Chirped-pulse phase-sensitive reflectometry

Reflectometría sensible a la fase con pulsos *chirpeados*

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ABSTRACT:

In this work, a new distributed fiber sensor named chirped-pulse phase-sensitive OTDR is presented. It is based on a phase-sensitive OTDR using direct detection and linearly chirped pulses. The new sensor allows the dynamic and quantitative measurement of temperature/strain changes, with mK/nε resolution. The technique does not require a frequency sweep or coherent detection. It is presented the fundamentals of the sensor and measurements of temperature, vibrations and music.

Key words: Distributed fiber sensing, temperature sensor, distributed acoustic sensor, chirped pulse, phase-sensitive OTDR.

1.- Introduction

Distributed Optical Fiber Sensors (DOFS) allow for the continuous measurement of different physical parameters (temperature, strain, birrefringence) over long fiber distances and therefore provide a cost-effective solution for the monitoring of large civil infrastructures such as bridges, tunnels, pipelines or railways. In particular, phase-sensitive optical time-domain reflectometry (ΦOTDR) is an interesting solution that is gaining considerable attention in recent years [1], mostly within the framework of distributed vibration detection [2]. Commonly, ΦOTDR works analyzing changes of intensity in the trace which indicate the presence of perturbations such as temperature and strain changes or vibrations. However, the intensity variations will depend nonlinearly on the applied perturbations. Therefore, traditional ΦOTDR sensors do not recover true strain variations unless a frequency sweep [3] is performed or coherent detection [4] is used for phase recovery. However, in this case the measurement times and complexity of the system are increased.

In this paper, we provide a method based on ΦOTDR using linearly chirped pulses, which allows for the quantitative measurement of distributed temperature or strain changes without the requirement of a frequency scan or phase-recovery techniques while maintaining the simplicity of a traditional ΦOTDR using direct detection. The new sensing technique is known as chirped-pulse phase-sensitive reflectometry. It allows for the linear and single-shot strain or temperature measurements along several tens of kilometers in the kHz frequency range with nε/mK resolutions, thereby enabling acoustic sensing.

2.- Operation principle

In this technique, as in traditional ΦOTDR, a highly coherent optical probe pulse is injected into a single mode fiber and the backscattered signal is analyzed in the temporal domain. Thus, when no perturbation is applied onto the fiber, the detected trace remains constant over the time. In the traditional case (non-chirped probe optical pulse), when a refractive index change Δn (i.e., temperature or strain change) occurs in a fiber section, the corresponding section of the power trace varies nonlinearly with the undergone change. In contrast, when a linearly chirped pulse is launched into the fiber, a refractive index change translates into a proportional temporal shift in the corresponding section of the power trace.

To demonstrate this idea, a linearly chirped pulse with a spectral content of 2.3 GHz was employed and the last 20 m of a 1 km fiber was heated. The experimental setup is similar to the presented in [5]. Traces were acquired with a frequency of 1 Hz. In Fig. 1a (Non-heated region) the trace remains constant over the time but in Fig. 1b (Heated region) the trace shifts longitudinally. As it can be seen, consecutive traces are separated by ≈ 0.43 ns (17 samples with 40 GHz sampling ratio) which corresponds to a temperature variation of ≈ $8\cdot 10^{-3}$ K [5].

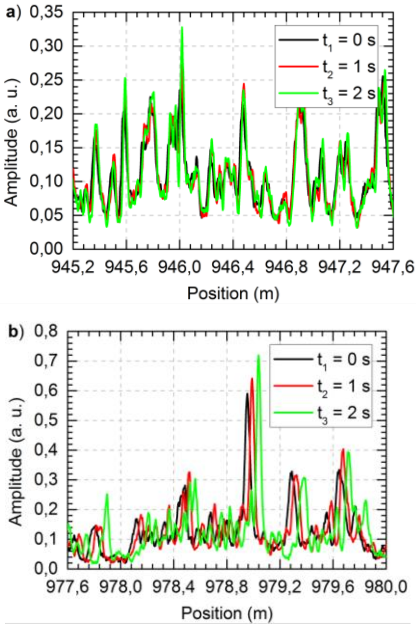

Fig. 1: Longitudinal shift of the ΦOTDR trace when temperature changes are applied to the FUT. a) Non-heated region b) Heated region.

