Laboratory evaluation of a phase-OTDR setup for railway monitoring applications

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Phase-sensitive optical time-domain reflectometry (phase-OTDR) has recently drawn increased attention for applications within the railway transportation sector. In this paper we present a laboratory approach to demonstrate the feasibility of an interrogator of vibrations along railways by means of fiber-optic cables. Contrary to the common use of piezo-electric phase modulators in laboratory setups, a vibration shaker is used to excite a plastic tube to which the fiber is attached. Measurement of event position and frequency is demonstrated in a range up to 7000 Hz.

Introduction

With the increasing number of passenger and freight trains on existing railway tracks, there is a growing demand for advanced monitoring of trains and railways. Applications range from train positioning, wheel flat detection, weighing in motion and broken rail detection to monitoring of level crossings, rock fall onto track, asset integrity and detection of trespassers. As a consequence, new technologies are being tested to find efficient monitoring solutions [1]. A technique that has drawn great attention is distributed acoustic sensing (DAS), which is a fiber-optic sensing technique based on the detection of Rayleigh backscattered light in optical fibers using optical time domain reflectometry (OTDR). The OTDR technique used for DAS is called phase-OTDR and is based on a highly coherent laser source, contrary to conventional OTDRs used for telecommunication links monitoring where low coherence is desired. Commercial applications for DAS exist in perimeter security [2] and oil well monitoring [3]. Recently, it has also been applied for railway monitoring [4]. For train and rail track monitoring DAS provides an excellent solution due to its distributed properties, its sensitivity to external perturbations and the fact that fibers in existing trackside telecom cables may serve as sensor fibers.

Theoretical background

The core component of the phase-OTDR is the highly coherent laser source (typical linewidth ~kHz). As the emitted pulse is propagating along the fiber, the backscattered electric field from scattering centers within the resolution cell, i.e. half the pulse width, interferes at the photo-detector, resulting in a registered intensity that depends on the instant distribution of scattering centers within the resolution cell. Upon a local perturbation, resulting in a change in relative positions of the scattering centers in the perturbed zone, the registered backscatter intensity from that zone will change. Subtracting two consecutive traces will result in a peak around the point of perturbation as shown in Fig. 1(b). Two main detection schemes are employed for phase-OTDR: direct detection [2] and coherent detection [5], see Fig. 2. The straightforward direct detection scheme relies on the registration of local changes in the backscattered intensity over time. With coherent detection the backscattered signal is mixed with a
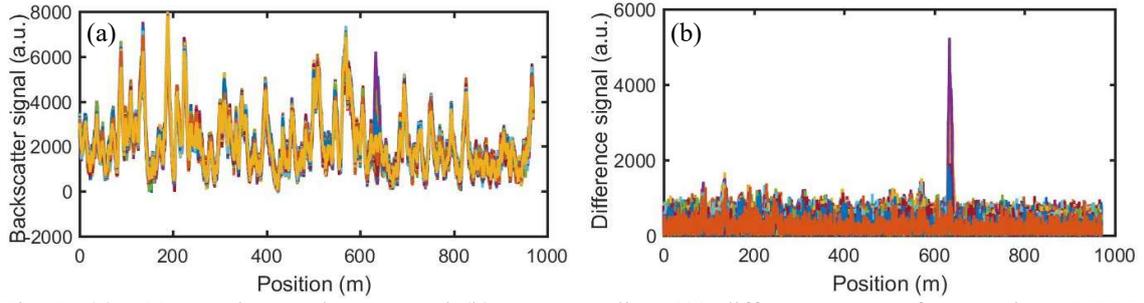
Fig. 1. (a) 500 superimposed traces and (b) corresponding 499 difference traces from a phase-OTDR measurement of a vibration event at the position 635 m.
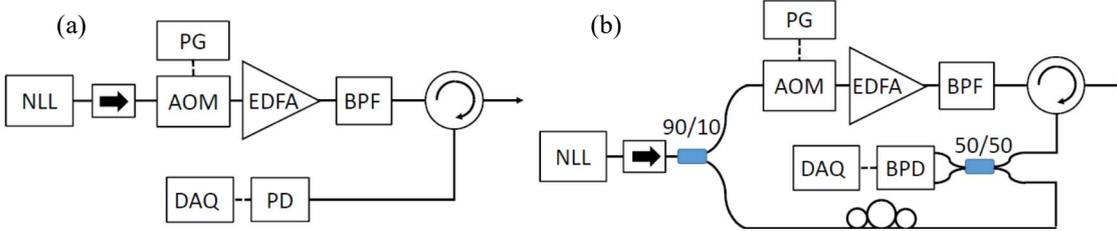

Fig. 2. Phase-OTDR setup using (a) direct detection and (b) coherent detection; NLL = narrow linewidth laser, AOM = acousto-optic modulator, PG = pulse generator, EDFA = fiber amplifier, BPF = band pass filter, PD = photo-receiver, DAQ = data acquisition card, BPD = balanced photo-receiver, → = isolator, oOo = polarization controller.

