Measurement of the Distributed Strain and Temperature by Modeling the Brillouin Spectrum

Mohamed Bouyahi, Amira Zrelli, Houria Rezig and Tahar Ezzedine
Communication System Laboratory Sys'Com, National Engineering School of Tunis,
University Tunis El Manar, BP 37, belvedere 1002, Tunis, Tunisia

Keywords: Stimulated Brillouin Scattering (SBS), Distributed Temperature Sensors, Optical Fiber Sensors.

Abstract: Actually, Structural health monitoring (SHM) presents an important field of researches, since we can monitor many civil structures using optical fiber sensors which give us the opportunity to explore the effect of shifting many parameters to detect and measure the influence of both temperature and strain in sensing fiber, we choose to work on Brillouin-scattering-based distributed sensor. In this paper, we make out the influence of shift temperature and strain in Brillouin scattering. The study proves the importance of Brillouin coefficients by fixing all of them. The Brillouin Spectrum will be modulating with Matlab codes.

1 INTRODUCTION

The progress of optical fiber technology and applications in recent years has improved in the SHM which has an important role in the construction phase and service stage. Lots of parameters, such as temperature, displacement, strain and material corrosion, are monitored to evaluate the safety of the structure. Optical fiber is sensible by many kinds of parameters (temperature, strain, pression, shape) and optics (refractive index, mode conversion). In this case, we choose to detect temperature and strain variation using optical fiber potentially over long distances. Whenever temperature or strain change, optical fiber detects this variation, the refractive index of silica (material of optical fibers) precisely changes in response to such variation. In Optical fibers, there are two nonlinear scattering phenomena which can be investigated: Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) and both are related to vibration excitation modes of silica. In this work we concentrate on studding SBS, which is observed at high guided light intensity, and affected by the change in refractive index. This change is recognized through the Brillouin shift. By measuring the change in Brillouin shift, the distribution of temperature and strain over long distances can be obtained, hence coined as distributed fiber sensors (Singh and Gangwar, 2007).

The vital fiber optic technologies which are developed for sensor applications are the distributed fiber optic sensing (Azizan and Shahimin, 2012) and (Singh and Gangwar, 2007). Distributed sensing, specially the one using Brillouin signal, is able to extract many information such as temperature and strain along the sensing fiber. The information extracted is highly concrete.

The goal of the sensor optical fiber is to determine the physical parameters of a fiber position. The distributed sensors optical fiber is important in monitoring of the broad structures (Bridge, Tunnel).

Detecting strain or temperature variation over small region can be considered as complicated. In this work we choose to limit our measurement to 20Km, then distributed sensor is the most useful model in long distance. So, long measuring time is needed to achieve distributed measurement. The characteristics of BOTDR (Brillouin Optical Time Domain Reflectometry) help us to measure strain and temperature along arbitrary regions. BOTDR is a distributed optical fiber strain sensor whose operation is based on Brillouin scattering.

BOTDR is a coherent detection method using a pulsed light. The main idea is to launch a light into the optical fiber and then generate spontaneous Brillouin scattering Therefore, the Brillouin scattering occurs when the aquastic wave propagating within the fiber, interact with the light. It causes a frequency shift of the backscattered

Bouyahi M., Zrelli A., Rezig H. and Ezzedine T..
Measurement of the Distributed Strain and Temperature by Modeling the Brillouin Spectrum.
DOI: 10.5220/0005562600360041
In *Proceedings of the 6th International Conference on Optical Communication Systems* (OPTICS-2015), pages 36-41
ISBN: 978-989-758-116-8

spectrum into two components Stokes and anti-Stokes.

Scattered Photons light can then either make energy when there is absorption of acoustic phonons (Anti-Stokes component) or lose energy in the event of emission of phonons (Stokes component).

