OPTICAL FIBRE LONG-BRAGG GRATING SENSORS FOR SPACE DISTRIBUTION OF INDUCED BIREFRINGENCE

Jozef Jasenek, Norbert Kaplan, Jozefa Červeňová, Branislav Korenko

Institute of Electrical Engineering, FEEIT STU Bratislava, Ilkovičova 3, 812 19 Bratislava
E-mail: Jozef.Jasenek@stuba.sk, Norbert.Kaplan@stuba.sk, Jozefa.Cervenova@stuba.sk, Branislav.Korenko@stuba.sk

Received 10 May 2016; accepted 17 May 2016

1. Introduction

Optical fibres (OF) and mainly special OF such as photonic crystal fibres, polarization maintaining OF or OF with inscribed Fibre Bragg Gratings (FBG) are now broadly applied in the space distributed sensing of many physical quantities [1], [2]. Due to their importance the amount of investment into this field is growing rapidly worldwide [1]. At present many approaches to the design and the simulation of fibre optic sensors (FOS)do exist. Significant group of these sensors is based on optical fibres with inscribed FBG especially with so called Long-length FBG (L-FBG)(L≥100 mm) [3].These sensors make possible to obtain space distribution of the measured physical quantity along the L-FBG with relatively high space resolution. One of the most significant applications of these sensors is the measurement of local longitudinal and lateral mechanical stress in various construction materials. [5, 6]. However the lateral stress in the OF cross section induces the birefringence in the fibre core and consequently two main polarization modes do exist (slow and fast). As a result two local reflection spectra are present instead of one in non-birefringent OF. If the induced birefringence is rather small there is a problem to identify the maxima of spectrum and to evaluate the change of stress or other relevant physical quantity coupled to the birefringence. So it is necessary to have an appropriate description or model for the evaluation of the birefringence change from the basic parameters of the measured maxima in reflection spectra of OFS based on FBG.

In this paper we describe the model for the extraction of the local reflection spectra from the total reflected signal generated by L-FBG OFS using signal processing based on “Optical Frequency-Domain Reflectometry” (OFDR). The L-FBGs are considered as birefringent. Simulation results based on the “Short Time Fourier transform (STFT)” are presented. Two possibilities of the birefringence evaluation are described– one for the small birefringence based on determination of the oscillation period of the power reflection maximum along the FBG and the other one for the large birefringence based on the determination of maximum shift in the reflection spectrum.

2. Transmission matrices of elementary homogeneous birefringent FBG section

The description of the basic refraction index modulation in a birefringent FBG as the perturbation of the fibre core effective refractive index $\delta n_{eff}(z)$is given by the relation

$$\delta n_{eff,(x,y)}(z) = [\delta n_{eff,(x,y)}(z)]_{av}.\{1 + \nu.\cos[(2\pi/\Lambda).z]\} \tag{1}$$

where $[\delta n_{eff,x,y)}(z)]_{av}$ is the constant averaged effective index value of one FBG period (DC index change), Λ is the designed FBG period and ν is depth of the index modulation (visibility). Indexes (x, y) indicate (and will be used in the same way in the next relations) the values corresponding with fast and slow modes respectively. This perturbation induces the mode coupling between all allowed modes and influences the transmission and reflection spectra of all modes. If one considers an elementary homogeneous and birefringent FBG section of length Δz in single mode OF with the forward and backward propagating modes only, the relation between the complex amplitudes of forward modes $R_{x,y}(z)$ and backward modes $S_{x,y}(z)$ can be described by the matrix equation as follows:

$$\begin{bmatrix} R_{x,y}(0) \\ S_{x,y}(0) \end{bmatrix} = T^G_{x,y} \begin{bmatrix} R_{x,y}(\Delta z) \\ S_{x,y}(\Delta z) \end{bmatrix} \tag{2}$$

where

$$T^G_{x,y} = \begin{bmatrix} \mathrm{T}_{11\,x,y} & \mathrm{T}_{12\,x,y} \\ \mathrm{T}_{21\,x,y} & \mathrm{T}_{22\,x,y} \end{bmatrix} =$$

$$\begin{bmatrix} \cosh\left(\gamma_{B\,x,y}\Delta z\right) - j\frac{\sigma_{x,y}}{\gamma_{B\,x,y}}\sinh\left(\gamma_{B\,x,y}\Delta z\right); & -j\frac{\kappa_{x,y}}{\gamma_{B\,x,y}}\sinh\left(\gamma_{B\,x,y}\Delta z\right); \\ j\frac{\kappa_{x,y}}{\gamma_{B\,x,y}}\sinh\left(\gamma_{B\,x,y}\Delta z\right); & \cosh\left(\gamma_{B\,x,y}\Delta z\right) + j\frac{\sigma_{x,y}}{\gamma_{B\,x,y}}\sinh\left(\gamma_{B\,x,y}\Delta z\right); \end{bmatrix} \tag{3}$$

where $\gamma_{Bxy} = \sqrt{(\kappa^2_{x,y} - \sigma^2_{gx,y})}$. (4)

