Spectral shadowing compensation for distributed vibration sensing based on weak FBGs array using double-pulse and direct detection

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Distributed optical fibre vibration sensors have contributed to improve structural health monitoring. In particular, phase-sensitive optical time-domain reflectometry (phase-OTDR) allows distributed vibration sensing by analyzing the interference properties of the backscattered/reflected signal when an optical pulse is launched into the sensing fibre. As the Rayleigh backscattered light is relatively weak, fibre Bragg grating (FBG) arrays can be inscribed in the sensing fibre to increase the signal to noise ratio. This approach is nevertheless subject to a parasitic effect called spectral shadowing. In this paper, a spectral shadowing compensation technique is proposed. The approach involves interrogating the cascade of FBGs with two consecutive pulses. The delay between the two pulses is configured such a way that the phase-OTDR trace contains the interference between the signals reflected by two successive gratings as well as the signals independently reflected by each FBG. The compensation method is theoretically explained, simulated and experimentally tested on a cascade of four FBGs separated by 10 m. Applying the Fast Fourier Transform at various positions along the phase-OTDR trace allows mapping the vibration frequency along the cascade of FBGs. The performed analysis shows that the spectral shadowing component is removed.

Phase sensitive optical time domain reflectometry (φ-OTDR) is one of the distributed optical fibre sensing families allowing structural health monitoring (SHM) [1]. SHM enable real-time monitoring and have ability of detecting internal failure when implemented in civil structures such as dams, tunnels, highways, railways, bridges pipelines. φ-OTDR shows good properties such as high sensitivity, fast response speed and long sensing distance. Over the past decade, research efforts have been made to develop a series of techniques to improve the performance of φ-OTDR sensing systems. However, the relatively low power of the Rayleigh backscattering signal is fundamentally limiting the performance of φ-OTDR. Fibre Bragg grating (FBG) arrays can be inscribed in the sensing fibre to increase the signal to noise ratio. This approach is nevertheless subject to a parasitic effect called spectral shadowing. Spectral shadowing occurs when a concatenation of gratings sharing the same spectral characteristics are addressed simultaneously. Distortion occurs in the downstream FBGs spectra due to light passing twice through an upstream FBG [2].

The FBG-assisted φ-OTDR setup is presented in figure 1. It is composed of the optical source, the FUT (fibre under test) and the receiver. The light source consists of an ultra-narrow linewidth laser (NLL) emitting a highly coherent and continuous light with a linewidth of 0.1 kHz and a wavelength of 1552.5 nm. A pulse function generator (PG) enables to generate an electrical pulse signal sent to an acousto-optic modulator (AOM) which modulates the continuous lightwave to obtain a double-pulse configuration. The pulse duration is equal to 60 ns and the delay between the two pulses is set to 80 ns. The pulse pair is emitted with a repetition rate of 20 kHz and is amplified by an erbium doped fibre amplifier (EDFA), filtered by a bandpass filter (BPF, bandwidth of 1 nm) and finally launched into the FUT through the first port of an optical circulator. The backscattered/reflected light is guided to the receiver through port 3 of the circulator. The receiver is composed of an optical amplifier, a photodetector (PD) with a transimpedance gain amplifier and a data acquisition card with 1 GS/s sampling rate. To study the effect of spectral shadowing crosstalk, four low reflectivity (0.04 %) FBGs have been inscribed in the FUT. The four FBGs share globally the same characteristics, having a length of 4 mm, a center wavelength of 1552.5 nm and a 3 dB bandwidth of 0.2 nm. The grating pitch is equal to 536.42 nm. Two successive FBGs are separated by 10 m (L_{FBG} = 10 m, distance between two successive FBGs). The array is preceded by a lead-in fibre spool of 2.18 km and terminated by a fibre spool of 0.5 km length. The first FBG (FBG_1) is attached to a shaker (SHR1). A part (2 m) of the fibre length included between the second and the third FBGs is attached to a plastic tube connected at its midpoint to a shaker SHR2. Unlike the first FBG, the others are static. The plastic tube has its ends clamped. SHR1 is driven by a sinusoidal signal at 700 Hz with a 1 g acceleration and SHR2 is driven by a sinusoidal signal of 2 kHz with a 0.1 g acceleration.

