Extending the Measurement of True Dynamic Strain via Chirped-Pulse Phase-Sensitive Optical Time Domain Reflectometry to 100's of Microstrains

Hari Datta Bhatta,[1*] Luis Costa,[2] Andres Garcia-Ruiz,[2] Maria R. Fernandez-Ruiz,[2] Hugo F. Martins,[2] Moshe Tur,[1] and Miguel Gonzalez-Herraez[2]
[1]*School of Electrical Engineering, Tel-Aviv University, 6997801, Tel-Aviv, ISRAEL*
[2]*Departamento de Electrónica, Universidad de Alcalá, Escuela Politécnica Superior, 28805, Madrid, Spain*
haridattab@mail.tau.ac.il

Abstract: It is experimentally demonstrated that a chirped pulse phase-sensitive OTDR can measure large and fast dynamic strains (~100's of με, ~100's of Hz) with SNR of ≥ 24dB. Signal smoothing and impact of error accumulation are also discussed.

OCIS codes: (060.2370) Fiber optics sensors; (120.4825) Optical time domain reflectometry.

1. Introduction

Distributed fiber optic sensors are normally used in monitoring large critical infrastructures such as oil/gas pipelines, bridges, buildings, air-planes, railway tracks etc. which can have changing temperature or strain. Among them, Raman and Brillouin based sensors are comparatively time consuming, as they require frequency scanning and/or a large number of averages in order to quantify the measurand. For environments in which the measurand is rapidly changing (as in e.g. certain aerospace applications), Brillouin sensors can be efficient for dynamic strain monitoring using either the fast- or slope-assisted BOTDA techniques [1] but only over short distances, which do not require averaging, being tolerant to very high pump pulses. In contrast, phase-sensitive optical time domain reflectometry (ΦOTDR) has shown its capacity to measure dynamic variations (not necessarily strain) along more than 100 km of fiber with few-meter resolutions [2,3], and 100's of Hz measuring bandwidth. In this technique, coherent laser pulses (laser coherence length >> pulse width) are launched into the fiber and the reflected waves from various scattering centers along the fiber (within the pulse width) interfere to give a time-domain noise shape trace. In the presence of vibrations (or refractive index changes due to any cause), the obtained time domain trace gets changed at the perturbed location, and a corresponding intensity change can be observed in the local trace pattern. However, even though the vibration detection is clear, the applied strain cannot be correctly converted into simple intensity changes because of the non-linear (and even non-monotonic) dependence of the interference intensity with the phase changes. Correct values of strain or temperature cannot be achieved with this technique unless actual phase measurements are performed [4,5]. The phase detection is generally a non-trivial problem, as it requires highly coherent lasers (coherence length at least equal to twice the length of the fiber) or otherwise the measured phase after beating with the local oscillator will be extremely noisy [6,7]. This issue can be avoided if frequency scanning is used. In this technique, traces of the intensity pattern are collected for successive center frequencies of the optical pulse over time. A given refractive index change in the fiber will cause a change in the optical trace at a given frequency, however it will be possible to recover the initial pattern of the measurement with an equivalent relative change in the pulse frequency [8,9], hence:

$$\frac{\Delta n}{n} = \frac{\Delta \nu}{\nu_o} \tag{1}$$

where ν_o is the initial central frequency of the laser pulse, n is the effective refractive index at desired fiber location, Δn is the change in the refractive index and $\Delta \nu$ is the required frequency change which compensates the changes in the refractive index and can show same initial time domain intensity trace. This method has already been applied to the static or semi-static measurements of strain [10], temperature [9] as well as birefringence [8] in the fiber.

Based on this idea, and to avoid direct frequency scanning, a new technique named chirped-pulse phase-sensitive optical time domain reflectometry (CP- ΦOTDR) has been proposed and experimentally verified by some of the authors [11]. This technique replaces the conventional transform-limited probing pulse by linearly chirped pulse. As a result, the shift of the frequency in response to e.g. an applied strain (Eq. 1) is observed in this case as a temporally shifted trace (i.e. a local longitudinal shift (Δt) in the ΦOTDR intensity trace). The local change of the refractive index is related to the longitudinal shift Δt of the trace as [11],

$$\frac{\Delta n}{n} = -\left(\frac{1}{\nu_o}\right) \cdot \left(\frac{\delta \nu}{\tau_p}\right) \cdot \Delta t \tag{2}$$

