Proposal and Real-Field Demonstration of Large-Scale Vibration Monitoring by Using Multi-Frequency Φ-OTDR Distributed Acoustic Sensing

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Abstract *We develop highly sensitive and accurate multi-frequency Φ-OTDR distributed acoustic sensing suitable for measuring large-scale vibrations over sub-με amplitudes. We capture more correct detailed vibration patterns on both underground and aerial sections of an optical fibre network deployed for telecommunication services in a real-field trial.*

Introduction

Distributed acoustic sensing (DAS) is a powerful tool to acquire environmental information surrounding an optical fibre [1]. Utilizing optical fibre communication network for DAS has recently gathered a great attention as we can monitor wide area without installing new sensors [2,3]. On underground sections of a fibre, applications such as seismology [4], traffic monitoring [2], threats detection (ex. detection of construction machine vibrations) [5,6] have been demonstrated. On aerial sections, applications including diagnosis of cable installation states [7,8] and weather monitoring [9] have been investigated.

To put these applications into practical use, high-performance DAS is strongly desired. High sensitivity over long measurement distances is essential for utilizing massive fibre network, but to measure correct vibration waveforms with wide dynamic range of measurable strain is also important. This is because telecommunication optical fibre cables experience a wide variety of vibrations from small changes (ex. microtremors) to large-scale ones (ex. large car movements, aerial cable sway/dancing by wind).

Meeting these requirements is an arduous task. For long measurement distances, phase OTDR (Φ-OTDR) is suitable, but it suffers from a problem of fading. Interference between scattered lights from innumerable scatterers generates many weak intensity points in the total backscattered signal, corresponding to dead points of sensitivity. Multi-frequency approach is a promising solution [10-14], in which multi-frequency pulses are multiplexed, and their signals are averaged. However, averaging methods such as the rotated-vector-sum method [15] highly efficient in terms of sensitivity are not always suitable for monitoring large-scale vibrations. High sensitivity is ruined when a fibre experiences large strain changes [16]. Main cause is difference in phase response between multiplexed frequencies arising from nonlinear response of phase to strain inherent in Φ-OTDR [17-19]. Although the recent work has tackled this problem by applying the rotation angle tracking (RAT) [16] to the rotated-vector-sum method, the overall performance has not been fully investigated. In addition, the recent progress has not been incorporated for real-field tests, thus the practical advantages towards actual applications are still unknown.

In this work, regarding the rotated-vector-sum method with the RAT, we reveal and address several problems of waveform distortion accompanied with the RAT. We propose the countermeasure using the reference frequency permutation average with the dynamic optical-intensity-based selection, which enables more accurate measurements of large-scale vibrations over sub-με amplitudes. With the multi-frequency DAS equipment incorporating all the improvements, we perform a real-field test utilizing an optical fibre cable (~ 4.3 km) deployed for telecommunication. On both underground and aerial sections, we succeed in capturing correct vibration patterns in greater detail such as car movements and aerial cable sway.

Measurement Principle & Lab Experiment

Fig. 1 shows the schematic of multi-frequency Φ-OTDR. Probe pulses with the multiplexes of N are launched into a fibre-under-test (FUT) (Fig. 1 (a)). A coherent receiver detects the backscattered light with a local light (LO). Spatiotemporal vectors $\boldsymbol{r}_i(z, t)$ for each frequency f_i are obtained on the IQ plane (I: In-phase, Q: Quadrature), where z is distance from the input end and t is monitoring time.

For averaging multi-frequency signals, the rotated-vector-sum method has been

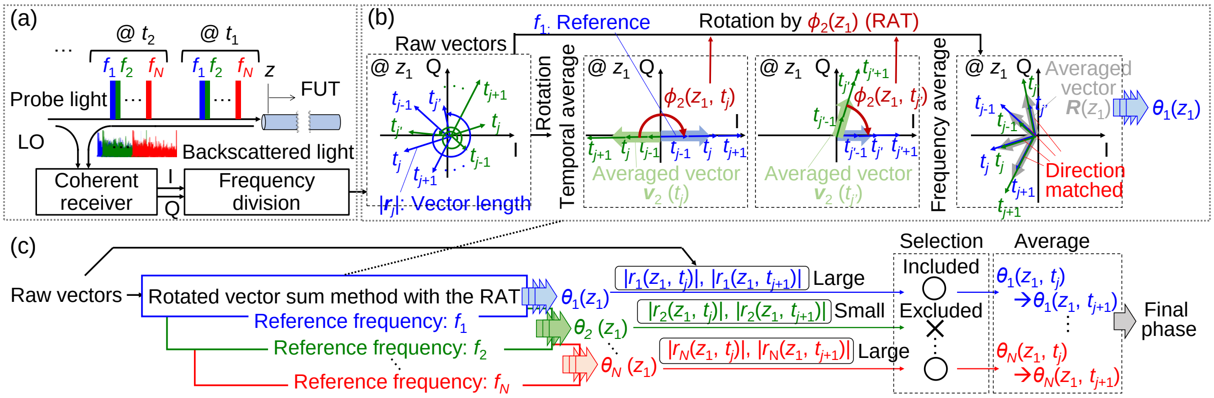

Fig. 1: Multi-frequency Φ-OTDR DAS. The simplified schematic and the proposed phase calculation method.

