

# AN INNOVATIVE ALGORITHM FOR FIBER BRAGG GRATING SENSORS INTERROGATION

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**Abstract** - The aim of the paper is to introduce an innovative algorithm able to determine the shift of the Bragg wavelength of a Fiber Bragg Grating (FBG) as it experiences a perturbation due to an applied strain. An accurate and precise evaluation of the FBG spectrum displacement is crucial for determining the amount of strain inducing such perturbations. The proposed method, very fast and simple to implement, is compared with the usually employed FBG demodulation techniques.

**Keywords:** Discrete Fourier Transform, Fiber Bragg Gratings, Monte Carlo Methods, Signal Processing Algorithms.

## 1. INTRODUCTION

The fiber Bragg gratings (FBGs) are sensors which are used for measuring strain, temperature, and pressure locally [1, 2]. As the FBG under analysis senses any kind of mechanical and/or thermal perturbation, its reflection spectrum experiences a shift in the wavelength domain. In order to properly evaluate the often small measurand changes leading to the FBG reflection spectrum displacement, an accurate measurement of it is required [3, 4]. This task is usually performed by monitoring the displacement of FBG reflection spectrum peak, occurring at the so-called Bragg wavelength. Several techniques, that are part of the whole FBG commercial assembly, employ a periodically tunable laser source to illuminate the fiber and produce the signal corresponding to the spectrum of the light interacting with the device, the so-called spectrometric technique [5]. For the spectrometric technique, once the FBG reflection spectrum is acquired, a method able to detect and track the spectrum peak is required. The simplest and typical techniques for these purposes are based on the FBG spectrum peak fit in the wavelength domain, followed by the detected Bragg wavelength peak tracking, allowing the evaluation of measurand changes. With this aim, the least-squares fit (LS) based on a gaussian model and the centroid of the FBG spectrum are usually considered [6, 7, 8]. All the methods which perform the FBG peak detection and tracking in the wavelength domain are characterized by significantly low time-consumptions, resulting in remarkable computing efficiency, and acceptable performance in terms of accuracy and precision of the detected Bragg wavelength shifts, as remarked in [6, 9]. In this paper a new method for FBG signal demodulation is introduced and takes advantage

of the Fast Fourier Transform tool, leading to faster and more accurate FBG spectra displacement evaluations. The following paragraphs deal with a brief description of the usual FBG demodulation algorithms (the LS and the centroid), the introduction to the implemented Average Squared Difference Function and a comparison among the time and accuracy performance granted by such techniques, in order to assess the enhancements led by the introduced technique.

## 2. FBG DEMODULATION ALGORITHMS

Typically, an FBG spectrum is acquired by means of a static interrogator based on spectral reconstruction technique. A laser light source (with tunable wavelength) is swept over the wavelength range with a sampling resolution  $\Delta\lambda$ , which characterizes and limits the FBG spectra peak tracking operation. The FBG spectrum is then obtained once the synchronization between the back-reflected FBG light and the spectrally swept laser source takes place [2, 9]. Thus, an algorithm able to track the FBG spectrum peak position in the wavelength domain is required, in order to quantify the measurand leading to such spectral perturbations. Usually, such task is performed in the wavelength domain and consists of extracting the FBG spectrum peak position (the Bragg wavelength,  $\lambda_B$ ) as the fiber itself is subjected to the perturbing effects led by the measurand. Several techniques are taken into consideration and they are able to perform an evaluation of the Bragg wavelength shift in the physical domain [8].

### 2.1. Least Squares Fit

The first method considered is the gaussian fit of the FBG spectra (the reference and the shifted ones), followed by the calculation of the  $\Delta\lambda_B$

The gaussian fit is implemented by minimizing the squared errors by means of the Gauss-Newton algorithm. The adjusted gaussian function is shown in 1

$$\rho_i = A \exp\left(-\frac{(C - \lambda_i)^2}{2V^2}\right) \quad (1)$$

In (1) the terms  $A$ ,  $C$ , and  $V$  are the adjusted parameters (amplitude, center, and deviation) and  $\rho_i$  is the calculated reflection spectrum amplitude for the  $\lambda_i$  wavelength. In this paper, only those points characterized by an amplitude larger than 0.5 have been considered.