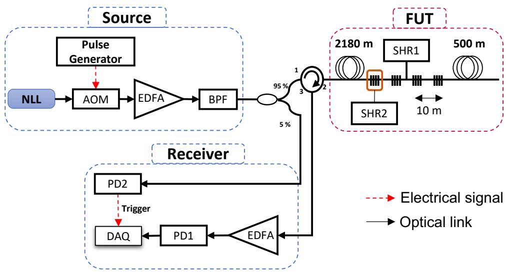

Figure 1: FBG-assisted φ-OTDR setup

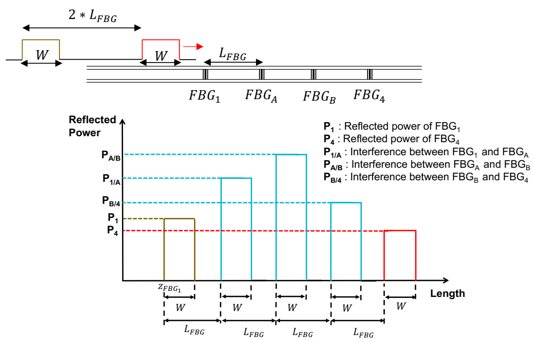

Figure 2: Double pulse principle

The interest of using double-pulse configuration instead of single pulse lies in a smaller Rayleigh-induced noise level [3-4]. The double-pulse approach allows measuring the interference of the signals reflected by two successive FBGs if the delay between the pulses corresponds in the spatial domain to twice the distance between two successive FBGs (denoted by L_{FBG}) and if the coherence length of the laser source is much larger than $2L_{FBG}$ [3]. The interference signal is sensitive to any external vibration applied between the two FBGs since it will locally modify the propagation constant. Figure 2 shows a section of the sensing fibre with four identical successive FBGs. Let us consider that this configuration is interrogated by a double pulse. The φ-OTDR allows measuring the P_1, $P_{1/A}$, $P_{A/B}$, $P_{B/4}$ and P_4 powers corresponding to the power reflected by FBG_1, the power related to the interference between the signals reflected by each FBG pairs (FBG_1 and FBG_A, FBG_A and FBG_B, FBG_B and FBG_4) and the power reflected by FBG_4.

The main idea of the proposed spectral shadowing compensation method is to interrogate the cascade of FBGs with a double-pulse signal for which an extra delay between the two pulses has been generated. This delay is obtained by reducing the delay between the two pulses to $2kL_{FBG}$ where k is the reduction coefficient ($k \in [1 - \frac{W}{2L_{FBG}}, 1]$ where W is the pulse width). This additional delay allows to obtain extra data on the phase-OTDR trace: the signals reflected independently by each FBG can also be measured (not only their interference) [4]. This extra information can be used to remove the spectral shadowing as explained below.

Each FBG is characterized by the magnitude and the phase of its reflection and transmission complex coefficients $\underline{r}$ and $\underline{t}$. They depend on parameters such as effective refractive index, index modulation depth, periodicity, visibility and grating length.

Considering a complex electric field E_{in} at the FBG array input, a complex reflection coefficient $r_A(r_B)$ for $FBG_A(FBG_B)$ and complex transmission coefficient t_A for FBG_A, the electric fields E_A and E_B reflected respectively by FBG_A and FBG_B and observed at the sensing fibre input are given by [2]:

$$E_{AB} = E_A + E_B \tag{1}$$

$$= E_{in}T^2(t)r_A(t) + E_{in}[T(t)]^2[t_A(t)]^2 r_B(t)e^{j\Delta\varphi(t)} \tag{2}$$

where $T(t)$ is the product of the complex transmission coefficients of all FBGs preceding FBG_A and Δφ(t) twice phase difference between FBG_A and FBG_B. Δφ(t) contains information about external effect (here a vibration) applied between FBG_A and FBG_B. The reflected powers defined in the previous paragraph yield:

$$P_A = E_A E_A^* = |E_{in}|^2|T(t)|^4|r_A(t)|^2 \,;\, P_B = E_B E_B^* = |E_{in}|^2[T(t)]^4|t_A(t)|^4|r_B(t)|^2 \tag{3}$$

$$P_{AB} = |E_{AB}|^2 = E_{AB}E^*_{AB} = |E_{in}|^2|T(t)|^4|r_A(t)|^2 + |E_{in}|^2|T(t)|^4|t_A(t)|^4|r_B(t)|^2 \tag{4}$$

$$+2|E_{in}|^2|T(t)|^4|t_A(t)|^2|r_A(t)||r_B(t)|\cos(\Delta\varphi(t) + \theta(t))$$

The consine component can then be determined from P_A, P_B and P_{AB} :

$$cos\big(\Delta\varphi(t) + \theta(t)\big) = \frac{P_{AB}(t) - P_A(t) - P_B(t)}{2[[P_A(t)]^{1/2}[P_B(t)]^{1/2}]} \tag{5}$$

Monitoring any event between FBG_A and FBG_B can be done by detecting variation of phase component $\Delta\varphi(t) + \theta(t)$. Furthermore, spectral shadowing from previous FBGs can be suppressed ($|T(t)|$ is deleted and no more present in the final formula).

To compensate spectral shadowing, simulation and experimentation have been achieved based φ-OTDR on the experimental setup presented in Figure 1. Simulations were achieved in python by computing 1000 φ-OTDR traces with a sampling resolution of 4 mm and a time resolution of 50 µs (20 kHz). By using the convolution product, each trace of φ-OTDR was computed with double pulse signal by considering a rectangular shape for each pulse and neglecting the Rayleigh backscattering signal and the fibre attenuation. To induce vibration, the shakers were simulated by adding variations $\Delta n = \Delta n_m \sin(2\,\pi f t)$ in the effective refractive index in each part of the FUT section being subject to vibration. The frequency vibration f was set to 700 Hz (2 kHz) for SHR1 (SHR2) with a maximum refractive index variation Δn_m of 1.8×10^{-5} (10^{-8}) induced by the vibration.

