Experimental validation of coherent-OTDR vibration sensor using mechanical transducers

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A new optical fiber-based vibration sensor based on a coherent OTDR is experimentally studied. Equipped with mechanical transducers that squeeze the fiber over a 3 mm length, this sensor can recover vibrations from several Hz (due to the presence of zero frequency noise) to 5 kHz (because of the limited data triggering speed). This sensor, together with the use of several mechanical transducers, could be used as a quasi-distributed sensor. Contrary to recently proposed polarization-based sensors, vibrations can be univocally determined and localized all along the fiber even if they are characterized by identical frequency components.

Introduction

Measuring vibrations is of high importance as they are an indicator of the ageing of civil structures (bridges, buildings) and industrial machines. With vibration sensors it is possible to prevent structural damages and to avoid dramatic consequences such as building collapses. Many kinds of vibration sensors already exist, but fiber optics vibration sensors are particularly interesting due to their ability to provide quasi-distributed and distributed information with only one interrogating element while conventional sensors (for instance, piezoelectric and piezoresistive accelerometers) are punctual. Fiber optics sensors have also the advantages, compared to conventional sensors, of being usable in harsh environments such as EM-disturbed, high temperature, humid or nuclear environments.
The present vibration sensor is based on a recently proposed coherent OTDR (*Optical Time Domain Reflectometry*) [1]. In this sensor, as the source linewidth is very narrow (200 kHz), coherence effects can no longer be neglected and different contributions within the pulse interfere with each other during its propagation. The obtained trace, known as φ-OTDR, shows this interference along the fiber length. As a vibration has for effect to modify this interference signal, if the traces are dynamically acquired, it is possible to recover the frequency spectrum.
This paper is divided as follows: in the first part the set-up as well as the sensor principle are explained. In the second part the experimental results are given: a mechanical transducer developed at the University of Mons [2] is used as the vibration transducer. The third part is dedicated to perspectives.

Sensor principle

The experimental set-up is given in Fig.1 [1]. A 8 dBm CW lightwave at the optical frequency f (of the order of THz) is emitted by an external cavity laser (ECL), whose 3

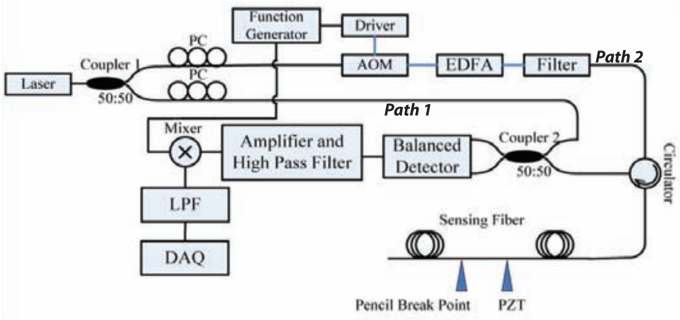

Figure 1: *Experimental set-up of the coherent-OTDR vibration sensor. PC: Polarization Controller, AOM: Acousto-Optic Modulator, EDFA: Erbium Doped Fiber Amplifier, PZT: Piezoelectric Transducer, LPF: Low-Pass Filter, DAQ: Data Acquisition card*

dB linewidth is 200 kHz. A 3 dB coupler (*Coupler 1*) divides the power into two different paths:

- *Path 1* : it consists of a CW lightwave whose SOP (*State of Polarization*) can be modified with a PC (*Polarization Controller*). Its power can also be adjusted with an attenuator (not represented in Fig. 1). At Coupler 2 the lightwave coming from this path has an optical frequency equal to f;

- *Path 2* : the CW lightwave, coming from Coupler 1, is first pulsed (50 ns or 100 ns) with an AOM (*Acousto- Optic Modulator*). This operation also induces a frequency shift equal to Δf, here, 200 MHz), giving a lightwave at the optical frequency $f + \Delta f$. This pulse is then amplified with an EDFA (*Erbium Doped Fiber Amplifier*), filtered (in order to reduce ASE *Amplified Spontaneous Emission*) and finally launched into the 900 m sensing fiber via a circulator. During its propagation, the pulse is continuously Rayleigh backscattered and a tiny contribution comes back to the circulator and Coupler 2. As previously mentioned, as the laser linewidth is very narrow, the different contributions within the pulse interfere with each other.

At the detector, it is possible to recover the interference term between the two optical signals, i.e. a beat signal at the optical frequency Δf. The detected current *I(t)* is indeed proportional to the optical power at the coupler output:

$$I(t) \propto E_{Lo}(t)^2 + E_b(t)^2 + 2E_{Lo}(t)E_b(t)Kcos(2\pi\Delta ft + \varphi(t)) \quad (1)$$

In this equation, φ(t) is the phase difference between the backscattered signal and the light coming from Path 1. The multiplicative factor *K* takes into account the polarization influence.
The useful signal here is the AC component at Δf. Heterodyne detection is used in order to recover the information at this frequency : the detected signal is first multiplied with the AOM driving signal, which has a frequency Δf. At the mixer output, among many signals, a baseband signal is obtained. A lowpass filter (LPF) with a cut-off frequency of 6 MHz, is used in order to only keep this baseband contribution. This signal is finally sampled with a data acquisition card (DAQ) at a rhythm of 100 MHz, i.e. one point every meter, giving a φ-OTDR trace. These traces are recorded dynamically (at a maximal

rhythm of 10 kHz). At each position it is then possible to observe the temporal evolution of the interference signal and after calculation of the Fast Fourier Transform (FFT), the frequency spectrum.

