graph. The wavelength ($\boldsymbol{\lambda}$) is considered as an absolute parameter in OF, reflected signal is processed in OF grating such that its information remains fight off power fluctuations along this path [7]. Moreover, these optical sensors remain to water, sharking, vibration or stress, moisture, high temperature…

III. Measurement of Temperature/Humidity and Strain

A. Temperature and Strain Measurement

Working with Bragg fiber, we choose to evaluate the relationship between SV and TC. Using MATLAB codes we choose to vary the value of ΔT and fixed SV. The equation which related wavelength to temperature and SV is expressed as:

$$\Delta\lambda_B(H,\varepsilon) = K_\varepsilon.\Delta\varepsilon + K_H.\Delta H \tag{2}$$

K_ε the strain sensitivity coefficient (nm/με), K_H humidity sensitivity coefficient (%). Generally K_ε and K_H depend on the nature of grating fiber.

Wu et al. show that the Bragg wavelength shifts $\Delta\lambda_T$ and $\Delta\lambda_\varepsilon$ are linear in response respectively to a strain change Δε and a TC ΔT. Therefore, they assume that Bragg wavelength shifts can be expressed as [15]:

$$\Delta\lambda_B(T,\varepsilon) = K_\varepsilon.\Delta\varepsilon + K_T.\Delta T \tag{3}$$

In a further step, by reducing this system of equation we obtain

$$\begin{bmatrix}\Delta\lambda_\varepsilon\\ \Delta\lambda_T\end{bmatrix}=\begin{bmatrix}K_{T1} K_{T2}\\ K_{\varepsilon1} K_{\varepsilon2}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix} \tag{4}$$

From the work of Wu et al. [15] K_{T1} is equal to 8.07 ± 5.4 x 10-2 pm/°C and K_{T2} = 8.30 ± 5.0 x 10-2 pm/°C. In the first step, we choose to work with Δε between 500 με and 8700 με and $\Delta\lambda_B$ between 215.7 and 1235 in MATLAB codes.

Fig. 2 is a diagram where we put in the variation of temperature (0-80 °C) at different values of strain (SV is between 550 and 8700 με). From this diagram, we can confirm that vibrations of molecules inside a civil structure generate a significant increase in temperature if the value of strain exceeds 5500 με. On the other hand, when the temperature is between 0 and 20 °C, SV does not exceed 1620 με. These results are compliant with (2) and (4).

Equally, Fig. 2 is a diagram variation of strain under TC, when temperature is more than 80 °C, SV exceeds 7000 με and when temperature is under 20 °C, SV is feeble, it is inferior to 1000 με. Thus, the resultants obtained in Figs. 5 and 2 confirm that temperature and strain measurement depend on each other.

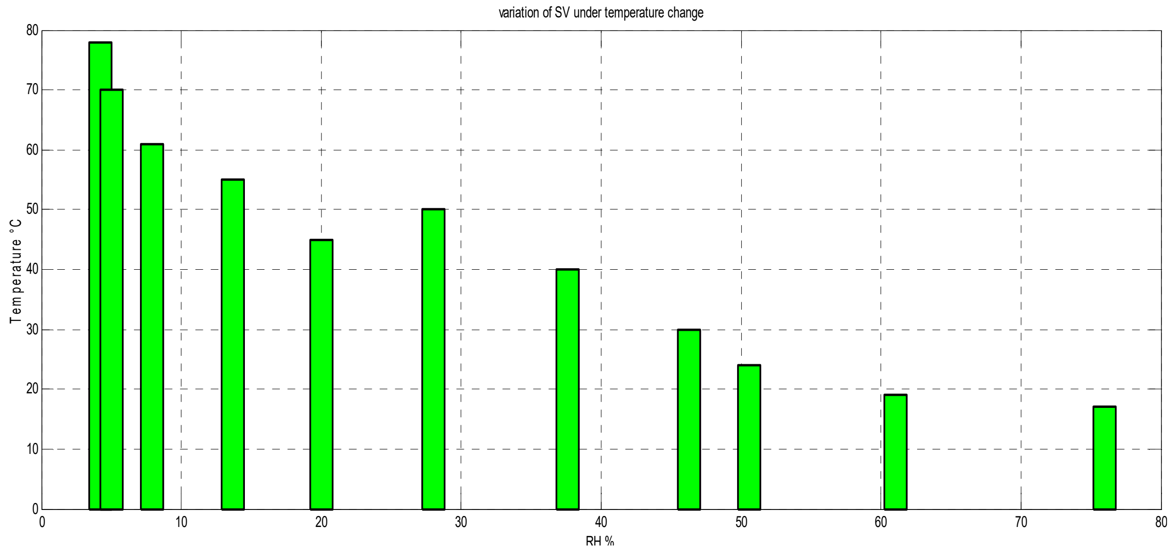

Fig. 2 Variation of SV under TC

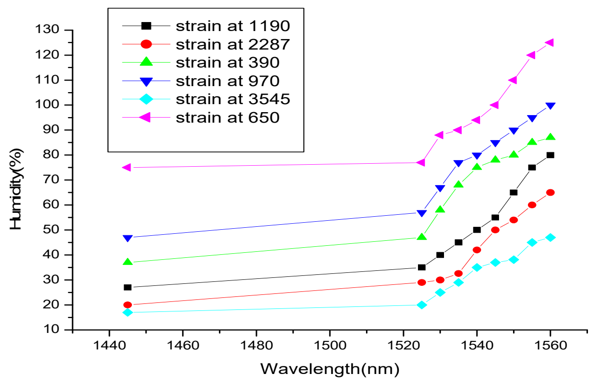

Fig. 3 Humidity variation at different SV

TABLE I
PARAMETER VALUES

Parameter	Value
ξthe thermo-optic coefficient	$8.542\ 10^{-6}°C^{-1}$
α coefficient of thermal expansion	$0.56210^{-6}°C^{-1}$
ρ_{ij} the coefficient of Pockel of the stress-optic	$\rho_{11} = 0.12$ and $\rho_{12} = 0.27$
V Poisson's ratio	0.18-0.3
η	8.6 x 10-6/η.