where, ν_o is the central frequency of the laser pulse,$\delta \nu$ is the probe pulse bandwidth and τ_p is the pulse width. As it can be seen, the linear frequency chirp of the pulse ($\delta \nu/\tau_p$) translates the shift of frequency into a different time location [11]. Note that this measurement principle is valid as long as $\delta \nu \gg 1/\tau_p$ and $\Delta t \ll \tau_p$. From the measured value of Δt, one can now deduce the change in applied local strain $\Delta\varepsilon$, responsible to the observed temporal shift [11]:

$$\frac{\Delta\nu}{\nu_o} = -\left(\frac{1}{\nu_o}\right)\cdot\left(\frac{\delta\nu}{\tau_p}\right)\cdot\Delta t \cong -0.78\Delta\varepsilon \Rightarrow \Delta\varepsilon = \left(\frac{1}{0.78}\right)\cdot\left(\frac{1}{\nu_o}\right)\cdot\left(\frac{\delta\nu}{\tau_p}\right)\cdot\Delta t \qquad (3)$$

The local Δt is measured at the given location by computing windowed cross-correlations between the measured trace and a reference one. This technique provides a relative measurement with respect to an initial reference state in a single shot and with a speed limited only by the length of the fiber (and the available SNR), making it almost ideal for dynamic strain measurements. It is also highly efficient because there is neither a need for phase recovery, nor for frequency scanning [11]. Note, however, that the conditions for correct measurement given above impose restrictions on the maximum strain change that can be measured in a single shot with a given chirp value. Empirically it has been found that the maximum measurable frequency changes should not exceed 3% of $\delta\nu$. If larger values of shot-to-shot strain change need to be measured, either the trigger rate has to be increased (which is limited by the fiber length) or the chirp of the generated pulses has to be increased (which imposes experimental problems). In addition, this requires increasing the bandwidth of the detector and the digitizer, which implies increasing the cost and probably worsening the SNR of the system. In addition, the constant need for a reference update may contribute additional noise to the measurements, impairing their quality.

Previously, [11], this technique was successfully applied to the measurement of semi-static strain (and temperature) variations up to 300 με. Extending these results, this research work focusses on the measurement of large dynamic strains (approaching 1000με with frequencies from 50 to 200 Hz) with comparatively high spatial resolution (3.5 m resolution, 210 m-long fiber) using CP-ΦOTDR. This is the first experimental report of such large dynamic strain measurement with any type of ΦOTDR scheme. For this range of strain and spatial resolution values, the chirp bandwidth had to be significantly wider, beyond the capabilities of the scheme described in [11]. In addition, the processing of the delays in this case entails an additional level of complexity, as frequent reference updates are needed and outlier measurements appear. The sections below present the experimental setup, measurement technique, results and summary of the work developed in this context.

2. Experimental Setup and Measurement Procedure

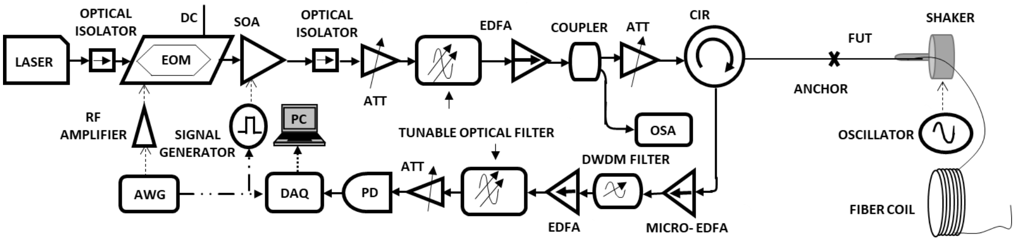

Fig. 1: Experimental setup for the CP-ΦOTDR

Acronyms: EOM: electro optic modulator, ATT: attenuator, EDFA: erbium doped fiber amplifier, CIR: circulator, FUT: fiber under test, OSA: optical spectrum analyzer, PD: photo diode. DAQ: data acquisition system, AWG: arbitrary waveform generator, RF: radio frequency, DWDM: dense wavelength division multiplexing, DC: direct current voltage supply, SOA: semiconductor optical amplifier