## 2.2. Centroid

The centroid algorithm (operating in the wavelength domain) outputs a point corresponding to the geometric centroid of a spectrum and it is calculated by means of (2).

$$\lambda_B = \frac{\sum_{i=1}^M \lambda_i \cdot \rho_i}{\sum_{i=1}^M \lambda_i} \quad (2)$$

In (2), the term  $M$  is the FBG spectrum vector length,  $\lambda_i$  and  $\rho_i$  refer to the  $i^{\text{th}}$  point wavelength and reflectivity amplitude respectively. The term  $\lambda_B$  is the Bragg wavelength where the maximum FBG reflectivity takes place. In order to calculate  $\Delta\lambda_B$  occurring between two different FBG spectra due to an applied strain, the Bragg wavelength is tracked and compared to the one relative to the FBG spectrum in its reference status. The current Bragg wavelength minus the one relative to the reference spectrum gives the Bragg wavelength shift, which allows the calculation of the measurand changes.

The performance granted by these two techniques are compared with the introduced Average Squared Difference Function (ASDF) method based, described later on. These comparisons, shown later, have the purpose of illustrating the significantly enhanced performance (in terms of accuracy and time consumption) of the proposed ASDF technique for the determination of the Bragg wavelength shift experienced by a given fiber.

## 2.3. Average Squared Difference Function

The ASDF is here used to detect the wavelength shift between two given spectra by identifying and measuring the degree of similarity of two given waveforms as a function of the lag (in wavelength domain) applied to one of them. A similar type of function can be introduced. This kind of function is, for example, largely used for the calculation of the time-delay between two signals, [11]. It is defined by (3), according to [11].

$$R_{ASDF}(l) = \frac{1}{M} \cdot \sum_{k=1}^M [x(k\lambda) - y(k\lambda - l)]^2 \quad (3)$$

In (3),  $x$  and  $y$  refer to the reference and shifted spectra, respectively. The main assumption is that the application of any given perturbation to the fiber, causes a rigid displacement of the reflection spectrum in the wavelength domain without appreciable distortions. The idea behind the ASDF, is to compute the mean squared error values as the varying wavelength lag  $l$  in (3) changes. Once  $l$  is imposed, being  $M$  the spectra vector length, the mean of the sum of squared differences between the two spectra (as the wavelength changes) is calculated.

As the imposed wavelength lag  $l$  varies, a series of values is obtained and follows the trend outlined in Fig. 1. The spectra are supposed to be shifted at a wavelength

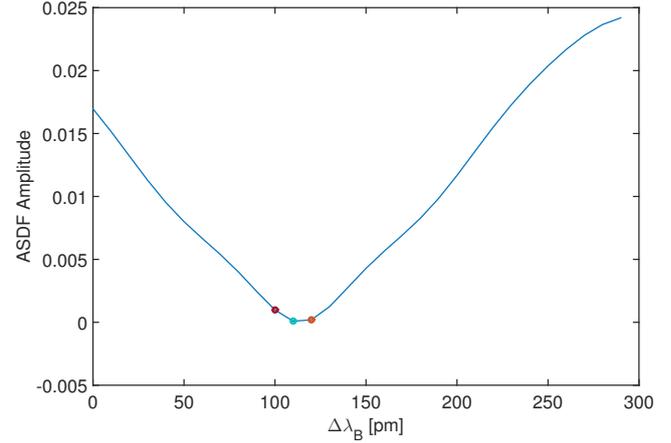


Fig. 1. ASDF for the FBG spectra in Fig. 1. The pictured points are subjected to the Gaussian fit for the determination of the interpolated ASDF pitch x-position.

lag where the ASDF exhibits its minimum. Thus, the estimator of occurred Bragg wavelength shift is the ASDF pitch. In this case, due to spectral resolution limitations, a Gaussian 3-point fit about the detected pitch is needed. The authors implemented this procedure in order to obtain shifts at sub-resolution extent. With the aim of improving the computational of the ASDF calculation, the authors uses the Fourier Transform tool, leading to (4).

$$R_{ASDF} = -2 [\mathcal{F}^{-1}(\mathcal{F}(y) \cdot \mathcal{F}^*(x))] + \sum_{i=1}^M x_i^2 + \frac{1}{M} \sum_{i=1}^M y_i^2 \quad (4)$$

In (4),  $\mathcal{F}$  and  $\mathcal{F}^{-1}$  refer to the Fourier Transform and its inverse respectively. Vectors  $x(\lambda)$  and  $y(\lambda)$  represent the FBG spectrum at its undisturbed status and the same one after an applied strain.  $M$  is the vector length.

