Distortion-suppressed sampling rate enhancement in phase-OTDR vibration sensing with newly designed FDM pulse sequence for correctly monitoring various waveforms

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Abstract: The FDM-based sampling rate enhancement method proposed herein detects vibration waveforms more accurately than previous methods while reducing phase unwrapping failures; it can measure vibrations with larger amplitude and higher frequency than heretofore.

1. Introduction

Utilizing optical fiber cables deployed for telecommunication as distributed vibration sensors is gaining a lot of attention [1-3]. Assessing the potential risk of communication failure, one attractive application [3], requires that we be able to correctly measure the waveforms of the wide variety of vibrations the cables may experience. Since the vibration strength typically ranges from a few nε to a few με, we require a measurement technique with matching vibration range and sensitivity (sub-nε order). Rayleigh-based high sensitivity sensing has the potential to meet such requirements. Phase sensitive optical time domain reflectometry (Φ-OTDR) is of a particular interest because it provides quantitative measurements with simple setup. Recent advances have alleviated major problems with Φ-OTDR. Coherent detection enables long measurable range of several tens of kilometers. Several methods successfully tackle fading noise. Among the ones used in coherent detection, the technique that averages the complex vectors is known to be effective [4, 5]. One simple setup for the technique is frequency-division-multiplexing (FDM) [5]. FDM is also the solution to overcome the trade-off between measurement length and measurable vibration frequency [6]. FDM enhances the sampling rate by launching different frequency pulses at different times, which extends the upper limit of measurable frequency [6].

FDM-based sampling rate enhancement seems suitable for avoiding phase unwrapping failures. Such failures are a significant but not-well-resolved problem as they hinder the monitoring of vibration waveforms that have both high frequency and large amplitude. By sufficiently increasing the sampling rate, it seems possible to determine absolute values of strain changes between all adjacent sampling points below π. However, the previous method cannot be used in such a way because it permits strong distortion and so fails to correctly capture the vibration waveform. To resolve the issue, we propose a novel FDM technique that can directly compensate the distortion for the first time. Our newly designed input pulse sequence enables the application of effective time-domain averaging to suppress the distortion. The sampling-rate-enhanced technique of the proposed method is shown to measure vibration waveforms correctly while successfully reducing phase unwrapping failure. The method, easily combinable with fading suppression techniques, allows us to monitor vibration waveforms that have both high frequency and large amplitude. This is crucial for visualizing the optical fiber cable states in sufficient detail so as to proactively counter communication failures.

2. Principle

2.1. *Problem of conventional FDM-based sampling rate enhancement methodology*

FDM Φ-OTDR used for enhancing sampling rate is shown in Fig. 1(a). Different frequency pulses are launched at different times. From the detected backscattered light, spatiotemporal complex vectors of each frequency are discriminated; their angles correspond to optical phases. The optical phase of a backscattered light is calculated as

$$\theta(nt,z)=\theta_i\big((i+mN)t,z\big)\ \ (n\in\mathbb{Z})\ \ when\ n\equiv i(\mathrm{mod}\,N), \qquad (1)$$

where t is time interval between adjacent pulses, z is fiber length from the input end, θ_i is phase calculated from the frequency f_i, and N is the number of multiplexed frequencies. Integer m is chosen such that the equation holds. The time interval t can be made smaller than the lower limit of single frequency system by the factor of N.

However, the optical phase obtained by Eq. (1) is strongly distorted because vector angles of different frequencies are not the same even if they capture the same fiber state. Phase variation from time nt to time $n't$ contains the frequency-dependent distortion factor of

$$\theta(n't,z)-\theta(nt,z)=\theta_{i'}\left((i'+m'N)t,z\right)-\theta_i\left((i+mN)t,z\right)=\Delta\theta(n't,nt,z)+\phi(i',i,z)+\phi_N\quad(n,n'\in\mathbb{Z}),\ (2)$$

where $\Delta\theta$ is real phase change, $\phi(i',i)$ is the distortion factor between frequency $f_{i'}$ and f_i, and ϕ_N is sum of other phase noises including fading noise. This is illustrated in Fig.1 (b). The distortion has the period of Nt, but its amplitude is not small because it ranges from $-\pi$ to π with uniform probability. As the distortion is added to the real phase change and the other phase noises, it causes serious problems. Phase unwrapping of once-wrapped summed waveform of the real phase change and the distortion can generate unwanted frequency signals different from the original vibration frequency, including the sum- and difference-frequency of the original vibration frequency and the distortion frequency. In the worst cases, phase unwrapping failures are induced at many points, making the calculated phase change quite different from the correct waveform. The previous work of [6] calculates the difference function $f(nt)$ of the obtained phase change and its self-delayed function by the delay of Nt, making it possible to extract the vibration frequency. However, this method doesn't compensate the distortion, so the correct waveform is not obtained. Correspondingly, calculation of phase unwrapping of $f(nt)$ is not really effective in avoiding phase unwrapping failures. Up to now, no method that can cope with the distortion has been proposed.