$\sigma_{g,x,y}$ are the „general self-coupling coefficients" (DC-coefficients)" and $\kappa_{x,y}$are „alternating coupling coefficients" (AC-coefficients) for fast (x) and slow (y) modes respectively. They are given by relations

$$\sigma_{gx,y} = (2\pi/\lambda).[n_{effx,y} + (\delta n_{effx,y})_{av}] - (\pi/\Lambda) \quad \text{and} \quad \kappa_{x,y} = (\kappa_{x,y})^* = (\pi/\lambda).\nu.[\delta n_{effx,y}]_{av} \tag{5}$$

λ is the optical radiation wavelength in free space and $n_{effx,y}$are effective refractive indexes of the fast and slow modes in the fiber core.

The amplitude reflection coefficient of the FBG is generally defined as $\rho = [S(0)/ R(0)]$. Using (2),(3) and putting $R_{x,y}(0) = 1$ and $S_{x,y}(\Delta z) = 0$ the reflection coefficients for fast and slow modes can be expressed according to [7] as

$$\rho_{x,y} = \frac{S_{x,y}(0)}{R_{x,y}(0)} = S_{x,y}(0) = \frac{T_{21x,y}}{T_{11x,y}} =$$

$$= \frac{-\kappa_{x,y}.\sinh\{[\sqrt{(\kappa^2_{x,y} - \sigma^2_{g\,x,y})}].\Delta z\}}{\sigma_{gx,y}.\sinh\{[\sqrt{(\kappa^2_{x,y} - \sigma^2_{g\,x,y})}].\Delta z\} + i.[\sqrt{(\kappa^2_{x,y} - \sigma^2_{g\,x,y})}].\cosh\{[\sqrt{(\kappa^2_{x,y} - \sigma^2_{gx,y})}].\Delta z\}} \tag{6}$$

As a result for the evaluation of reflection spectra of the homogeneous elementary FBG section the elements of the $\boldsymbol{T^G_{x,y}}$ matrices (3) can be used.

3. Model of the L-FBG sensor system based on OFDR

The basic idea of the FBG sensor consists in the interaction of FBG with the external physical quantity like strain what results in the measurable change of the reflected FBG spectrum.

In some cases external physical quantities may cause the OF with the inscribed FBG to become birefringent.

We use for sensing purposes the ***"L-FBG"*** in combination with the ***"Optical Frequency-Domain Reflectometry"***. The basic idea of such a system can be explained using Fig. 1. Signal from the tuneable laser source TS is launched through 3dB fiber coupler C1into couplers C2 and C3 which are the inputs of two fibre interferometers – first consisting of the C2, mirrors M1, M2 and photodiode PD1 and the second one of C3, M3, L-FBG and photodiode PD2. Signal from the first interferometer terminated by the mirrors M1 and M2 is detected by the photodiode PD1and is given by the relation