## 3. METHODOLOGY

This section describes the operations implemented in order to evaluate the performance of the proposed ASDF method and compare it to the conventionally considered demodulation techniques operating in the wavelength domain (gaussian least squares fit and centroid algorithms here considered), [10]. The algorithms under comparison, have been applied on numerically simulated FBG spectra. For the FBG reflection spectrum simulation, the author considered the so-called Transfer Matrix Method, widely cited in technical literature [1, 2, 3, 5]. Other peculiar characteristics of the simulated fiber are going to be presented in the full version of the paper. The Transfer Matrix Method is a powerful tool which allows significantly fast simulations of FBG reflection spectrum for any apodization and strain condition [12]. In this paper, the authors consider a uniform fiber (with a core grating period constant through the fiber length), subjected to an applied

strain  $\epsilon$ , constant through the FBG main axis and time-linearly varying. The simulations produced a set of spectra, exhibiting Bragg wavelength shifts from 2.34 pm up to 114 pm. In order to evaluate the performance of the FBG demodulation algorithms (the gaussian LS, the centroid, and the proposed ASDF methods), each spectrum is considered characterized by a white Gaussian noise expressed by the spectrum Signal-to-Noise Ratio (SNR) from 10 dB up to 60 dB (in steps of 2 dB). The Monte-Carlo method implemented has the purpose of assessing the algorithms performance for several FBG spectra noise levels. It consists of a set of  $M=1000$  randomly noisy spectra (for a specified  $\Delta\lambda_B$ ).

The statistical parameter taken into account is the Root Mean Square Error defined as follows.

$$RMSE = \left[ \frac{1}{M} \sum_{i=1}^M (\Delta\lambda_{i,calc} - \Delta\lambda_{eff})^2 \right]^{-2} \quad (5)$$

These quantity is calculated among the simulated spectra, repeated  $M=1000$  times, for each considered SNR value.

#### 4. RESULTS

In this section, a series of performance comparisons between the three presented algorithms are shown.

Figures 2 and 3 show the RMSE value against the actual imposed  $\Delta\lambda_B$  for noisy spectra characterized by SNR values of 10 dB and 60 dB.

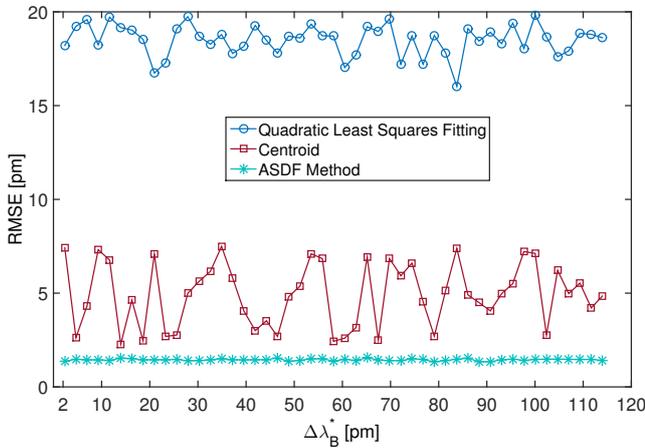


Fig. 2. RMSE of the detected  $\Delta\lambda_B$  vs the effective Bragg wavelength shift, for SNR of 10 dB.

Each figure show a relative insensitivity of the RMSE trend vs. the effective  $\Delta\lambda_B$ , although a quasi-oscillatory trend is evident and more exacerbated for the LS fit and the centroid methods. In both cases, the error given by the ASDF method (in the evaluation of the  $\Delta\lambda_B$ ) is dramatically reduced. In addition, as one can expect, an increase of the SNR of the input FBG spectra causes a decrease of the RMSE.