The simulation of Brillouin Spectrum is an intense research subject notably for sensors' applications also in systems of transmission by optical fiber. However, modelisation of both temperature and strain's influence (through coefficients of C_T, C_ε) is not well explored. These sensing coefficients are usually obtained by the calibration measurement of Brillouin spectrum. Also by analyzing the distorted Brillouin spectrum, strain's information can be found.

This paper focuses on the development of a simulation model using MATLAB for a distributed Brillouin spectrum fiber optic sensor. SBS is specifically implemented. We will present the Brillouin gain spectrum which is depicted by each value of the frequency difference.

2 BRIEF THEORY AND METHODOLOGY

Structural health monitoring (SHM) has many tools which are used to detect damage in different structures: one of the most promising tools is Scattering mechanism Optical Fiber (OF). This mechanism has a high durability, immunity to electromagnetic interference and exact measurement.

2.1 Scattering Mechanisms

When we speak about optical fiber, we mean a cylindrical dielectric waveguide (non conducting waveguide) that transmits light along its axis, based on the reflection process.

The physical parameters of optical fiber can be affected by temperature and strain. So the fiber sensors are able to detect the variation of temperature and strain over long distances.

These parameters have become the essence of distributed fiber optic sensing. The Rayleigh, Raman, and Brillouin scattering represent the basic scattering mechanism of the distributed sensing techniques which commonly occurred inside the fiber. The distributed fiber sensing is a really attractive technique for structural health monitoring (SHM). It provides information of strain and temperature about a section or the complete structure with durability, robustness and measurement reliability. The distributed optical fiber sensing systems give us the opportunity to determine physical parameters. When large structures are to be monitored, such as bridges, dams and tunnels, this mechanism can be suitable.

We will demonstrate that both the bandwidth of Brillouin gain (and the intensity of Brillouin scattering light) and Brillouin frequency shift have good linear relationship to the strain and temperature of the optical fiber, which can realize simultaneous temperature and strain measurement by using one optical fiber, with a lower accuracy.

A pulse of laser is launched into the fiber, we amplify the input signal pulse in an optical fiber in a similar way as it undergoes in EDFAs, erbium-doped fibre amplifiers. The directional coupler is backscattering the light to the same fiber to measure. The pulse propagates along the fiber to the receiver.

The backscattering of light is resumed of the scattering of incident photon in the fiber by the acoustic photon of the medium. This mechanism generates the frequency shift when we are measuring the temperature and strain.

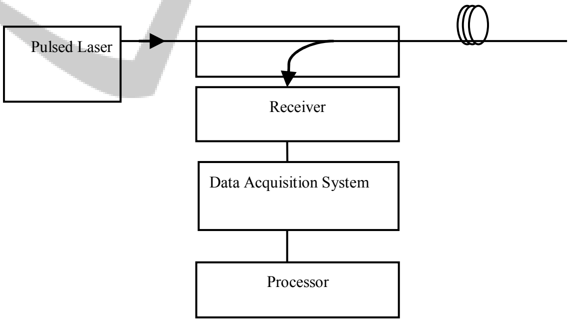

Figure 1 : Optical Time Domain Reflectometer functional schematic.

The backscattering signal refers to the Stokes frequency of the Stimulated Brillouin Scattering (SBS) and the occurrence of the bathochromic shift (the Stokes component) $w_s = w_p - w_{fa}$ with respect to the pumping beam, where w_{fa} denotes acoustic photon of the fiber. The fundamental difference from Brillouin and Raman scattering is the interaction of light photon with acoustic phonons in contrast with the Raman scattering where there is an interaction between light photons and molecular vibrations. The frequency of acoustic photon is determined by the following formula (Halina, 2005).

$$w_{fa} = \frac{4\pi n v_s}{\lambda} \tag{1}$$

v_s indicates the speed of sound in optical waveguide

n is a refraction index.