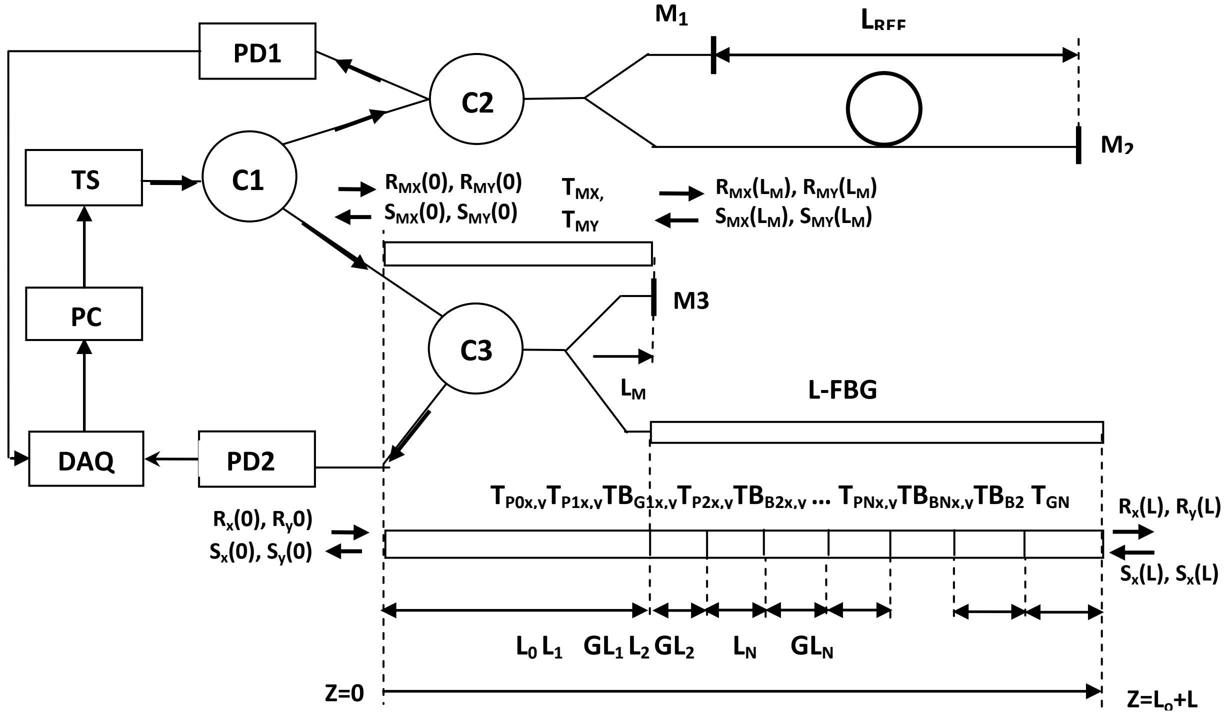

Fig. 1 *The simplified scheme of the sensing system based on L-FBG and OFDR*

$$\boldsymbol{I_{PD1}} \sim \cos(2n_{eff}L_{REF}\,k) \tag{7}$$

where L_{REF} is the distance between M1 and M2. This signal oscillates periodically with wave number k. The periodicity is adjustable by L_{REF} and is given by

$$\Delta k = \pi/(n_{eff}L_{REF}) \tag{8}$$

This signal is used for the equidistant sampling of the measured signal from the second FBG interferometer.

The second „measuring interferometer" is created by C3, M3, L-FBG and PD2. The whole measuring arm of L- FBG interferometer consists generally of N partial birefringent L-FBG sections indexed by "i"= 1toN. Each partial L-FBG section of length L_i is created by M_{ij} series of further elementary and homogeneous birefringent FBG-s of length „Δz" and described by individual local birefringent grating parameters $\gamma_{ijBx,y}$, $\sigma_{gijx,y}$, $\kappa_{ijx,y}$ as defined by (4-5). So the length of the particular L-FBG section is $GL_i=(M_{ij}.\Delta z)$. There are also pieces of "connecting birefringent single-mode fibres" of the length L_i between particular L-FBG sections. The transmission matrices of the elementary homogeneous FBG sections $\boldsymbol{T}^{\boldsymbol{G}}_{ix,y}$ are defined by (3) and the phase shifting transmission matrices $\boldsymbol{T}^{\boldsymbol{P}}_{ix,y}$ of connecting sections are defined as follows

$$T^{P}_{i\,x,y} = \begin{bmatrix} e^{-j\,n_{effx\,,y}L_i k} & 0 \\ 0 & e^{j\,n_{effx\,,y}L_i k} \end{bmatrix} \quad (9)$$

The resulting transmission matrices for the slow and fast modes of the whole L-FBG can now be represented by a proper multiplication of all particular local matrices of the elementary homogeneous FBG-s $\boldsymbol{T}^{\boldsymbol{G}}_{ijx,y}$ indexed by "ij" and those of "connecting sections" $\boldsymbol{T}^{\boldsymbol{P}}_{x,y}$ indexed by "i" as follows (see Fig. 1).

$$T^{G}_{ijx\,,y} = \left[T^{P}_{0x,y}\right].\left[T^{P}_{1x,y}\right].\left[T^{G}_{11x,y}\right].\left[T^{G}_{12x,y}\right]\dots.\left[T^{G}_{1M1x,y}\right].\left[T^{P}_{2x,y}\right].\left[T^{G}_{21x,y}\right]\left[T^{G}_{22x,y}\right].\dots\left[T^{G}_{2M2x,y}\right].$$

$$.\left[T^{P}_{3x,y}\right]\dots.\left[T^{P}_{Nx,y}\right].\left[T^{G}_{N1x,y}\right]\left[T^{G}_{N2x,y}\right].\dots\left[T^{G}_{N(MNx,y)}\right]. \quad (10)$$

According to (6) having the coefficients $T_{11x,y}$ and $T_{21x,y}$ of the total reflection matrix (10) the resulting L-FBG reflection spectrum can be calculated.

