A New Approach to Solve the Inverse Scattering Problem Using a Differential Evolution Algorithm in Distributed Fiber Bragg Grating Strain Sensors

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Abstract: A differential evolution method is proposed to recover the deformation field in a fiber Bragg grating, overcoming known limitations of ambiguity and performance. Results show its capacity to determine deformation fields in a chirped grating.

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1. Introduction

Fiber Bragg gratings (FBG) are in-fibre structures that can be employed in sensing applications [1]. A strained FBG presents structural modifications, resulting in changes in its reflection spectrum [1]. If an FBG is subjected to a uniform strain profile, its reflection spectrum will be simply wavelength shifted. Nevertheless, a non-uniform strain profile can also result in the broadening and deformation of the reflection spectrum. An efficient computational method that solves the well known inverse scattering problem [2] in fiber Bragg gratings would allow the use of the sensor in field applications and also in embedded systems. To the authors' knowledge, such an efficient solution is still a problem to be explored. Other works proposed methods to solve the scattering problem under specific circumstances, requiring FBGs with low reflectivity [3], information about the phase of the FBG spectrum [2, 4], or a monotonic [5] strain profile. Another work [6] proposed the usage of a genetic algorithm for determining the strain profile of an FBG. However, two FBGs subjected to the same strain were required to overcome the ambiguity drawback, yet requiring computational time of hours.

This work proposes a method based on differential evolution (DE) to determine the strain profile of an FBG strain sensor. The method uses only one chirped FBG, and phase information is not required. The ambiguity problem is solved by adding a continuity constraint in the optimization method. Simulation results showed that the proposed method can recover the strain profile applied to the FBG, requiring two orders of magnitude less time than the method proposed by Cheng et al [6]. Besides, this approach establishes the basis for the practical use of distributed sensing with FBG, where an FBG can simultaneously monitor multiple points.

2. Methodology

A distributed deformation field along a chirped FBG will cause changes in the grating pitch and induce refractive index changes in the fiber by the photo-elastic effect [7]. The change in the pitch caused by a strain field in a uniform section of the FBG, ε, is given by Eq. 1 and the change in the core refractive index is given by Eq. 2, where p_{11} and p_{12} are the fiber photoelastic coefficients and ν is the Poisson ratio. Those structural changes results in modifications on the FBG's reflection spectrum.

$$\Lambda(z)' = \Lambda(z)\,(1+\varepsilon) \tag{1}$$

$$\overline{n}' = \overline{n} - 0.5\overline{n}^3(p_{12} - \nu(p_{11}+p_{12}))\varepsilon. \tag{2}$$

On this inverse scattering problem the structural parameters of the chirped FBG are determined from the measured reflection spectrum. Here, a differential evolution method is developed to determine the deformation field by using the known parameters of the unstrained grating. The FBG under analysis is divided into 20 segments corresponding to 20 uniform FBGs, a compromise between accuracy and computational performance. The structural parameters of an FBG segment will be the length L, the average refractive index $\overline{n}$, and a sinusoidal refractive index modulation function with pitch Λ and amplitude Δn_0.

A population of 100 candidate solutions is evolved iteratively by using the standard DE/rand/1/bin [8] scheme. Each candidate solution is comprised of 20 parameters corresponding to the strain in each one of the 20 segments in which the analyzed grating is decomposed. The fitness of a candidate solution is computed by applying the candidate strain profile to the known unstrained FBG structure by using Eq. 1 and 2. Then, the reflection spectrum (for 64 wavelengths uniformly distributed) is computed by the transfer matrix method [9]. The mean squared error (MSE) between the computed reflection spectrum and the target (measured) spectrum is multiplied by -1, and the resulting value is employed as the fitness value. Thus, when the MSE decreases, the fitness increases. A crossover parameter $CR = 0.95$, and a mutation factor $F = 0.7$ were used. The strain values were limited in the $[0,2]$ mϵ range, in the same order of magnitude as the experiments reported in the literature [6, 7]. The initial population is generated randomly, and the evolutionary process occurs with a total of 2000 generations. After this process, the solution with the highest associated fitness is selected.

As already discussed elsewhere [6,7], without phase information, a number of distinct strain profiles can result in the same reflection spectrum. To obtain an unambiguous strain profile with a single grating, a chirped FBG with Gaussian apodization was used. Additionally, a constraint to the candidate solutions was employed to avoid unfeasible strain profiles that would result in similar target spectra. This constraint imposes that the strain at each segment of the FBG must not differ more than 0.2 mϵ from the strain at the neighbor segments. Each segment that violates this constraint incurs in a fitness penalty equal to the exceeding value times 10 (arbitrary weight). This additional restriction forces the convergence to a single solution. A value of 0.2 mϵ was arbitrarily chosen, and can be changed according to the application.