As a result of interaction between the matter and light photons the energy exchange occurs via acoustic photons leading to the third-order polarization of the medium.

$$P^{(3)} = \chi^{(3)}_{ijkl} E_j E_k E_l \tag{2}$$

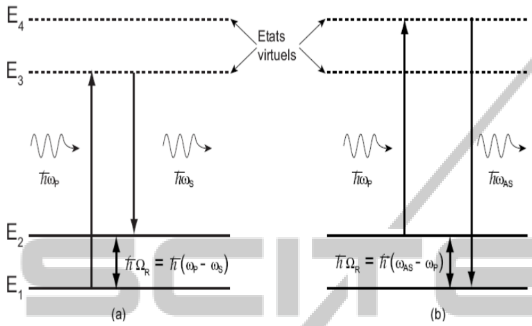

Figure 2: Scheme of Brillouin Scattering.

E_1 and E_0 are states that correspond to the electronic states; the states are enumerated with the quantum numbers v which denotes the vibration states. This occurs when a photon of light with energy of $\hbar w_p$ is lower than the resonance energy $\Delta E = E_1 - E_0$(Hui and and O'Sullivan, 2009).

2.2 Project Methodology

$$\varepsilon_s = \frac{F}{E * A}(\cos^2\theta - \sin^2\theta) \tag{3}$$

The variation is detected by sensor Fiber Brillouin is ε_s which is based on F. F is the force applied by concrete, A is the surface of optical fiber, E Young Module and θ the direction of light in the fiber (Luo and Hao, 2013).

The Brillouin Frequency Shift (BFS) of back scattering is linearly sensitive to strain and temperature.

It's expressed by:

$$\Delta V_B(T,\epsilon) = C_T\,\Delta T + C_\varepsilon\,\varepsilon \tag{4}$$

When $\Delta V_B(T,\epsilon)$ is the variation of Brillouin Frequency Shift; C_T, C_ε are the sensing coefficients of temperature and strain, ε is the strain variation and ΔT is the temperature variation. In the Fig. 1 we fixed the strain between 274.7 and 1463.3 $\mu_\varepsilon$with variation of the frequency between 1.23 and 1.32 MHz. In the Fig. 4 we fixed the temperature between 23.6 and 69.5 $C°$ with variation of the frequency between 1.23 and 1.32 MHz.

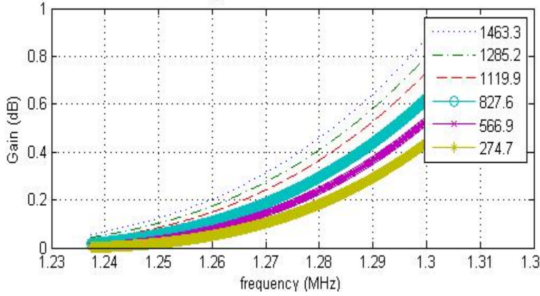

Figure 3: Gain with Fixed Strain.

$$g_B(w_{fa}) = g_0 \frac{(\Delta V_B(T,\epsilon)/2)^2}{(w_{fa} - w_B)^2 + (\Delta V_B(T,\epsilon)/2)^2} \tag{5}$$

Where $g_B(\Omega)$ is the Brillouin gain and Ω is calculated by $\Omega = w_P - w_S$, and means that $\Omega = w_{fa}$. The $w_B$denotes the Frequency Brillouin shift. When there is a propagation of the signal with attenuation the gain increases.

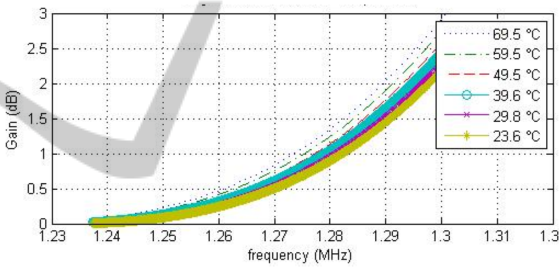

Figure 4: Gain with Fixed Temperature.

The Fig 3 and 4 are modified with a small variation of strain or temperature or both. The refractive index is linearly dependent on the temperature and strain of the fiber. The acoustic velocity that depends on temperature and strain can also be solved using $V_B$and refractive index that is dependent on temperature and strain (Liu and Bao, 2012).