The simulation allows to get superposed φ-OTDR traces as presented in figure 3 (a). The φ-OTDR detects five different peaks: the peak related to the power reflected by FBG_1, three interference peaks corresponding to the three successive pairs (FBG_1 and FBG_2 ($I_{1/2}$), FBG_2 and FBG_3 ($I_{2/3}$), FBG_3 and FBG_4 ($I_{3/4}$)) and a peak related to the power reflected by FBG_4. The reduction of the delay between the pulses with k = 0.8 allows to obtain different power levels reflected by each FBG using interference peak. For the pair FBG_2-FBG_3, P_A and P_B reflected respectively by FBG_2 and FBG_3 and P_{AB} ($I_{2/3}$) can be identified. Therefore, the compensation formula (5) can be applied to remove the spectral shadowing crosstalk. Figure 3 (b) shows the FFT of interference signal between FBG_2 and FBG_3 at 2212 m where vibration at 2 kHz is applied. Frequency of 2 kHz applied between FBG_2 and FBG_3 is clearly detected. But undesirable frequency component at 700 Hz is also detected. This is induced by the vibration applied on the first FBG at 2190 m through spectral shadowing. Equation (5) is applied to eliminate the unwanted spectral shadowing by using P_A, P_B and P_{AB} as showed in figure 3 (c). The local vibration (2 kHz) is still detected due to the variation of the phase component $\Delta\varphi(t) + \theta(t)$ but the unwanted frequency component at 700 Hz is removed showing the efficiency of the compensation formula.

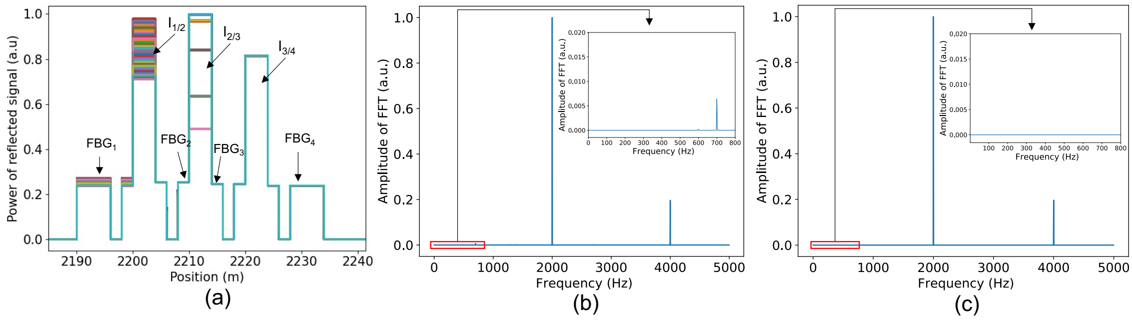

Figure 3: Simulated φ-OTDR: (a) Reflected signal power versus position over time; (b) FFT of interference signal at 2212 m (inset: zoom 0-1400 Hz) (c) FFT of compensated power at 2212 m (inset: zoom 0-1400 Hz).

An experimental work reproducing the condition of the simulation was performed. The measured traces are presented in figure 4(a). Undesirable frequency component at 700 Hz is detected as showed in figure 4(b). Applying compensation method enables to remove the undesirable frequency component at 700 Hz (fig 4(c)) showing the efficiency of the method.

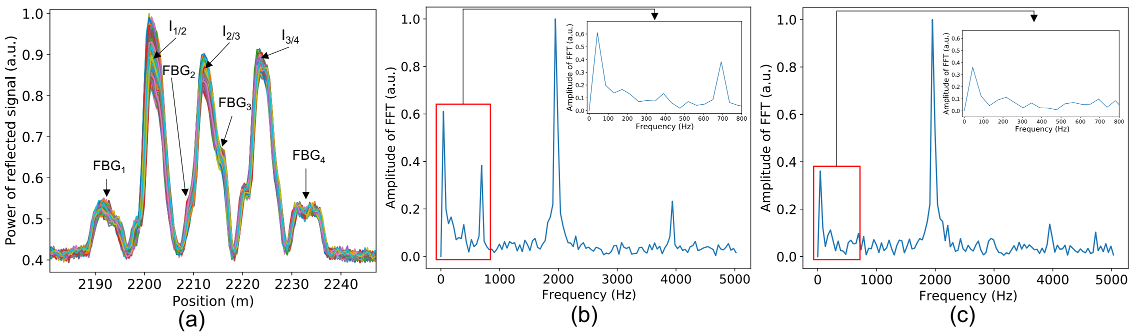

Figure 4: Experimental φ-OTDR: (a) Reflected signal power versus position over time; (b) FFT of interference signal at 2212 m (inset: zoom 0-1400 Hz) (c) FFT of compensated power at 2212 m (inset: zoom 0-1400 Hz).

To conclude, FBG assisted φ-OTDR interrogated with a double pulse have been achieved with four FBGs (of 0.04 % reflectivity) separated by 10 m. By adding an extra delay between the two pulses, reflected power by each FBG can be detected and spectral shadowing can be deleted. The proposed approach was validated by simulation and experimental analyses.

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