The signal I_{D2} seen by the diode D_2 is given by the sum of the signal $S_{M3x,y}(0)$ reflected from the reference mirror M3 and the $S_{BGx,y}(0)$ reflected from the whole L-FBG. It is given by

$$I_{D2} = |\boldsymbol{S}_M(0) + \boldsymbol{S}_{BG}(0)|^2 = \left|(S_{M3x}(0) + S_{BGx}(0))\boldsymbol{u}_x + (S_{M3y}(0) + S_{BGy}(0))\boldsymbol{u}_y\right|^2 \quad (11)$$

where $S_{M3x,y}(0) = \exp[i(2n_{effx,y} L_0.k+\pi)]$ and $n_{effx,y}$ are effective refractive indices of fast and slow modes in the fibre core, L_0 is the distance given in the Fig. 1, k is the wave number in vacuum. Equation (11), (10) and (3) indicate that total interference signal seen by D2 represents the sum of the reflecting spectra of fast and slow modes from all local birefringent homogeneous elementary FBGs modulated by the corresponding beating frequencies which are defined by positions of the elementary sections with respect to the M3 position and by the fibre effective refraction indices of fast (n_{effx}) and slow (n_{effy}) modes. It is important to stress that it is true only if the reflectivity of each elementary FBG is less than nearly 10 % and the depth of the refractive index modulation νin each elementary FBG is not greater than approx. 0,4 [7,8]. Under these conditions the total signal at PD2 can be expressed as the sum of the particular modulated local reflection spectra $R_{ijx,y}(k)$

$$R_{D2} = \sum\nolimits_{i,jx,y} R_{ijx\,,y}(k).\cos\left(2n_{effx\,,y}.z_{ij}.k\right) = \sum\nolimits_{i,jx,y} R_{ijx\,,y}(k).\cos\left(\omega_{ijx,y}.k\right) \quad (12)$$

Each component $R_{ijx,y}(k)$ is modulated by harmonic beating signal with the frequency $\omega_{zx,y}$ that is defined by the position of the particular elementary FBG and by the indexes of refraction $n_{x,y}$ for slow and fast modes as follows

$$\omega_z = 2n_{effx,y}.z \quad (13)$$

It is important to be aware that both reflection signals corresponding with fast/slow modes are simultaneously measured and due to their coherence they can mutual interact. The amount of this interaction strongly depends on the birefringence value. For high birefringence the reflection maxima wave number separation is sufficient for the unambiguous evaluation of the local birefringence. But in the case of a small birefringence both spectra are partially overlapped and it is difficult to read the separation of maxima. But in this case however the mutual interaction of both spectra coherent signals generates the periodical modulation of the total signal along the grating at constant wave number. It can be shown that the periodicity T_z of the spectrogram along the L-FBG is dependent on the local birefringence($n_{effx} - n_{effy}$)as given by ([9])

$$T_z=\pi/(n_{eff}.\Delta k_{xy}) =[\lambda/2)]/[n_{eff}(n_{effx} - n_{effy})] \quad (14)$$

Equation (12) is the crucial for the processing of the signal measured by the photodiode PD2. If one applies the „Short Time Fourier Transform“(STFT) procedure to the measured total reflection spectrum R_{D2} and $\omega.z=\omega.z_1=(2n_{effx,y}).z_1$ is constant he can obtain the reflection spectra corresponding to the location $z=z_1$. In this way by repeating this procedure for all positions corresponding with all elementary FBGs one can get the reflection spectrogram providing complete information about all reflection spectra distributed along the L-FBG.