Let us consider an interaction between the pumping and the Stokes beams of the intensities I_p and I_s, respectively. Let us assume that they represent continuous waves CW (or quasi-CW). The intensities of the beams can be characterized by the following system of equations (Halina, 2005).

$$I_S(L) = I_S(0)\exp(g_B(\Omega) I_0 L_{eff} - \alpha_s L) \tag{6}$$

$$L_{eff} = \frac{|1 - \exp(-\alpha_p L)|}{\alpha_p} \tag{7}$$

$I_S(L)$ the intensity stokes depend of the length of fiber.

L_{eff} the length of effective fiber.

L refers to length of real fiber.

The intensities of the beams by length of fiber can be characterized by the following system of equations.

$$\frac{dIs}{dz} = -g_B(\Omega)Ip(L)Is(L) + \alpha_s Is(L) \tag{8}$$

$$\frac{dIp}{dz} = -\frac{w_p}{w_s} g_B(\Omega)Ip(L)Is(L) - \alpha_p Ip(L) \tag{9}$$

The progress of Brillouin Scattering in optical fiber is governed by a set of two inter-related equation under steady-state condition (Azizan and Shahimin, 2012) and (Singh and Gangwar, 2007).

The $Ip(L)$, $Is(L)$, $g_B(\Omega)$, α_s and α_p represent the pump intensity, the Stokes intensity, the Brillouin Gain coefficient, coefficients describing loss in an optical fiber for the Stokes and the pumping beams.

3 FEASIBILITY ANALYSIS AND ERROR EVALUATION OF BOTDA BASED SIMULTANEOUS STRAIN AND TEMPERATURE MEASUREMENT

$$\varepsilon_{corr} = \varepsilon + (\alpha_{st} + \alpha_c).\Delta T \tag{10}$$

In this session we simulate the error of the concrete and steel, ε_{corr} which represents the value of error (Sikali, 2012). ε represents the value of strain, α_{st} is the value of steel, α_c is the value of concrete and ΔT the value of temperature.

In our simulation we fixed the coefficient of Brillouin Frequency Shift by $C_\varepsilon(\epsilon)$ and $C_T(\epsilon)$.

$$C_\varepsilon(\epsilon) = [0.048 * (1 + [4.16 * 10^{-4} \pm 2.29 * 10^{-4}] * \Delta T)] \frac{MHz}{\mu \in} \tag{11}$$

$$C_T(\epsilon) = [1.06 * (1 + [2.73 * 10^{-6} \pm 2.04 * 10^{-5}] * \epsilon)] \frac{MHz}{°C} \tag{12}$$

$$\Delta V_B{}'(T, \epsilon) = \Delta V_B(T, \epsilon) * (1 + \beta * R) \tag{13}$$

The $\Delta V_B{}'(T, \epsilon)$ is the variation of Brillouin Frequency Shift with error. $\Delta V_B(T, \epsilon)$ is the Brillouin Frequency Shift (He and Zhou, 2014), β bruit variation and random value R between [-1, 1].

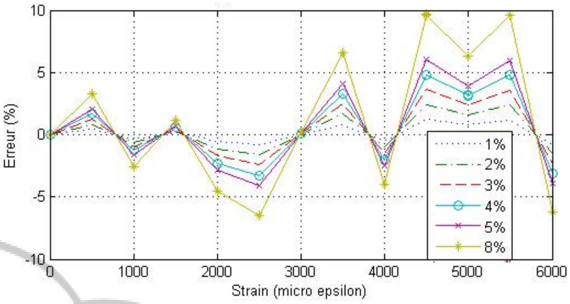

Figure 5: Error with Fixed Strain.