2.1. *Experimental Methodology*

The proposed method was evaluated in a simulated setup, where a FBG with a chirp of 2 nm/cm, $l = 1$ cm, $\Lambda_0 = 532.4$ nm, $\overline{n} = 1.457$, $\delta n_0 = 2.5 \times 10^{-4}$, was strained under a standard deformation field. Also, it was used a Gaussian envelope in the FBG index modulation. Three distinct strain profiles were tested, leading to experiments named E_1, E_2, and E_3, as depicted in Fig. 1. In each experiment, the chirped FBG was subjected to the respective strain profile, and the proposed method was used to recover the applied strain profile from the FBG reflection spectrum. A set of 64 sampled wavelengths were uniformly distributed in the range between 1552 nm and 1559 nm. Here, the fiber photoelastic coefficients were taken as $p_{11} = 0.113$, $p_{12} = 0.252$, with a Poisson ratio $\nu = 0.16$ [10].

The mean absolute error (MAE) between the obtained and the target strain profile was used as error metric. Each experiment was repeated 30 times and the mean MAE and the experimental standard deviation where computed for each experiment. All experiments were performed on an Intel(R) Core(TM) i7-3520M 2.90GHz CPU, using all cores in parallel in the fitness evaluation.

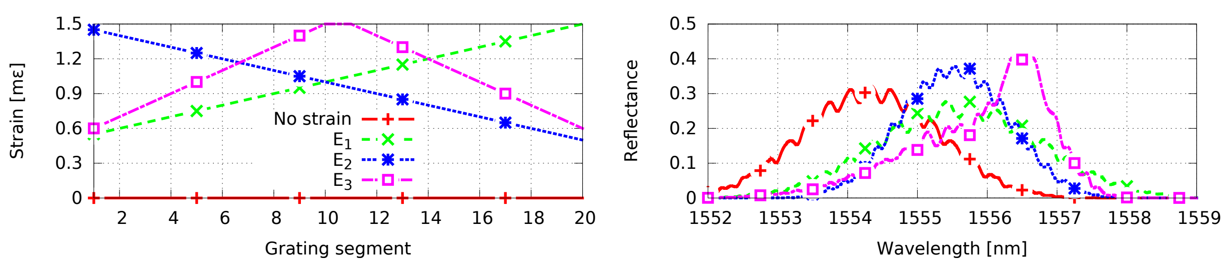

Fig. 1. Strain profiles for experiments E_1, E_2, and E_3, with the corresponding reflection spectra.

3. Results and Discussion

The mean error and the corresponding deviation for experiments E_1, E_2, and E_3 are, respectively: 0.053 ± 0.012 μϵ, 0.060 ± 0.064 μϵ, and 0.022 ± 0.008 μϵ. These results show that the solutions converged to the expected values. Fig. 2 shows the best solution and its corresponding reflection spectrum in one run of experiment E_3, for 100, 300, and 2000 generations.

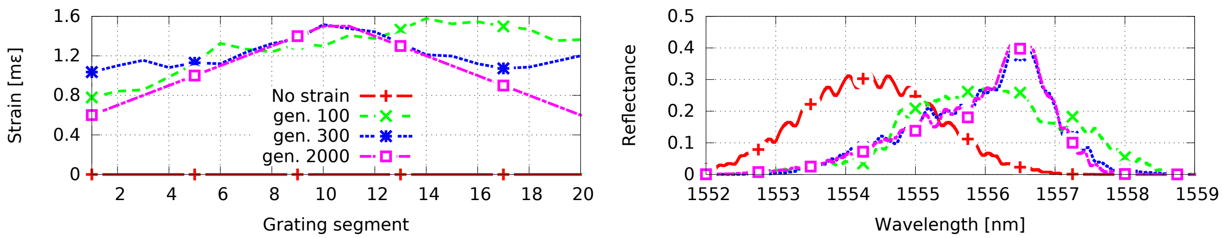

Fig. 2. Example of the evolutionary process during one repetition of experiment E_3.

The implementation took approximately 13 s to converge to the final result. The example shown in Fig. 2 suggests that depending on the application requirements, the termination criterion can be changed to stop the process earlier. The performance can also be enhanced by reducing the number of segments in which the analyzed FBG is divided. The method has shown a performance about two orders of magnitude better than the genetic algorithm proposed by Cheng and Lo [6], for the same number of FBG segments under similar strain fields. Also, in similar setups a low cost interrogator could be employed, as the required resolution is roughly 100 pm. The implementation of the proposed method is publicly available [11].

4. Conclusion

This work shows a new method based on DE to determine the strain profile of an FBG sensor based on the magnitude of its reflection spectrum. It is related to a genetic algorithm previously reported in the literature [6]. Nevertheless, the method proposed here does not required the simultaneous use of two FBGs and also shows a superior computational performance. The method provides the basis for distributed strain sensing, allowing a single FBG to monitor multiple points simultaneously. Also, it can be adapted to applications such as distributed temperature monitoring and in the fabrication of FBGs with arbitrary spectral response. Future works includes experiments to verify the method performance under practical conditions.

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