The relationship between Δn suffered by a fiber section and the temporal shift is [5]:

$$\frac{\Delta n}{n} = \left(\frac{1}{\nu_0}\right)\cdot\left(\frac{\Delta \nu_p}{\tau_p}\right)\cdot \Delta t \qquad (1)$$

where ν_0 is the central frequency of the probe pulse, τ_p the temporal length, $\Delta\nu_p$ the chirp spectral content and Δt the measured temporal shift, obtained by means of temporal correlations. Finally, Δn is related with the temperature change ΔT or strain $\Delta\varepsilon$ with the expression [3]:

$$\frac{\Delta n}{n} = -6.92\cdot 10^{-6}\cdot \Delta T = -0.78\cdot \Delta\varepsilon \qquad (2)$$

where n is the effective fiber refractive index. Thus, these results demonstrate the potential for dynamic and high resolution of this new distributed fiber sensor.

3.- Experimental measurements

3.1.- Temperature

To evaluate the long term stability of the sensor, it is monitored the temperature change of a 1 km fiber under test (FUT). The last 20 m were heated from 23 °C to 27.5 °C and cooled to the starting temperature, over approximately 270 minutes, while the entire fiber was monitored. These results are represented in Fig. 2.

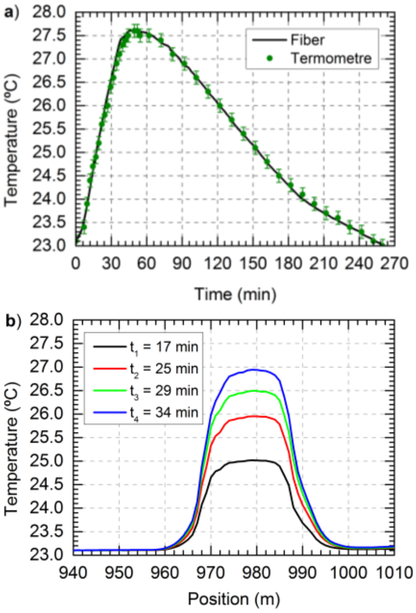

Fig. 2: Measured temperature variations when temperature is raised from 23 °C to 27.5 °C and back to 23 °C in 20 m of fiber around meter 979 of the FUT, over 270 minutes. (a) Temperature evolution of meter 979 along time (b) Temperature profile along 70 m of fiber at different times.

Figure 2a shows the temperature evolution of the meter 979 of the FUT – the center of the heated section. The black line represents the fiber temperature measured with the ΦOTDR, while the green dots are the thermometer measurements (green lines represent the measurement error of the thermometer). As it is observed, the fiber follows perfectly the temperature variations with a negligible accumulated error. Finally, Fig. 2b shows the temperature profile along 70 m of fiber around the heated section at different times. The heated section is perfectly detected by the system which has enough spatial resolution (10 m) to observe a heated section of 20 m. As expected, in the regions outside the heated section (which were kept at constant temperature), the ΦOTDR sensor recorded a constant temperature with no variations over time [5].

3.2.- Strain and vibrations

After the temperature measurements, the feasibility of the proposed sensor for dynamic and static strain measurements was analyzed.

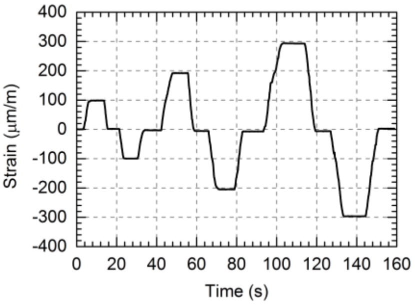

Fig. 3: Measured strain variations when strain applied to the fiber is manually varied (using a linear translation stage) from 0 με to ± 300 με and back to 0 με, near the end of the FUT, over 160 seconds.