reference signal, and the amplitude as well as the phase component of the backscattered signal can be extracted from the AC part of the beat signal which has a beat frequency equal to the AOM phase shift. Due to the random nature of the scattering process, sometimes causing fading of the signal, the detected intensity in the direct detection case is not necessarily proportional to the magnitude of the perturbation. With coherent detection, extraction of the phase component however gives a possibility to determine the magnitude since the phase difference between two locations can be determined [5]. For our applications, the main purpose is to find the position and the frequency of the perturbation, which suggests that the direct detection method should be sufficient. However, given its possible sensitivity advantages, coherent detection is included in our study by considering the amplitude part of the sensor response, which corresponds to the response of the direct detection scheme [5]. A comparison between the two approaches is made using the following signal-to-noise (SNR) definition for a single difference trace i:

$$SNR_i = 10 \cdot log\left(\frac{max(I_{peak})}{rms(I_{noise,env})}\right)_i \quad , \tag{1}$$

where $max\ (I_{peak})$ is the maximum value of the difference trace within the perturbation zone and $rms\ (I_{noise,\ env})$ is the root-mean-square value of the envelope of the difference trace outside the perturbation zone. For a number of difference traces the mean SNR and the standard deviation can be used as a measure of the signal variation. This SNR is compared with the SNR calculated with the same formula for a point outside the perturbation zone, giving a measure of the possibility of detecting the perturbation.

Experimental Setup

A phase-OTDR setup according to Fig. 2 was used, based on a laser with 0.1 kHz linewidth and 40 mW continuous output power. Pulses of width 100 ns and a repetition frequency of 20.4 kHz were created with the AOM, which was driven by a 160 MHz RF signal. The pulses were amplified by an EDFA, followed by a 0.9 nm bandpass

filter, resulting in a pulse peak power of 95 mW at the phase-OTDR output. Detection of the backscatter signal was made using a balanced photo-receiver with a gain-dependent bandwidth of 180 (5) MHz for the coherent (direct) detection case, and the detected signal was sampled by a 1 GHz digitizer. The fiber under test was 4.7 km, with 2 m of the length being glued with tape to a 16 mm diameter plastic tube. The plastic tube was clamped at both ends, and the midpoint (fiber position 635 m) was excited by a shaker capable of a maximum acceleration of 50g. A lower and a somewhat higher acceleration, their ratio being 1:7, were used in the tests. In each case, 14 measurements were made: no. 1 with no input signal, no. 2-7 using 50-800 Hz and no. 8-14 using 1000-6900 Hz. Totally 800 consecutive traces were recorded for each measurement, and SNR data was calculated using (1) around 635 m (vibration) and 850 m (unaffected).