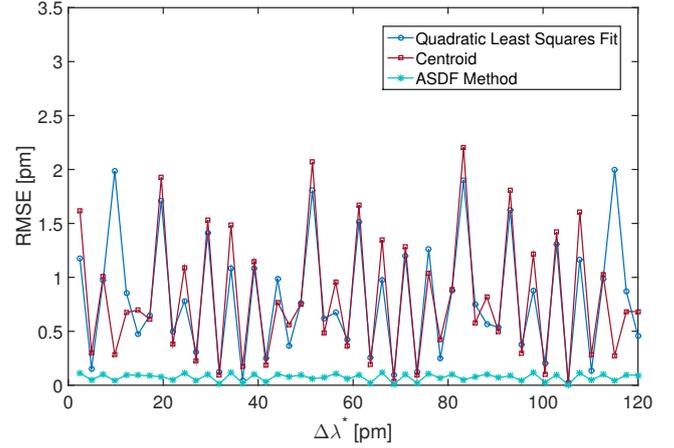


Fig. 3. RMSE of the detected  $\Delta\lambda_B$  vs the effective Bragg wavelength shift, for SNR of 60 dB.

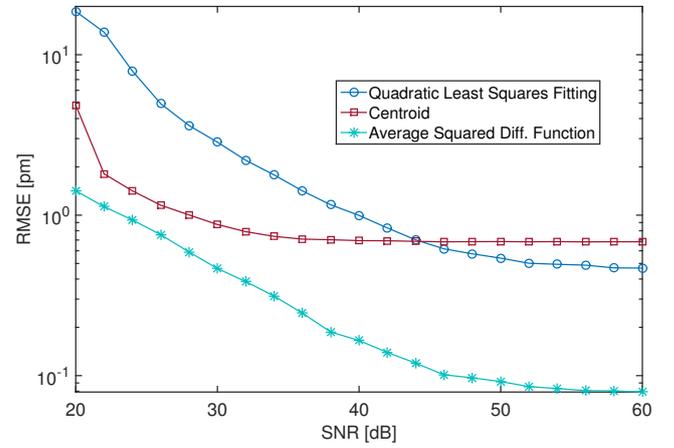


Fig. 4. RMSE of the detected  $\Delta\lambda_B$  vs the effective Bragg wavelength shift, for SNR of 60 dB.

Figure 4 shows the trend of the RMSE against the input spectra SNR for an imposed  $\Delta\lambda_B=114$  pm.

For each SNR value, the proposed ASDF method performs remarkably better.

Table I shows also a computation time comparison. The parameter here considered, is the average time taken for the implementation of each algorithm on two given FBG input spectra. As shown, the proposed ASDF technique allows also low computation time.

All the simulations have been performed in MATLAB<sup>®</sup> running on a 8 Gb memory Intel<sup>®</sup> Core<sup>™</sup> i7 3632QM (@2.20 GHz) computer.

#### 5. CONCLUSION

In this paper, the authors introduce the Average Squared Difference Function as a novel FBG demodulation technique based on computations performed in the Fourier domain. The main purpose is to assess the increased

Table 1. Average computation time required by each method.

Method	Average Time [s]
Quadratic least-squares fit	$1.5 \cdot 10^{-3}$
Centroid algorithm	$7.2 \cdot 10^{-4}$
Proposed ASDF Method	$1.05 \cdot 10^{-4}$

performances granted by such technique, if compared with the ones usually used in the FBG signal demodulation ambit. The performance index here considered, is the accuracy and is related to the ability exhibited by a method to provide unbiased Bragg wavelength shifts. This feature can be further expressed as the degree of closeness of the mean value of a sample of calculated  $\Delta\lambda_B$  to  $\Delta\lambda_{B,eff}$ . The quantity considered by the author is the Root Mean Squared Error, as defined in (5). The set of FBG spectra, properly repeated and replicated by means of Monte-Carlo method, has been achieved by means of Transfer Matrix Method (TMM), a mathematical tool which allows a very accurate and fast simulation of the FBG reflection spectrum experiencing an applied strain, once the FBG physical properties have been defined. The repetitions and the replications of the simulated FBG spectra have the purpose of assessing the technique stability (as the ability of providing results not significantly spread) and its behaviour towards simulated FBG spectra noise levels. The commonly used techniques considered for FBG signals demodulation purpose are the gaussian LS and centroid algorithms. The authors performed a series of accuracy performance comparisons among the already cited typical FBG demodulation techniques and the proposed one. These comparisons have been carried out for several effective Bragg wavelength shifts and for different SNR levels, in order to ascertain the techniques performance in specified conditions. The performed comparisons show a remarkable increase of both accuracy and time consumption performance granted by the proposed ASDF technique.

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