4. Simulation results

We have verified the validity of the above described model on the L-FBG containing the four homogeneous L-FBG sections with designed FBG wavelengths set as follows:λ_{1Bx}=1550 nm, λ_{1By}=1550,020nm,λ_{2Bx}=1551,000 nm, λ_{2By}=1551,050 nmλ_{3Bx}=1552,000 nm, λ_{3By}=1552,100 nmλ_{4Bx}=1553,000 nm, λ_{4By}=1553,500 nm and with corresponding „wavelength birefringences“ $\Delta_{\lambda Bixy} = \lambda_{iBx} - \lambda_{iBy}$: $\Delta\lambda_{1Bxy}$= 20 pm, $\Delta\lambda_{2Bxy}$= 50 pm, $\Delta\lambda_{3Bxy}$= 100 pm and $\Delta\lambda_{4Bxy}$ = 500 pm. The periodicities of particular elementary FBGs sections were taken as Λ_{1B} = 531.17550788 nm, Λ_{2B} = 531.51820175 nm, Λ_{3B}=531.86089563 nm, Λ_{2B} = 532.20358951 nm. Due to simplicity all four FBG sections are connected to gether with three non birefringent OF sections with effective refractive index n_{effx} = 1.459028. All sections have the same length equal to 10 mm. The resulting signal detected by the photodiode PD2 was calculated using the relations (3), (9), (10) and (11). Finally the numerical “Short Time Fourier Transform” with Hanning window width of 960 pm was applied to the signal (11). As a result the corresponding spectrogram was obtained as i tis shown in Figure 2. It can be seen that in the case of rather law birefringence (section 1) the clear periodicity T_z of the detected signal along that section, defined as $T_z=[\pi/(n_{eff}.k_o)]$, allows comfortably to evaluate the measured birefringence [9]. The beating period in this case evaluated from Fig. 2 is approximately T_z = 40 mm and calculated value according (14) is T_z = 41,16 mm what is acceptable agreement. The corresponding birefringence is $\Delta_{neff-xy} = n_{effx}-n_{effy}$= 0.00002655.

Going to the higher birefringences (sections2 and 3), the overlapping of “fast” and “slow” spectra decreases and consequently periodicity is growing and the depth of power modulation is decreasing. The situation from the point of view of measured data extraction is going to be worse. With growing birefringence the spectrogram is continually splitting into two easily distinguished spectrograms as it is seen in section 4 with highest birefringence. The reflection maxima wavelengths difference $\Delta\lambda_{xy}=\lambda_x-\lambda_y = 2\Lambda(n_{effx}-n_{effy})$ can now be easily used for the birefringence evaluation.