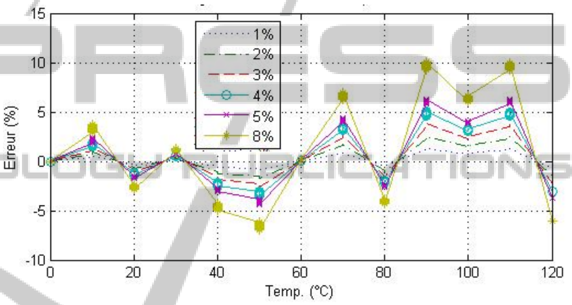

Figure 6: Error with Fixed Temperature.

In Fig 5 and 6 we calculate the error obtained by Brillouin Frequency Shift with error mines Brillouin Frequency Shift.

Table 1: Variation of BFS and Brillouin Wavelength under temperature and strain loads.

Strain (με)	Temp. (°C)	Variation of BFS(MHz)	R
500	10	17	0.846221
1000	20	34	-0.525152
1500	30	51	0.202647
2000	40	68	-0.672137
2500	50	85	-0.838118
3000	60	102	0.01964
3500	70	119	0.681277
4000	80	136	-0.379481
4500	90	153	0.831796
5000	100	170	0.502813
5500	110	187	0.709471
6000	120	204	-0.428892

This parameter of simulation is selected for one simulation; the Brillouin Frequency Shift is theoretically calculated. The random value R is generated by the Matlab Software. The level noise signal β are 1%, 2%, 3% 4% 5% and 8%. Fig. 5 and 6 show the strain and temperature applied on the Brillouin sensor decoupled by Eq. (13). It can note the value of the strain decoupled by the noise which agrees well with the theoretical value.

4 RESULTS AND DISCUSSION

To verify the accuracy of simulation, the pump and the stokes waves propagation over a 30 km-long fiber, we focused on the same value used in the (Belal and Newson, 2012), (Azizan and Shahimin, 2012) and (Singh and Gangwar, 2007) for all simulation parameter. We choose the pump power, $P_p(0) = 4.2\ \text{mW}$, the Brillouin gain coefficient, $g_B = 1.2 * 10^{-11}\text{m/W}$, the mode effective area, $A_{eff} = 86\ \mu m^2$, the fiber attenuation constant, $\alpha_p = \alpha_s = 0.217\ \text{dB/km}$, and the initial Stokes intensity, $P_s(0) = 1.726\ \text{mW}$. The Fig. 7 shows the results of the simulations, that the graph published in (Azizan and Shahimin, 2012) and (Singh and Gangwar, 2007).

The pump power and Stokes power depend on the length of the fiber. These powers are calculated by the next equation:

$$P_p(z) = P_p(0) * \exp(-\alpha_p * z) \tag{14}$$

$$P_s(z) = P_s(0) * \exp(-\alpha_s * z) \tag{15}$$

$$P_s = A_{eff} * I_s \tag{16}$$

$$P_p = A_{eff} * I_p \tag{17}$$

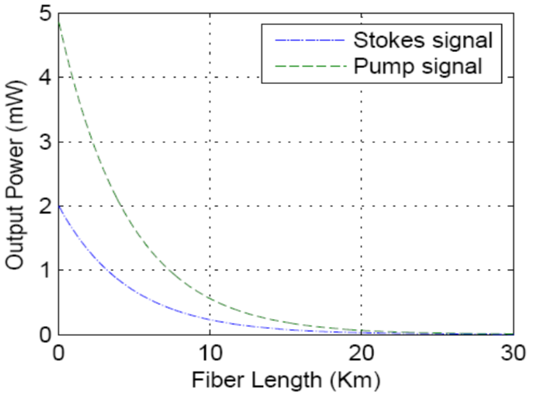

Figure 7: Pump and Stokes wave evolution over 30 km-long.

Fig. 7: shows that the output power is in terms of fiber length, so it is clear that when the fiber length increases, more signal power (pump and Stokes) decreases.

The results obtained demonstrate that the power vanishes from 20 Km long.