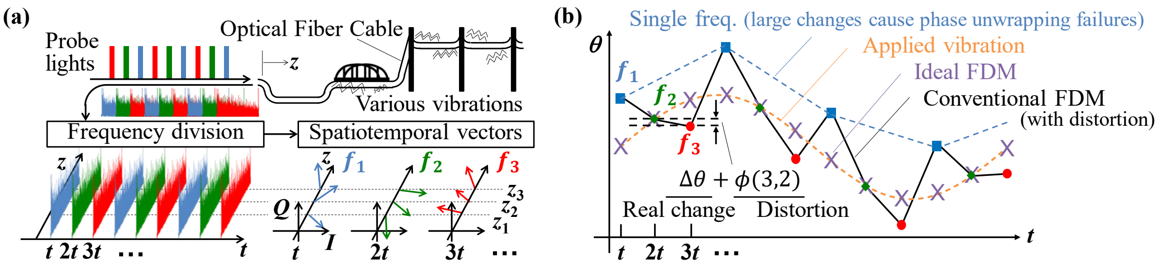

Fig. 1. Conventional FDM. (a) Schematic. (b) Measured waveforms (ϕ_N is assumed to be 0 for simplicity).

2.2. Proposal of new FDM technique for sampling rate enhancement

For correctly monitoring the vibration waveforms, we propose a new FDM method that directly suppresses the distortion $\phi(i',i)$ for the first time. The key concept is incorporating the time-domain averaging used in the double averaging approach [5]. Although the time-domain averaging was proposed to calculate rotation angles for frequency-domain averaging, the rotation angles used and the distortion in Eq. (2) have the same physical origin. Therefore, time-domain averaging can be used to compensate the distortion. In order to use time-domain averaging, however, different frequency pulses must be launched simultaneously, which is not realised in conventional configuration. Therefore, we design a new pulse sequence using a complementary frequency. Its schematic is shown in Fig. 2(a). The complementary frequency (f_C) pulses are launched with time interval $(N+1)t$ so that pulse sequences with length of $N(N+1)t$ are repeatedly launched into the fiber. Since the pulses of f_i and f_C are simultaneously launched at time $(iN+i-N)t$, we can perform time-domain averaging to estimate the distortion factor $\phi(i,C)$ between f_i and f_C accurately. The distortion factors $\phi(i',i)$ can be calculated simply as

$$\phi(i',i,z)=\phi(i',C,z)-\phi(i,C,z).\qquad(3)$$

From the estimated values, we can obtain the distortion-suppressed waveform in the sampling rate enhanced manner, which effectively suppresses phase unwrapping failures. In principle, the measurable amplitude/frequency range is improved by the factor of N. Although the complementary frequency approach needs extra bandwidth, the proposal has several advantages over other considerable designs. It enables continuous monitoring with the enhanced sampling rate without deteriorating the measurement length. The complementary frequency signals can be used to suppress the fading noise. The design is easily combined with FDM-based fading suppression. Figure 2(b) shows an example in which N is set to three for enhancing the sampling rate and three (or four) frequencies are used for fading suppression at each time.

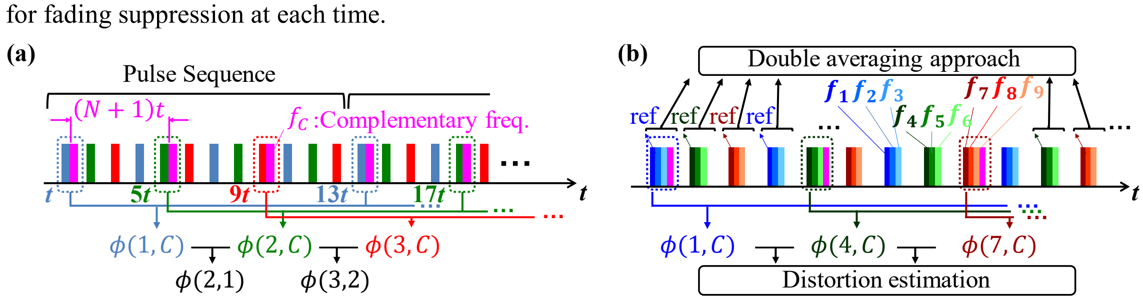

Fig. 2. Proposed method. (a) Designed sequence (N=3). (b) Combination with FDM-based fading suppression.

3. Proof-of-concept experiments using three multiplexed frequencies and the complementary one

Experimental setup was basically the configuration used in [6]. The key difference lies in the input pulses – the proposed pulse sequence consisted of three multiplexed frequencies and the complementary one, as shown in Fig. 3(a). Sinusoidal vibration (55 nε, 250 Hz) was applied to the optical fiber stretcher (OFS). Figure 3(b) compares the average of power spectral densities (PSDs) of the phases at all non-vibrating locations before OFS obtained by the proposal and that obtained by conventional method using Eq. (1). Both the power of the distortion frequency and the noise floor were successfully suppressed (~15dB). The residual peaks that appeared were presumably due to the incompleteness of the signal processing, but they were much smaller than the distortion. Figure 3(c) compares phase spectrograms. The Y axis values are for 100m region including OFS. As shown in Fig.3(c), the vibrating OFS region was more clearly detected by the proposal. Figure 3(d) compares the averages of PSDs of different sections on the OFS. The ratio of the signal to surrounding noise was improved by >10dB. These results show that the proposed method successfully compensated the distortion. It should be mentioned that sum- and difference-frequency were observed in Fig.3 (d), as predicted in 2.1. Fig. 3(e) directly compares the vibration waveforms on the OFS obtained by the single frequency method, conventional method, and the proposal. The proposal detected the waveform with less phase unwrapping failures and greater accuracy than the other methods.