The setup used for the CP- ΦOTDR experiment is shown in Fig. 1. A narrow linewidth (~20 KHz) external cavity laser (ECL) diode source emits light at 1550 nm, and is externally modulated through an electro-optic modulator (EOM) driven by an arbitrary waveform generator (AWG, sampling rate 65 GSps). The AWG delivers chirped pulses in the microwave range (5 GHz bandwidth, centered at 6.5 GHz), and the EOM is operated at the point of carrier suppression, resulting only in the generation of upper and lower optical sidebands. The AWG chirped pulses have a 35 ns pulse width (~3.5 m spatial resolution) and a repetition rate of 200 KHz. The SOA gates the output signal and provides very high extinction ratio of the pulses, of the order of ~50 dB. Proper synchronization between SOA and AWG is ensured. After the SOA, the obtained light pulses pass through a tunable optical filter to select higher sideband. The power level of the pulse is adjusted through an EDFA and an optical attenuator, before being delivered into the fiber. The FUT is a 210 m fiber out of which 3.5 m are connected to a dynamic strain-generating system with one end fixed to an anchor and the other end attached to an electrically-controlled shaker which generates longitudinal sinusoidal displacements. The shaker system has been placed on a separate optical table in order to mechanically isolate it form the optical setup. The frequency and amplitude of the driving signal in the shaker can be controlled. The Rayleigh backscattered signal coming from the FUT is amplified by another EDFA, and another set of filters is used to remove the unnecessary spectral components. The required level of the signal is adjusted using an attenuator in order to protect the high bandwidth photodiode. A real-time oscilloscope captures the time domain trace. Oscilloscope and AWG are synchronized to avoid acquisition noise and jitter. The sampling rate of the scope was set to 40 GHz.

For the measurements, the shaker frequency was varied between 50 Hz to 200 Hz with variable strain levels. Local trace to trace cross-correlations (with a window size of 3.5 m) are calculated with respect to an initial reference trace to detect the temporal shift corresponding to the applied strain change. Because of the limits in the measurement procedure explained above, the reference trace in these conditions (large dynamic strain) needs to be updated for *every shot*. In order to enhance the accuracy of the correlation calculations, parabolic fitting is carried out to extract the exact correlation lag corresponding to the maximum correlation peak. Post processing of correlation shifts using a 3-point median filter removes lag estimations lying outside the expected window of appearance, corresponding to anomalous correlation peaks. With the experimental parameters given above, the nominal strain sensitivity of the system is 23 nε (corresponding to one sample with a sampling step of *dt* =1/40GHz). The total temporal shift at any time is calculated by the integration of the accumulated previous shifts, thus error accumulation towards low frequencies should be expected in the final strain measurements.

3. Results and Discussion

This section describes the experimental results obtained using the CP-ΦOTDR scheme described above to measure large dynamic strains.

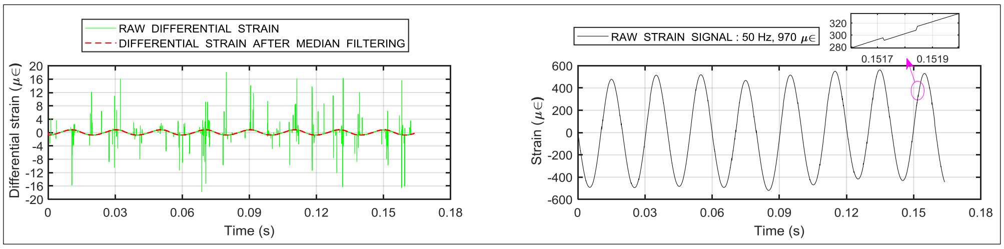

Fig. 2: Left: Differential strain signal- per scan before processing (green curve); smoothed by median filtering (dotted red line), Right: Strain signal achieved (50 Hz,970 µ□) without median filtering (shows discontinuities as in zoomed section)

CP-ΦOTDR trace signals were acquired for 160 milliseconds, with a trigger rate of 200 KHz. Fig. 2 shows the results obtained for an applied 50 Hz strain signal with a peak to peak amplitude of ~970 µε. On the left, the green curve shows the instantaneous differential strains obtained through the correlation shifts measured from one trace to the next one. The presence of outliers is clearly visible as sudden abnormal jumps. On the right, the corresponding integrated strain signal is obtained (i.e. the actual strain measurement). The effect of the outliers results in sudden jumps in the integrated strain signal, as seen in the zoomed section. The signal to noise ratio (SNR) of the raw strain signal obtained is around 20 dB, which is mainly limited by these anomalous delay estimations. These may occur either due to low SNR on the retrieved optical signal, or whenever each successive measurement surpasses the limit time-shift of the system due to signal decorrelation with the reference. Whenever the anomalous estimations in differential strains are not too densely packed, median filtering may be applied, as shown in Fig. 2 (red dashed curve on the left). The strain signal achieved after median filtering appears impressively smooth as the discontinuities get removed. The integrated strain is shown in Fig. 3 (left). Note that now the discontinuities in the signal have been eliminated. In terms of the signal quality, the median filter increases ~ 4 dB of SNR. The calculated standard deviations for peak to peak amplitudes of the retrieved strain signals is around 1%, which qualifies CP-ΦOTDR to measure large dynamic strains. Measurements at different frequencies were performed as shown in Fig 3 right. The minimum SNR of 24 dB was achieved in all cases.