demonstrated to be highly efficient [15,13,20,21]. Every frequency vector is rotated by an angle $\phi(z)$ so that the direction is the same as a chosen reference frequency (f_1 is chosen as an example in Fig. 1 (b)), and then multi-frequency vectors are averaged. The length of the averaged vector $\boldsymbol{R}(z)$ is maximized, meaning the sensitivity of the final phase θ representing vibration waveform calculated from $\boldsymbol{R}$ is also maximized. Rotation angle $\phi(z)$ can be constant when we monitor small vibrations, however it is not suitable for large-scale vibration measurements [16]. This is due to nonlinear response of phase [rad] to strain [ε] caused by interference of scattered lights [17-19]. Interference depends on an optical frequency, so difference in phase response between multiplexed frequencies becomes large according to the strain change. Thus, using the constant rotation angle $\phi(z)$ independent of t cannot hold the high sensitivity.

This problem is addressed by tracking the optimal rotation angle $\phi(z, t)$ [16], as illustrated in Fig.1 (b). However, the rotation angle tracking (RAT) method raises two kinds of waveform distortion, which we clarify here for the first time. First, the waveform distortion caused by the nonlinear response itself remains as the same to that of the reference frequency. Although the overall sensitivity is better compared to using each one of the multiplexed frequencies, the effect of suppressing the nonlinear response by the average of multi-frequency signals [14] is compromised. Second, the rotation angle fluctuates due to measurement noise if the intensity of the reference frequency is small. When vectors of other frequencies rotated by the fluctuated angle are summed with the small vector of the reference frequency, large waveform distortion occurs. These issues prevent correct measurements of vibration waveforms.

We propose the countermeasure (Fig.1 (c)). Against the first problem, we develop the reference frequency permutation averaging (RFPA). In the RFPA, different from conventional methods in which one specific frequency is chosen as the reference and only the corresponding phase is used, we calculate the phase variation θ_i by using the rotated-vector-sum method with the RAT by choosing each frequency f_i as the reference. Multiple phase variations are obtained according to the number of multiplexes N; $\theta_i = 1, 2, \ldots, N$. RFPA calculates the average of θ_i at this final phase state (not the vector state). By adding this extra average, RFPA can revive the effect of suppressing the distortion caused by the nonlinear response. Against the second problem, we develop the dynamic intensity-based selection (DIBS) used in the RFPA. In the DIBS, we exclude the phases obtained by using the reference frequencies of the weak intensity (= short vector length $|\boldsymbol{r}|$) in the average of θ_i. Because the vector length varies over time, the selection rule for which frequencies are excluded is dynamically updated. DIBS can suppress the impact of the rotation angle fluctuation. DIBS is different from conventional selections because excluded-frequency signals are still used in the phase calculation when the other frequencies are chosen as the reference.

Validity of the multi-frequency Φ-OTDR DAS incorporating all these proposed methods was confirmed by a proof-of-concept experiment. Fig. 2 (a) shows the experimental setup. CW laser with the narrow bandwidth (< 100 Hz) was utilized for local and probe light. A single-side-band modulator (SSBM) and an acousto-optic modulator (AOM) were utilized to fabricate the probe light. The number of multiplexes N was 8. Pulse width of each component was 50 ns. A 60-m-long optical fibre stretcher (OFS) was placed at 10 km from the input end. Sine vibration (3 Hz, 0.35 με) was applied to the OFS. We compared the rotated-vector-sum method using the constant rotation angle without the proposal, the method incorporating only the RAT, and the method including the RAT and the RFPA with the DIBS. Fig. 2 (b)–(g) show waterfall graphs and