Results and Discussion

Results show that position (Fig. 1) and frequency of the event can be localized and detected, however the peak detection ability depends on the signal conditions. In Fig. 3 the SNR values from measurements with a direct detection setup are shown for the two shaker accelerations. For the lower acceleration, as seen in Fig. 3(a), the SNR is not good enough at high frequencies to enable peak detection above the noise floor. Nevertheless, as shown in Fig. 4(a), the high frequencies can still be clearly detected at the point of vibration using FFT analysis of the time evolution (800 traces) of the detected intensity at 635 m. For the higher acceleration, the SNR enables clear peak detection for all frequencies as shown in Fig. 3(b), but the elevated acceleration generates extra frequency components in the setup as seen in Fig. 4(b). Measurements with the coherent detection setup (Fig. 5, Fig. 6) give similar results, but with no improvement due to the trade-off between bandwidth and gain of the photo-receiver.
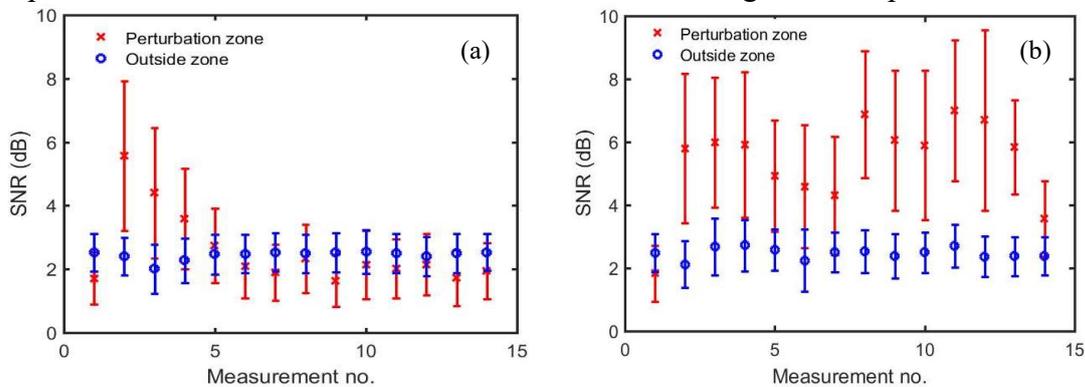
Fig. 3. SNR for measurements made using direct detection for (a) low and (b) high acceleration.
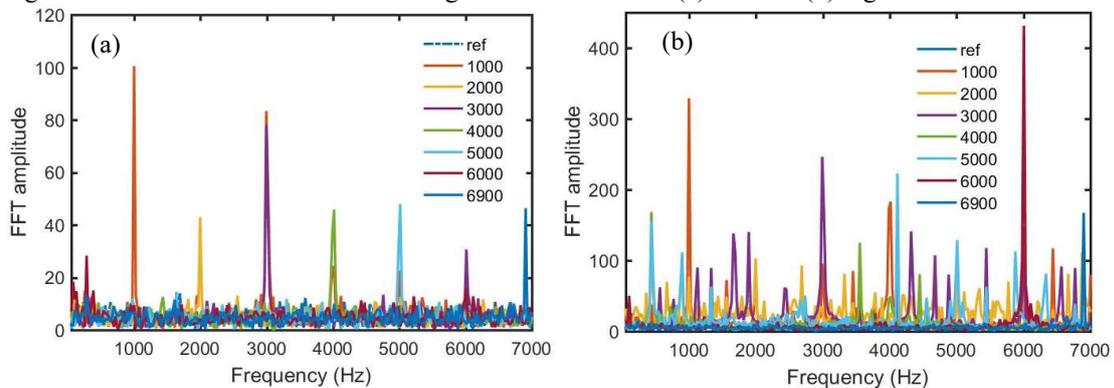
Fig. 4. Frequency spectrum for 800 traces with direct detection for (a) low and (b) high acceleration.
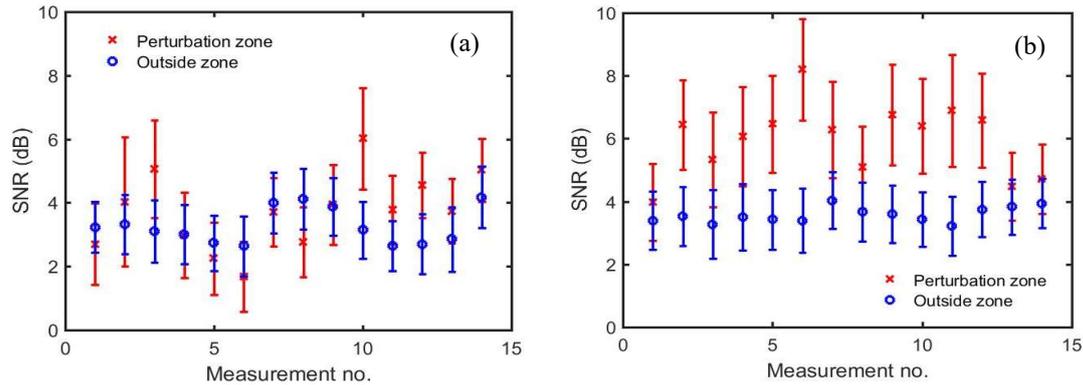
Fig. 5. SNR for measurements made using coherent detection for (a) low and (b) high acceleration.
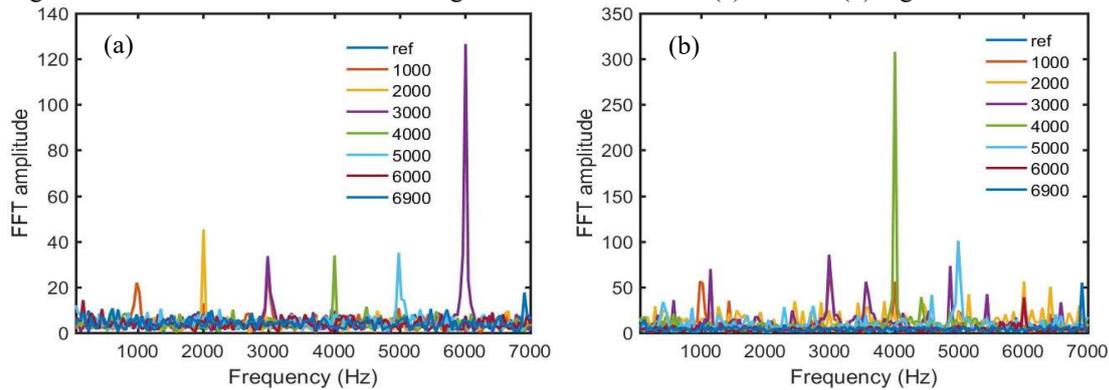

Fig. 6. Frequency spectrum for 800 traces with coherent detection for (a) low and (b) high acceleration.

Conclusions

The system is able to register position and frequency of vibrations with the localization probability increasing with the amplitude of vibration. In the absence of a localization peak at a particular frequency, the frequency can still be detected at the vibration position, which suggests that filtering can improve the localization for events having certain characteristic frequencies.

Acknowledgements

References

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