Experimental results

During the experiments the vibration transduction is induced as a crushing of the fiber (transversal to its propagation axis) induced by a mechanical transducer developed at the University of Mons [2]. This transducer is shown in Fig. 2. This component is such that when the shaker vibrates, the inertia of the transducer provokes a transversal strain on the fiber. This in turn modifies temporally the interference signal, as previously explained. It is then possible to recover the frequency spectrum at the perturbation location.

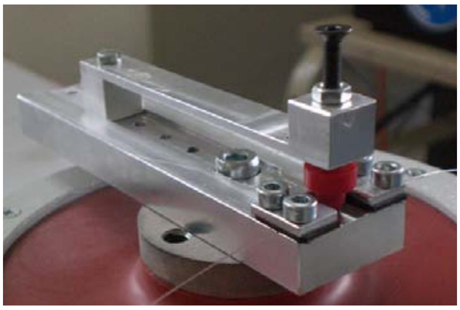

Figure 2: *Mechanical transducer based on the crushing of the fiber*

Fig. 3(a) and (b) show the measured frequency spectra when inducing, respectively, a 40 Hz and a 4.75 kHz sine vibration at z = 520 m. These figures show that the spectra at that position are typical of sine vibrations, with one peak at the vibration frequency.
Note that as the recording speed is 10 kHz, the highest detectable frequency is equal to 5 kHz as a result of Shannon theorem. Frequencies beyond this value would be aliased. The lowest detectable frequency is equal to around 5 Hz as a result of zero frequency noise.
It is interesting to compare this vibration sensor to previously published polarization vibration sensors [3, 4].
The present vibration sensor has the drawback of being more complex to implement and more expensive, principally due to the presence of a very narrow linewidth laser source. But, contrary to polarization vibration sensors, the present sensor will not suffer from the similar frequencies problem (as a reminder, in polarization sensors, a frequency on the first sensor is present on each following sensor, as a result of the light polarization state modification). In the present case, the interference within the pulse is a purely local phenomenon. A frequency at one position will not be present at the following positions while it it the case in polarization sensors as a result of the SOP modification.

Conclusion and perspectives

In this paper we present an experimental validation of a recently proposed coherent-OTDR vibration sensor. In this kind of system, as the laser source is very narrow, different contributions within the pulse interfere with each other, which gives a φ-OTDR trace. A vibration - induced here with a mechanical transducer - has for effect to temporally modify this interference signal. As φ-OTDR traces are dynamically recorded, it is possible

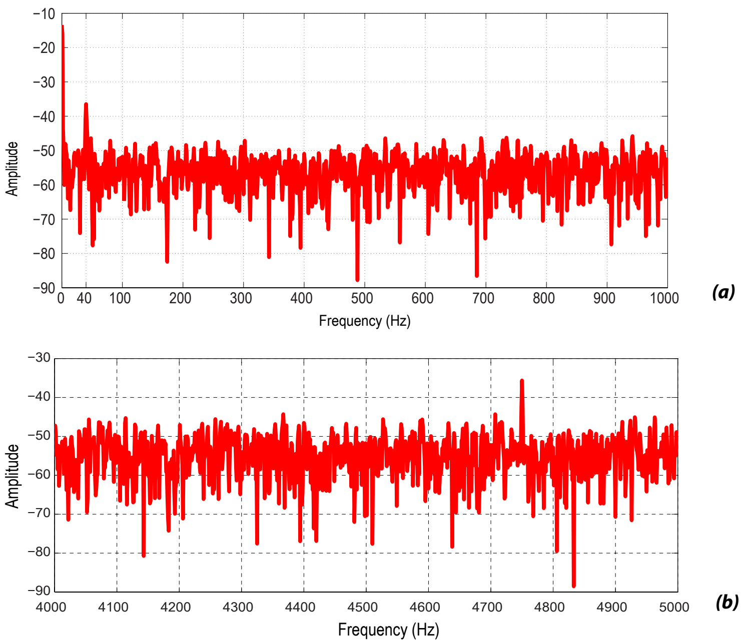

Figure 3: *Observed frequency spectrum at the vibration position : (a) 40 Hz sine vibration, (b): 4.75 kHz sine vibration*

to recover the frequency spectrum at every position along the optical fiber. Experimental results showed that equipped with mechanical transducers developed at the University of Mons, this sensor can indeed recover the frequency spectrum from practically DC (presence of zero frequency noise) to 5 kHz (limited by the Shannon theorem). The main drawback of the present sensor is its complexity, cost (due to the presence of the very narrow linewidth laser) and sensitivity to external noises. On the other hand, contrary to polarization sensors, it does not suffer from the similar frequencies problem.

References

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