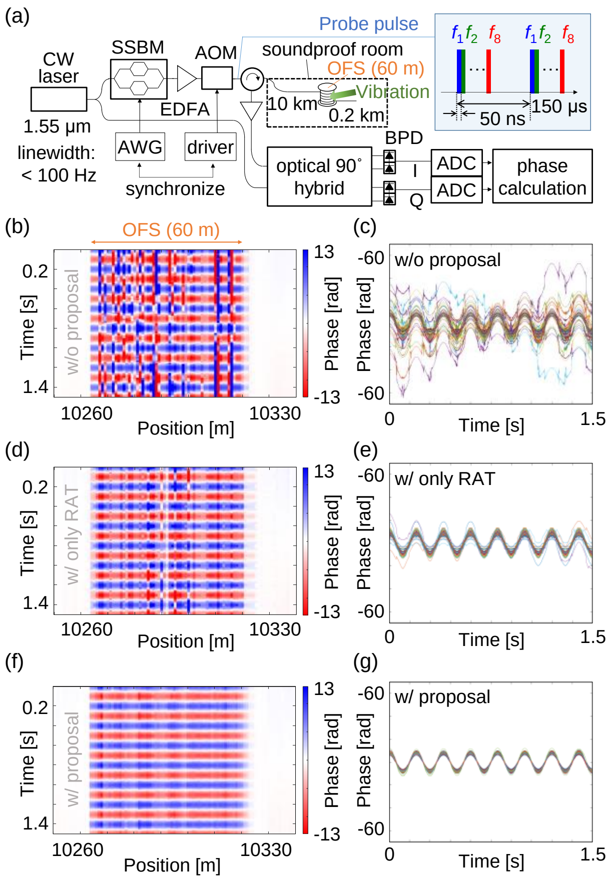

Fig. 2: Proof-of-concept laboratory experiment.

time-domain waveforms at all positions on the OFS. By incorporating all the proposed methods, we successfully suppressed both the sensitivity degradation and the waveform distortion, thus confirmed the validity of the proposal.

Real-Field Trial

We performed a real-field trial utilizing an optical fibre cable (~ 4.3 km) deployed for telecommunication services. The cable was on an underground section up to a 2-km point, and from that point it was on an aerial section.

On the underground section, we captured traffic movements. Fig. 3 shows the waterfall graphs ((a), (b)) and the slices at one time (T = 0.41 s) ((c)) obtained by using the conventional method and the proposed method. Vibrations (> ~ 5 Hz) were discriminated from temperature by using high-pass filter. Although both methods captured car movements, the conventional method failed to measure detailed vibration patterns due to the unwanted phase jumps. The proposed method suppressed such dead points, thus successfully captured the more detailed vibration patterns.

On the aerial section, we captured cable sway by wind. Fig. 4 (a) shows the waterfall graphs, and (b) shows the slices at one time (T' = 0.44 s). The proposed method could capture the vibration patterns more correctly in the aerial section, too.

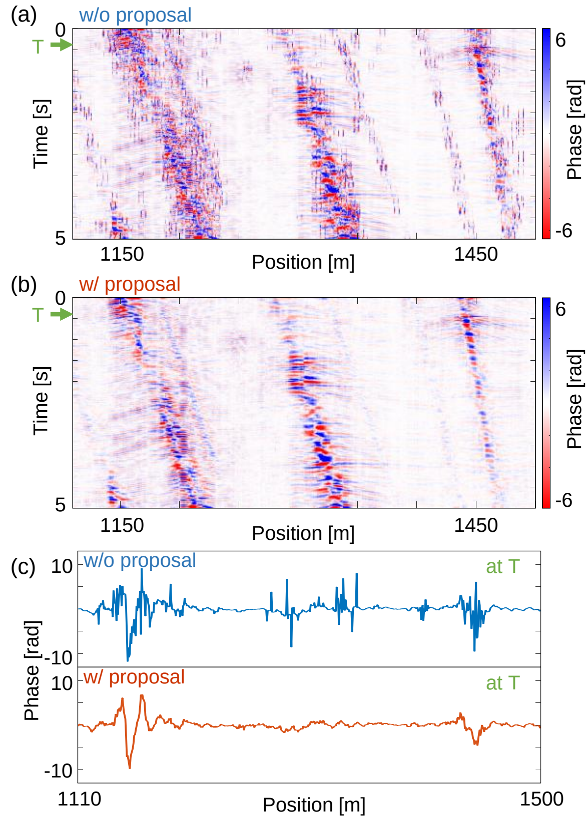

Fig. 3: Traffic monitoring.

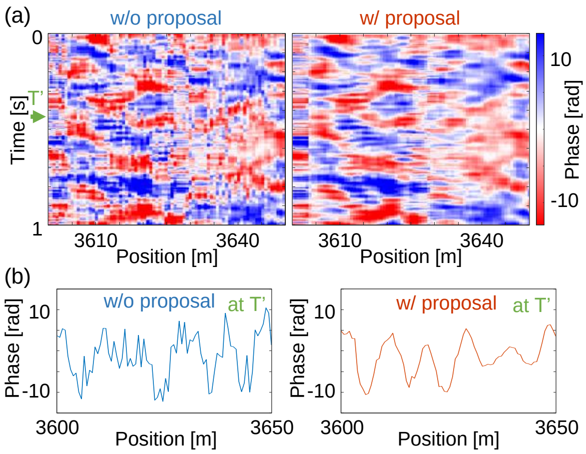

Fig. 4: Monitoring of aerial cable sway.

Conclusions

We developed the highly sensitive and accurate multi-frequency Φ-OTDR DAS suitable for large-scale vibration measurements. The proposed DAS utilized the rotated-vector-sum method incorporating the rotation angle tracking and the reference frequency permutation averaging with the dynamic intensity-based selection. We successfully captured more correct vibration patterns such as car movements and aerial cable sway occurring on the optical fibre network deployed for telecommunication services in the real-field trial. The proposed DAS will be useful for analysing vibration data in greater detail towards practical applications.

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