Cascaded FBGs Interrogated by a Phase-OTDR for Vibration Sensing

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***Abstract*—Phase Optical Time Domain Reflectometry (Phase-OTDR) can achieve the characterization and localization of vibration from the measurement of backscattered signal. However due to the weakness of the Rayleigh backscattered signal, the vibration information may be lost in the signal noise. For this reason, the increasing of the signal-to-noise-ratio (SNR), the Fibre Bragg Gratings (FBG) can be used as scattering centers. The goal of the project was to develop a novelty equally distributed sensor configuration to optimize the sensing capabilities and to analyze the problem of spectral shadowing. In this paper an algorithm is proposed and tested for eliminating this negative effect in the experimental setup.**

***Keywords*—Phase-OTDR, Fibre Bragg Gratings, distributed sensing**

I. Introduction

Phase-OTDR is used in many domains such as intrusion detection systems or railway vibration monitoring applications because it allows the implementation of vibration sensors that can achieve both localization and characterization of a vibration that occurs on a part of the optical fibre.

The Phase-OTDR uses a highly coherent laser source because it enables the in depth observation of local perturbations. The phase-OTDR - uses a narrow line-width laser as an optical source. The incident light will be then modulated into pulses with an acousto-optic modulator and a pulse generator. The pulses will then be amplified and filtered of noise. While the pulse is propagating through the fibre under test (FUT), after passing through the circulator, the backscattering signal which carries the vibration information, will be detected by a photodetector and recorded by a data acquisition card. When a vibration occurs on the FUT at a particular location, its refractive index changes at that location, because it is dynamically strained. The variation in refractive index affects the backscattered signal amplitude due to interference between the electric fields of the scattering centers, within one resolution cell. The spatial resolution is an important performance parameter since it gives the smallest acceptable distance between two successive events so that they can be completely distinguished by the OTDR. The spatial resolution is equal to half the pulse-width. Commercially available OTDRs typically propose pulse durations between 10 ns and 20 µs which corresponds to spatial resolution between 1 m and 2 km. Decreasing the pulse-width leads to a better spatial resolution [1].

Fibre Bragg Gratings (FBGs) are used as scattering centers because they provide a higher amplitude backscattered signal, thus enhancing the SNR [2]. A FBG is a permanent and periodic modification of the core refractive index along a short section of an optical fibre. It acts as a wavelength selective mirror reflecting a particular wavelength and transmitting all other wavelengths. Moreover, the spectral components shift as a function of perturbations applied on the grating. This property allows using the FBGs in vibration, temperature, strain or chemical sensing [3]. The problem that occurs by using the FBGs in cascade is the spectral shadowing effect which is defined as a change in the reflection spectra of the following FBG because of a change in the previous one. An algorithm is proposed and tested for eliminating this negative effect in the experimental setup.

II. Experimental results

A. FBGs- Parameters and Manufacturing

The 3 parameters that describe a fibre Bragg grating are:

- The length L over which the variation on the refraction index is realised (typically between a few mm up to a few cm).
- The periodicity or grating pitch.
- The amplitude of the refractive index modulation.

The *Bragg wavelength* is another characteristic of an FBG. It is the wavelength around which the reflection occurs. This reflection is defined by 2 parameters: reflectivity and transmittivity. You can observe this phenomenon in the figure below:

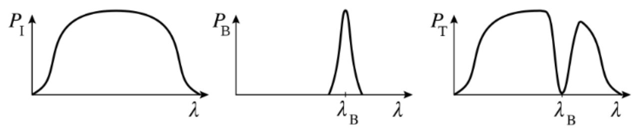

Figure 1: plot 1-Total input power; plot 2-Reflection spectrum; plot 3-Transmitted signal

There are 3 main methods for manufacturing of FBGs: the interference method, the phase mask technique and the point-by-point technique. The gratings used in this project were manufactured using the phase mask technique explained in the next paragraph.

An optical element (the phase mask) is used to spatially diffract the UV writing beam. The phase mask is a pattern of grooves etched into the UV-transmitting pure silica plate [3].

The FBGs were manufactured using the NORIA [4] - a manufacturing tool to produce FBGs. A Deep UV laser and a phase mask are used to transfer a periodic pattern into the core of a photosensitive optical fiber. The NORIA tool holds a number of different masks in a revolver like holder, each mask having a different pattern periodicity. This allows to manufacture FBGs from predefined recipes in an automated way. In addition, multiple FBGs in an array can be written along the fiber at any desired position using the accurate positioning stage.

In order to obtain the wavelength of the grating as close as possible to the one used by the OTDR laser (which was tunable between 1550 nm and 1555 nm), more phase masks and techniques were used in order to obtain the low reflectivity and same wavelength gratings that were needed.