According to Deng et al., measuring Δλ provides a means of determining the strain according to [3]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (GF).\Delta\varepsilon + \Delta T \tag{5}$$

where GF is the FBG gauge factor between 0.75 and 0.82, and ΔT is the TC relative to the temperature at installation. In the previous diagrams, we take the different measurement at wavelength shift equal to 550 nm in all cases. However, we already know that SHM system must be able to monitor different structure which means wavelength of OF take different values [1], [9], [2].

By the work of Zrelli et al., wavelength shift with strain and temperature variation is expressed as (6) [1], [7]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\frac{\eta^2}{2}[\rho_{12} - V(\rho_{11} - \rho_{12})])\Delta\varepsilon + (\alpha + \xi)\Delta T \tag{6}$$

In Fig. 3, we take a different measurement of humidity variation with an OF having wavelength between 1420 and 1560 nm, the fiber is excited in the order to obtain SV between [790-3545με].

B. Monitoring of Temperature, Humidity and Strain

To measure strains/temperatures, a pump light is sent into one end of the fiber optic cable and its reflected signal is received by a splitter [3]. Also the variation of strain is given by:

$$\Delta\varepsilon = \varepsilon_{RH} + \varepsilon_T \tag{7}$$

where ε_{RH} is the RH caused vibration and ε_T is temperature caused vibration. The values of SV, TC and RH are calculated through MATLAB codes, these results confirm information obtained in Fig. 4. SV is usually linearly depending on temperature, the increase in one leads to the increase of the other however RH is conversely affected. To monitor temperature in FBGS, we consider that the thermal response of OF grating is arisen due to the inherent thermal expansion of OF and the temperature dependence of the refractive index [13], [11].

We know that the shift in resonance λ_B with temperature can be expressed as [7], [10]:

$$\frac{\Delta\lambda_B}{\lambda_B} = S_{RH}.\Delta RH + S_T.\Delta T \quad (8)$$

Kronenberg et al. have determined the values of S_{RH} and S_T respectively as $2.21 \pm 0.10.\ e^{-6}$%RH and $7.79 \pm 0.08\ e^{-6}$/K [10]. (We use in our simulation these values to calculate humidity variation).

Using (6)-(8) we obtain:

$$\begin{pmatrix} \frac{n^2}{2}[\rho_{12} - V(\rho_{11} - \rho_{12})] - 1 \\ \alpha + \xi \end{pmatrix} . \begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} = \begin{pmatrix} S_{RH} \\ S_T \end{pmatrix} . \begin{pmatrix} \Delta RH \\ \Delta T \end{pmatrix} \quad (9)$$

We perceive from Figs. 4 and 5 that when strain is at 550 με and at temperature equal to 15 °C, RH is very higher and it varied between 45 and 57%. Moreover, when we arrange the SV at 750 με and temperature at 27 °C, RH % set enters 35%-50%. However, at high temperature values, T=60 °C and 61 °C, RH% increases strongly [12% at SV= 3600 με and 20% at SV=2150 με]. Thus, from all these diagrams (Figs. 2 and 4), we can deduce that RH and SV are inversely dependent; otherwise, it is clear that SV and ΔT are linearly dependent. Thereby, we can say that for the precise and simultaneous measurement of strain, temperature and humidity it is preferable and recommended to work with an OF that has a wavelength between 1550 and 1555.3 nm.

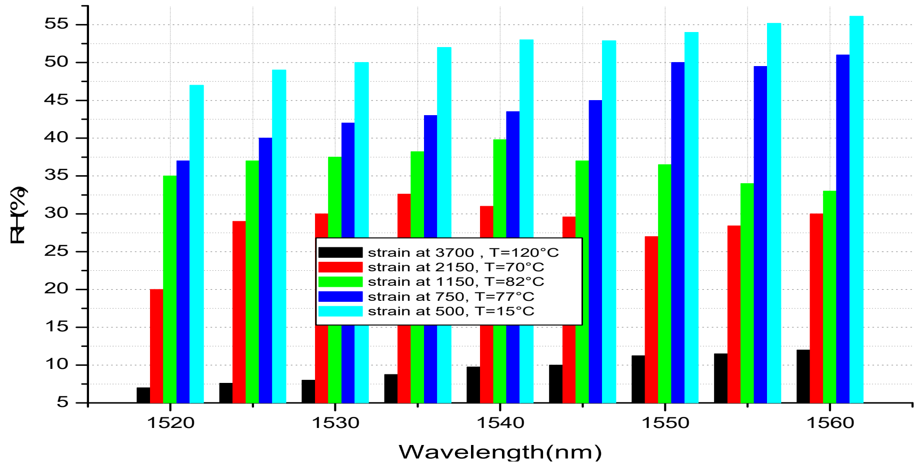

Fig. 4 Variation of RH % and strain under TC

IV. Conclusion

In this work, we focus on the propriety of Bragg sensors which are able to monitor humidity, temperature and SV. In this paper, at the first, we explain the methodology and theory of measurement of temperature, humidity and SV through Bragg Sensor. With different value of wavelengths we monitor vibration of OF, we demonstrate that temperature and humidity are strongly influenced by the vibration in the fiber, so we can deduce that the decrease of one, automatically enters the decrease of the other.

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