Firstly, the stability of the sensor over several minutes for large applied strains was analyzed. For this, deformations were applied by manually acting on a linear translation stage to which a fiber section near the end of the FUT was glued. Fig. 3 presents the strain variations measured by the ΦOTDR when deformations correspondent to strains varying from 0 με to ± 300 με and back to 0 με were applied. The calculated strain was observed to return to zero when the applied strain was returned to zero after 160 s. This again clearly demonstrates the long term stability of the sensor and that large measurement ranges are achievable [5].

In order to characterize the dynamic strain sensing capability of the sensor, the last 20 m of the FUT were strapped around a PZT, which applied deformations controlled by an electrical input. The ΦOTDR traces were now acquired with a frequency of 4 kHz. The dynamic strain measurements are presented in Fig. 4 [5]. Fig. 4a presents the measured strain when a 1 Hz sinusoidal strain is applied to the fiber by the PZT, with a maximum amplitude of 100 nε. As it is clearly observed, a good agreement between the experimental measure and the applied strain is observed.

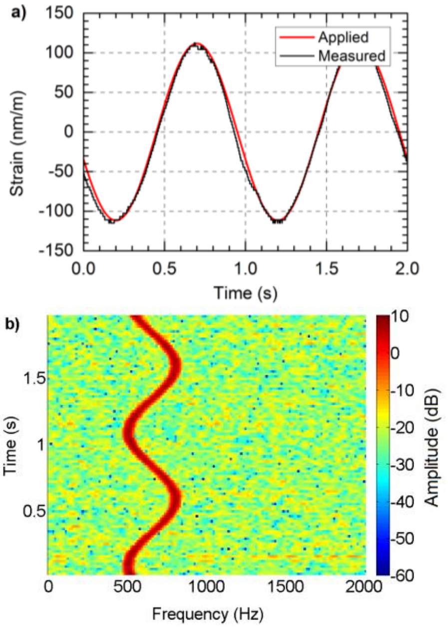

Fig. 4: Measured dynamic strain variations when strain is applied by a PZT in 20 m of fiber around meter 979 of the FUT. a) Measured strain for a 1 Hz sinusoidal strain with 100 nε maximum amplitude. (b) Spectrogram (logarithmic scale - dB) for an applied strain of a frequency sweep between 450 Hz to 850 Hz with a period of 1 s.

Figure 4b presents a spectrogram of the frequencies measured by the ΦOTDR when the PZT applied a frequency sweep between the frequencies 450 Hz to 850 Hz with a period of 1 s. The high linearity of the transfer function of the sensor is clearly demonstrated as no harmonics are observed. The signal to noise ratio (SNR) of the measured frequencies is >25 dB, which clearly indicates the potential of this technique for achieving simultaneously true strain measurements, high linearity and good SNR.

3.3.- Complex vibrations: music

Finally, it is demonstrated the capability of the sensor to recover complex vibrations like music. To do this, the first 5 seconds of the 5th symphony of Beethoven were applied to the last 20 meters of a 1 km fiber. The recorded signal is presented in Fig. 5. There is a good agreement between the experimental measure and the applied strain, the small disagreements coming more from the non-flat spectral PZT response and fiber mechanical coupling than from the sensor response. The signal recorded by the sensor was also perfectly understandable by human hearing when played by a speaker [6].

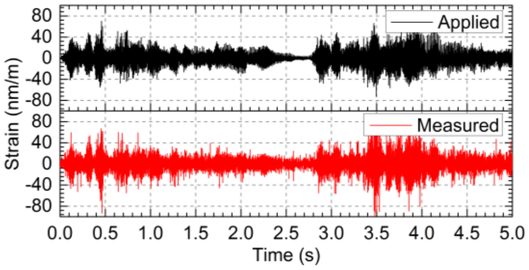

Fig. 5: Measured strain variations when strain applied by a PZT in 20 m of fiber around meter 979 of the FUT. First 5 seconds of 5th symphony of Beethoven has been recorded.

4.- Conclusion

In this work, we have presented a novel distributed fiber sensor which allows for the dynamic measurement of true strain or temperature variations using intensity only measurements and no sweep. Compared to traditional ΦOTDR, the need for a frequency sweep is replaced by the computation of simple local temporal correlations from trace to trace. Truly single-shot determination of perturbations (temperature change, vibrations and real acoustic signals) with nK and nε resolutions is achieved with this system.

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