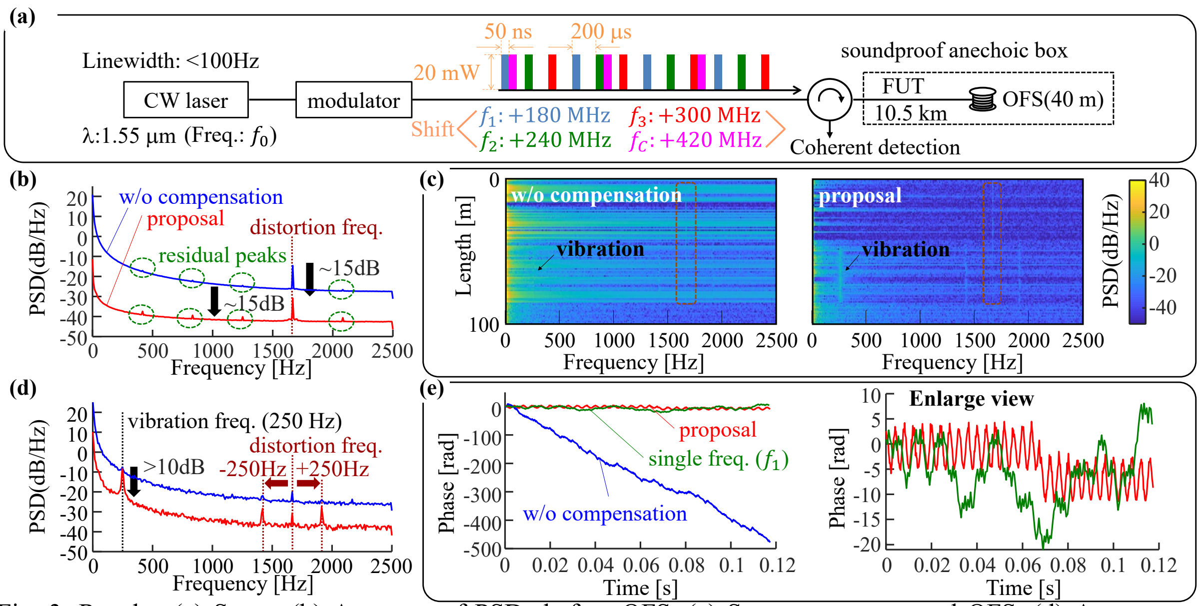

Fig. 3. Results. (a) Setup. (b) Averages of PSDs before OFS. (c) Spectrograms around OFS. (d) Averages of PSDs on OFS. (e) Characteristic vibration waveforms on OFS. In (b)-(e), the signal of f_C was not used to suppress fading noise in the proposed method for fair comparisons.

4. Conclusions

We propose an FDM-based sampling rate enhancement method using new pulse sequence for obtaining distortion-suppressed vibration waveforms and significantly reducing the phase unwrapping failures. In an experiment, the proposal detected the imposed vibration (250Hz, 55nε) waveform with better accuracy than conventional methods. The proposed technique enlarges the measurement range of vibrations to higher frequencies and larger amplitudes.

5. References

[1] Philippe, J., et al.: 'Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features', Nat. Commun., 2018, 9, (1), 2509

[2] G., A., Wellbrock, et al.: 'First Field Trial of Sensing Vehicle Speed, Density, and Road Conditions by Using Fiber Carrying High Speed Data', Proc. Optical Fiber Communication Conference, San Diego, USA, 2019, Th4C.7

[3] T., Okamoto, D., Iida, H., Oshida: 'Identification of Sagging Aerial Cable Section by Distributed Vibration Sensing based on OFDR', Proc. Optical Fiber Communication Conference, San Diego, USA, 2019, Th2A.26

[4] D., Cheng, Q., Liu, Z., He: 'High-fidelity distributed fiber-optic acoustic sensor with fading noise suppressed and sub-meter spatial resolution', Opt. Express, 2018, 26, pp 16138-16146

[5] Y. Waksiaka, et al.: 'Suppressing waveform distortion in phase-OTDR vibration sensing for visualizing optical fiber cable state', Proc. ECOC, Dublin, Ireland, 2019, W.1.E.3

[6] D., Iida, K., Toge, T., Manabe: 'Distributed measurement of acoustic vibration location with frequency multiplexed phase-OTDR', Opt. Fiber Technol., 2017, 36, pp 19-25