B. The setup

Multiple MATLAB programs were written to simulate the distributed sensor configuration, the novelty set-up: 10 equally distributed FBGs, with the Bragg wavelength around 1552 nm and very low reflectivity (<0.1%).

As the FBGs are used as scattering centers:

- if the pulse covers a grating, reflection occurs
- and if not, the reflection is assumed to be zero since the Rayleigh backscattered signal is neglected.

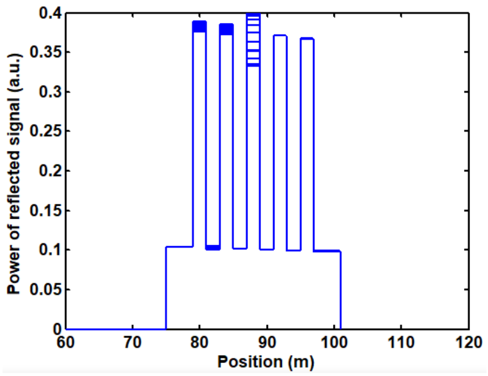

Figure 2: MATLAB simulation of the set-up with 2 different frequency vibrations applied on FBG4 and between FBGs 5 and 6

The new set-up brings more accuracy and more sensing points: a continuous sensor along the FUT instead of points of higher sensitivity and blind spots resulted from using the FBGs in pairs with different distribution along the fibre. The FBGs in the set-up are equally spaced with 4m between them. The experimental set-up contains 2 shakers placed on FBG4 and between FBGs 5 and 6 (where there is a plastic tube containing the 4 m of fibre between the FBGs).

When a vibration is applied between gratings and not on the actual grating, there is no change in the backscattered signals amplitude because only the propagation constant of the fibre is modified and the reflectivity and transmittivity of the gratings near the vibration are not changed.

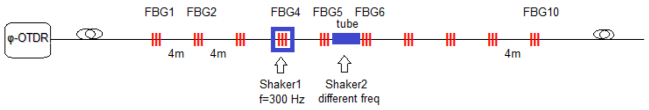

Figure 3: Experimental set-up: 10 equally distributed FBGs along the FUT (4 m spacing between the FBGs)

Different tests were made to observe the behavior of the sensors to different frequency vibrations on the 2 shakers. Shaker1, placed on the 4th grating was kept constant at a frequency of 300 Hz and, when interrogating at the position of the tube, that 300 Hz frequency was visible, so it propagated. This could mean that it was either the effect of spectral shadowing or the frequency was transmitted acoustically as the shakers were not perfectly isolated.

III. Acoustic Propagation vs. Spectral Shadowing

In order to be able to rule out spectral shadowing, an improvement on the isolation of the shakers was performed. The shakers were isolated using foam and egg cartons and more tests were made. After analyzing the results, the 300 Hz vibration frequency of Shaker1 was still visible at the position of the tube. Because there was no way of knowing for sure which option to rule out, the same measurements were made but moving the Phase-OTDR to the other side of the setup, meaning FBG10 will become FBG1 and so on.

The measurements from end B of the set-up would be able to give an exact representation of the idea of spectral shadowing, if it is the case. By applying the same frequency of 300 Hz on Shaker1 and interrogating at the same position, the tube, the frequency component should not be present because by reversing the ends, Shaker1 becomes the second one and the propagation along the fibre is unidirectional.

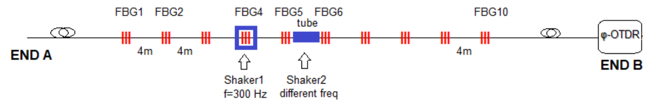

Figure 4: Experimental set-up: 10 equally distributed FBGs along the FUT, Phase-OTDR placed on end B

After conducting the measurements, it could be noticed that the 300 Hz frequency component is still present at the position of the tube, meaning that the isolation of the shakers was not enough to stop the acoustical transmission.

IV. Conclusion and Future Prospects

Fibre Bragg Gratings provide the capability to measure several parameters such as temperature, strain and many others due to the measurement of its spectral shift. Nowadays, the sensing sector is benefiting from the great potential of FBG based sensor systems. For sensing applications they offer a number of advantages including: a linear response over large ranges, robustness, easy installation, inexpensive manufacturing, small size and passiveness. Distributed Fibre Bragg Gratings used as scattering centers on a fibre under test, interrogated by a Phase-OTDR, increase the signal-to-noise-ratio of the signal carrying the vibration information. In order to eliminate the spectral shadowing problem that occurs when FBGs are cascaded, further improvements on the isolation techniques are needed. Only after removing this issue, the effect can be fully studied and an compensation algorithm can be implemented. In this paper, the proposed algorithm worked in the concordance with the practical results that was obtained with the proposed lab-setup.

References

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