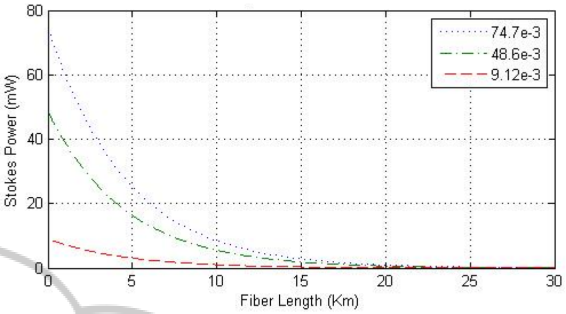

Figure 8: Stokes Power.

The attenuation of signal is depends on initial power stokes. When the initial power is high the signal is weak. The upper curve mean to the initial intensity of Stokes is to 74.7 mW, the middle curve means that the initial intensity of Stokes is to 48.6 mW and the lower is 9.12 mW.

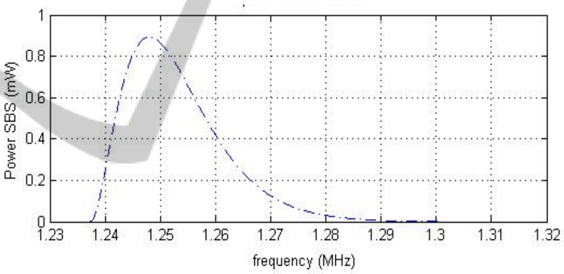

Figure 9: Spectrum of Brillouin.

The spectrum of Brillouin obtains her peak of frequency w_B at 1.247 (GHz).

5 CONCLUSIONS

The effects of temperature and stain shift on Brillouin scattering in optical fiber have been descripted. Brillouin spectrum is sensitive to the frequency's variation.

So to modulate this spectrum, we choose to fix the Brillouin coefficients through fixing temperature or strain and shifting one of them. This study gives a view how to model and measure Brillouin scattering.

In Structural Health Monitoring, many parameters over and above temperature and strain can be studied, such as presion, humidity, etc. So we have the opportunity to add other parameters using fiber bragg.

REFERENCES

Belal, M., Newson, T.P., 2012 "Experimental Examination of the Variation of the Spontaneous Brillouin Power and Frequency Coefficients Under the Combined Influence of Temperature and Strain", *Journal of Lightwave Technology.*

Azizan, S., Shahimin, M.M., Murad, S.A.Z., 2012 "Simple Distributed Brillouin Scattering Modeling for Temperature and Strain Sensing", *IEEE Symposium on Business, Engineering and Industrial Applications.*

He, J., Zhou, Z., Ou, J., 2014 "Simultaneous measurement of strain and temperature using a hybrid local and distributed optical fiber sensing system", Measurement.

Luo, J., Hao, Y., Ye, Q., Hao, Y., Li, L., 2013 "Development of Optical Fiber Sensors Based on Brillouin Scattering and FBG for On-Line Monitoring in Overhead Transmission Lines", *Journal of Lightwave Technology.*

Sikali Mamdem, Y., 2012 "sensors with optical fibers distributed by Brillouin effect: separation of the dependence at the temperature and the strain".

Singh, S. P., Gangwar, R., Singh, N., 2007 "non linear scattering effects in optical fibers", *Progress In Electromagnetics Research, PIER.*

Reshak, A. H., Shahimin, M. M., Murad, S. A. Z., Azizan, S., 2013 "Simulation of Brillouin and Rayleigh scattering in distributed fibre optic for temperature and strain sensing application", Sensors and Actuators A: Physical.

Hui, R., O'Sullivan, M., 2009 "Fiber Optic Measurement Techniques", *Elsevier Academic Press.*

Halina, A., 2005 "nonlinear phenomena in optical fibers".

Liu, X., Bao, X., 2012 "Brillouin Spectrum in LEAF and Simultaneous Temperature and Strain Measurement", *Journal of Lightwave Technology.*