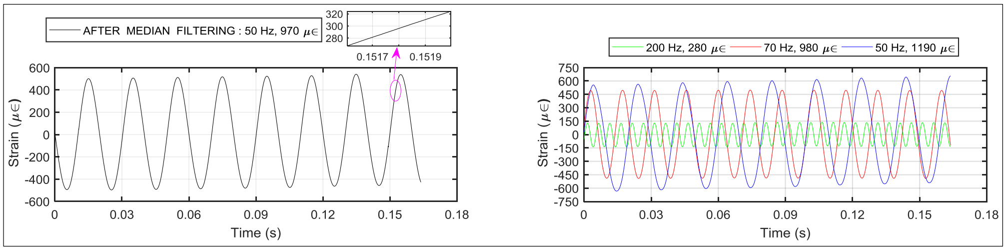

Fig. 3: Left: The smoothed signal (50 Hz,970 µ□) after median filtering, Right: Strain signals with various frequencies and levels (50 Hz-1190 µε, 70 Hz-980 µε and 200 Hz-280 µε)

Additional effects on the measurement can be observed in the spectral domain. Since the measurement technique is based on trace to trace windowed cross-correlations based on the reference update procedure described above, the measurement error is accumulated over time. This results in a growth of low frequency components due to the effective integration of the noise. To analyse its impact, a static point was measured outside the moving point. The static point was tested by calculating the strain over time based on both methods: with reference update (for each trigger, the reference is the previous trace) and without reference update (reference is always the first trigger of the whole measurement). The green curve of Fig. 4 represents the measurements based on the reference update (which is also used for the dynamic system) for the static point. As shown, the spectral components at lower frequencies are stronger (due to accumulated error) than the high frequency components, on the other hand without reference update the measurement presents uniform noise (as the error is fixed and bounded) over all the frequencies (shown by blue curve). As expected, the red curve in Fig. 4, shows the effect of the error accumulation (stronger components near low frequency region) for the dynamic point. The other observed phenomena are the presence of harmonics, which are mostly related to the mechanical behavior of the shaker and power amplifier. Nevertheless, measurements provide a good SNR of ~24 dB.

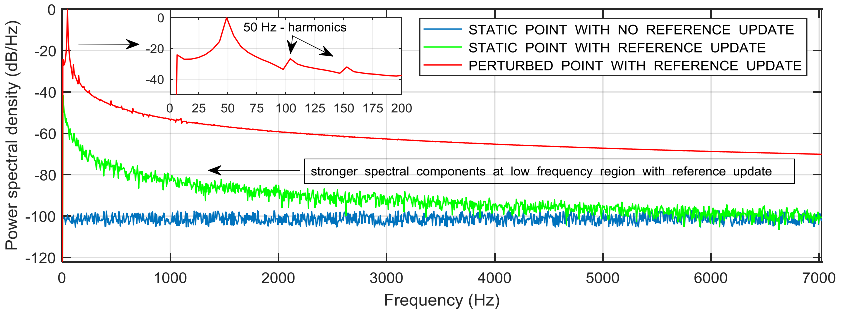

Fig. 4: Left: Frequency spectra for the unperturbed fiber(green) with reference update and without reference update(blue), Right: PSD of large dynamic strain signal (red, affected due to error accumulation)

Empirically we have verified that the maximum measurable frequency variations with this technique amount to roughly ~3% of the chirp bandwidth. If the equivalent strain change per scan over-crosses this value, there is measurement anomalies can occur in the form of an increasing number of outlier measurements on the differential strain as the signal slew rate increases. These cannot be fully corrected with the median filtering approach. Anyway, this experiment clearly demonstrates the CP-ΦOTDR capability to measure fairly large dynamic strains with acceptable good SNR characteristics.