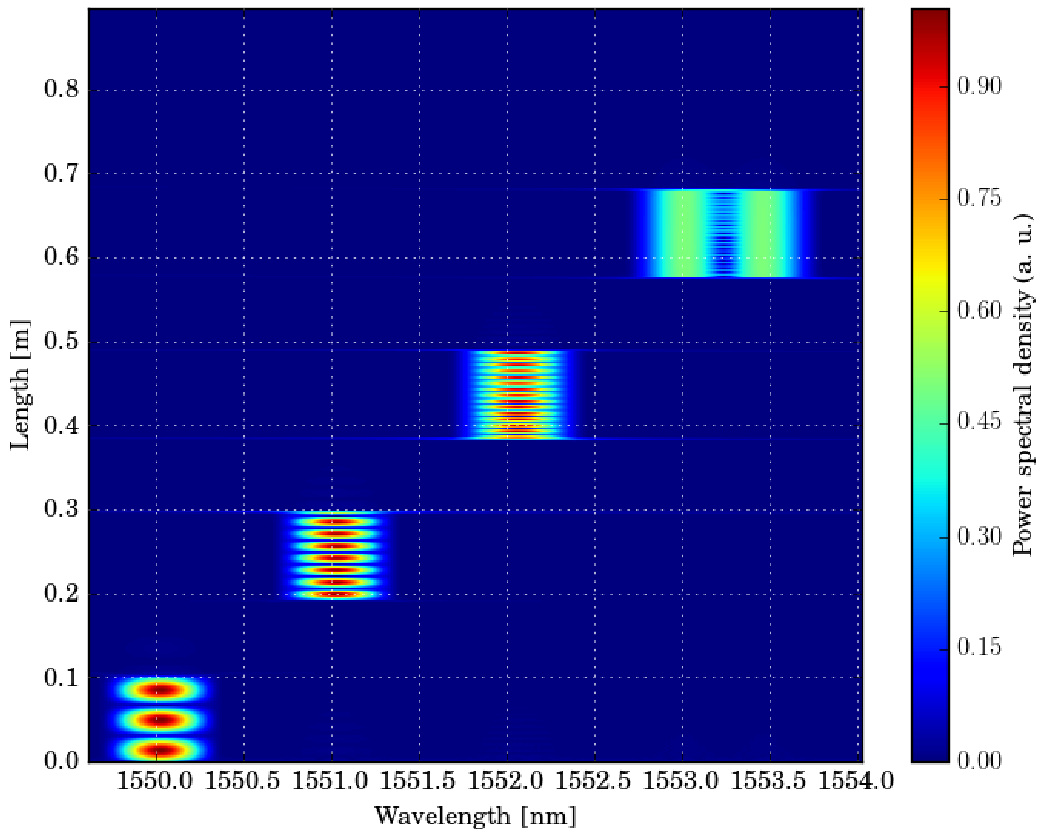

Fig. 2 *The spectrogram of the reflection spectra of L-FGB consisting of four 10 mm birefringent FBG sections and three OF connecting sections.*

5. Conclusion

At present time optical fiber sensors based on the FBG and especially on L-FBG are broadly applied in sensing system for measurement of several physical quantities like temperature, stress and others. Especially the measurement of lateral stress induces the birefringence in OF and also in FBG what implies that two FBGs signals appear in the sensing OF corresponding with slow and fast modes respectively. Therefore it is necessary to take it into account when transforming the influence of the measured external physical quantity into changes of FBG parameters and opposite when transforming the changes of measured reflection spectra parameters into measured external quantities.

In this article the optical fiber sensing system based on the combination of four birefringent sections L-FBG and FDOR is described and simulated. First the model of the system using the concatenated transmission matrix of the L-FBG arm in the fiber interferometer is brought. It makes possible to describe the resulting measured signal seen by the detector and containing the sum of the reflection spectra of the particular local elementary birefringent FBGs distributed along all L-FBG. Then by application of the STFT to that signal we can extract local reflection spectra on arbitrary location along the L-FBG. Special attention is devoted to the extraction of the induced birefringence when the birefringence is very low and when it is rather high. In the first case the longitudinal periodicity of the reflected power along the FBG can be used. For higher birefringence the wavelength shift value of reflected power maximum can be securely used. The simulation results clearly show the appropriateness of the used procedures.

Acknowledgement

This work was supported by the Development Agency under the contracts number APVV-0062-11 and the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic (VEGA), under the project no. 1/0405/16.

References

[1] David Krohn, Ph.D, Fiber Optic Sensors: Fundamentals and Applications, September, 2015, Light Wave Venture LLC, dkrohn@lightwaveventure.com, 203-248-1475

[2] J. Jasenek. Optical Fiber Reflectometry, Slovak University of Technology, 2004, ISBN 80-227-2002-X

[3] Childers, B.A., Froggatt, M. E., Allison, S. G., More, T. C., Hare, D. A., Batten, C. F., and Jegley, D. C.: Use of 3000 BG strain sensors distributed on four eight meter optical fibers during static load tests of a composite structure, Proc SPIE, vol 4332, pp. 133-142, Mar. 2001

[5] (7-W-2012)] – Igawa, H. Ohta, K., Kasay, T., Yamaguchi, I., Murayama, H., and Kageyama, K.: Distributed measurements wth a long gauge FBG sensor using OFDR, J. Solid Mech. Mater. Eng., Vol., No. 9, pp. 1-11, 2008

[6] (11-W-2012] - Igawa, H., Murayama, H., Yamaguchi, I., Kageyama, K., Uzawa, K., Wada, D., Ohsawa, I., Kanai, M., and Omichi, K.: Measurement of distributed strain and load identification using 1500mm gauge length FBG and OFDR, Proc. SPIE, Vol. 7503, pp. 750351-750354, Oct. 2009

[7] Erdogan, T.: Fiber Grating Spectra, Journal of Lightwave Technology, Vol. 15, No. 8, August 1997, pp. 1277-1293

[8] Murayama, H., Kageyama, K., Uzawa, K., Ohara, K., and Igawa, H. : Strain monitoring of a single-lap joint embedded fiber-optic distributed sensor, Structural Health Monitoring, 11(3), pp. 325-344, 2011

[9] Jozef Jasenek, Jozefa Červeňová, Branislav Korenko, Long Bragg Grating fibre optic sensors based on OFDR, Proceedings – APCOM 2015, Hotel Patria, Štrbské Pleso, June 24–26, 2015, ISBN 978-80-227-4373-0