4. Summary

We have demonstrated, for the first time, the measurement of large dynamic strains (up to >1000 με in amplitude, 50-200 Hz in frequency) with high spatial resolution (3.5 m resolution over a 210-meter fiber) using a ΦOTDR technique. In this case, the system relies on the high trigger rate and good SNR properties of CP-ΦOTDR which are essentially independent on the local trace shape variations. The measurement employs an adapted high chirp bandwidth setup and trace-to-trace correlation computation as described in [11], while updating the reference measurement in each and every pulse trigger. The net strain at any instant is obtained as the integration of the instantaneous strains accumulated, which yields into the growth of low frequency components due to summed up correlation noise. These errors tend to increase with increasing slew rate in the strain signal. Still, the processed strain signals show a SNR of $\geq$ 24 dB (0.16 s signal window) at the desired frequency which is enough to show the system's ability to measure large dynamic strains. This demonstration may open new possibilities for its applications in different areas such as aeronautics. Research on novel processing methods to avoid the error accumulation would become indispensable in trying to push these results further.

Acknowledgement: This work was performed in the framework of ITN-FINESSE, funded by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie Action grant agreement n° 722509.

5. References

[1] A. Motil, A. Bergman, and M. Tur, "[INVITED] State of the art of Brillouin fiber-optic distributed sensing," *Opt. Laser Technol.*, vol. 78, pp. 81–103, 2016.

[2] Z. N. Wang, J. Li, M. Q. Fan, L. Zhang, F. Peng, H. Wu, J. J. Zeng, Y. Zhou, and Y. J. Rao, "Phase-sensitive optical time-domain reflectometry with Brillouin amplification," *Opt. Lett.*, vol. 39, no. 15, p. 4313, 2014.

[3] H. F. Martins, S. Martin-Lopez, P. Corredera, J. D. Ania-Castanon, O. Frazao, and M. Gonzalez-Herraez, "Distributed vibration sensing over 125 km with enhanced SNR using Phi-OTDR over a URFL cavity," *J. Light. Technol.*, vol. 33, no. 12, pp. 2628–2632, 2015.

[4] G. J. Tu, X. P. Zhang, Y. X. Zhang, F. Zhu, L. Xia, and B. Nakarmi, "The Development of an Phi-OTDR System for Quantitative Vibration Measurement," *Ieee Photonics Technol. Lett.*, vol. 27, no. 12, pp. 1349–1352, 2015.

[5] A. Masoudi, M. Belal, and T. P. Newson, "A distributed optical fibre dynamic strain sensor based on phase-OTDR," *Meas. Sci. Technol.*, vol. 24, no. 8, 2013.

[6] L. Liokumovich, N. Ushakov, O. Kotov, M. Bisyarin, and A. Hartog, "Fundamentals of optical fiber sensing schemes based on coherent optical time domain reflectometry: Signal model under static fiber conditions," *J. Light. Technol.*, vol. 33, no. 17, pp. 1–1, 2015.

[7] M. R. Fernandez-Ruiz, J. Pastor-Graells, H. F. Martins, A. Garcia-Ruiz, S. Martin-Lopez, and M. Gonzalez-Herraez, "Laser Phase-noise Cancellation in Chirped-pulse Distributed Acoustic Sensors," *Journal of Lightwave Technology*, 2017.

[8] M. A. Soto, X. Lu, H. F. Martins, M. Gonzalez-Herraez, and L. Thévenaz, "Distributed phase birefringence measurements based on polarization correlation in phase-sensitive optical time-domain reflectometers," *Opt. Express*, vol. 23, no. 19, p. 24923, 2015.

[9] Y. Koyamada, M. Imahama, K. Kubota, and K. Hogari, "Fiber-optic distributed strain and temperature sensing with very high measurand resolution over long range using coherent OTDR," *J. Light. Technol.*, vol. 27, no. 9, pp. 1142–1146, 2009.

[10] Ling Zhou, Feng Wang, Xiangchuan Wang, Yun Pan, Zhenqin Sun, Ji Hua, and Xuping Zhang, "Distributed strain and vibration sensing system based on phase-sensitive OTDR," *IEEE Photonics Technol. Lett.*, vol. 27, no. 17, pp. 1884–1887, 2015.

[11] J. Pastor-Graells, H. F. Martins, A. Garcia-Ruiz, S. Martin-Lopez, and M. Gonzalez-Herraez, "Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses," *Opt. Express*, vol. 24, no. 12, p. 13121, 2016.