Frequency averaging with rotation angle tracking technique in phase-OTDR DAS for large-scale vibration measurement

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Abstract: Sensitivity degradation specific to frequency-multiplexed phase OTDR in measuring large strain change is clarified for the first time. We demonstrate one solution based on frequency averaging with rotation angle tracking technique to measure sub-με vibrations. (tel: +81 29.868.6350, e-mail: yoshifumi.wakisaka.ba@hco.ntt.co.jp). © 2022 The Author(s)

1. Introduction

Distributed acoustic sensing (DAS) is a powerful technique for obtaining environmental information surrounding optical fibers. Phase-OTDR-based DAS has many advantages such as quantitative data analysis, high sensitivity and long measurement distance, so it has been utilized in many applications [1, 2]. Along with the acceptance of these applications, continuous efforts have been devoted to enhancing measurement performance. These include not only the pursuit of sensitivity, but also various improvements. One of them is the enlargement of strain dynamic range [3]. To capture a wide variety of vibrations from small changes to large-scale variations, high sensitivity and wide dynamic range of strain amplitude are essential.

Regarding sensitivity enhancement, fading is the main challenge. Interference between scattered lights from many scatterers generates weak intensity points in the total backscattered signal, which degrades the measurement sensitivity. The multi-frequency approach (frequency-division-multiplexing) is a promising countermeasure [4]. Multi-frequency pulses are launched and their signals are averaged, which can eliminate the weak intensity points. The rotated-vector-sum method, a highly efficient averaging procedure, uses vector-based averaging on the IQ plane [5]. Each frequency vector is rotated and averaged to maximize the sensitivity. This method has been widely adopted and continuously enhanced [2, 6, 7].

Although this vector-based multi-frequency approach is powerful from the viewpoint of the sensitivity, when we enlarge the strain dynamic range, a problem arises in that the difference in the phase response between the optical frequencies becomes significant [4, 8]. Because the difference between the angles of the used frequency vectors largely changes over time when strong strains occur, the optimal rotation angles used in frequency averaging process are not fixed and may vary depending on the fiber state. This issue is crucial to monitor a wider variety of vibrations, but has not been reported and discussed yet.

In this work, we clarify this issue for the first time. We show that it prevents high sensitivity from being maintained when large strain changes occur. Thus, such changes increase the phase noise and noise-induced phase unwrapping failures happen. To circumvent this issue, our solution tracks the optimal rotation angles and utilizes them in frequency averaging. Without further post signal processing, it enhances robustness to large strain changes. The proposed method contributes to enlarging the strain dynamic range of phase-OTDR-based DAS while maintaining the high sensitivity of the multi-frequency approach.

2. Principle

Fig. 1 shows a schematic of the frequency-multiplexed phase OTDR. Multi-frequency pulses are launched into a fiber-under-test (FUT). A coherent receiver detects backscattered light. Spatiotemporal vectors for each frequency are discriminated from I (In-phase) and Q (Quadrature) components. They are rotated and averaged. The essence of the rotation is to maximize the length of the frequency-averaged vector [5]. The longer the averaged vector is, the higher the signal-to-noise ratio (SNR) becomes. Therefore, every frequency vector is aligned to the same direction before averaging. Optimal rotation angles can be evaluated with high accuracy by another averaging step in the time

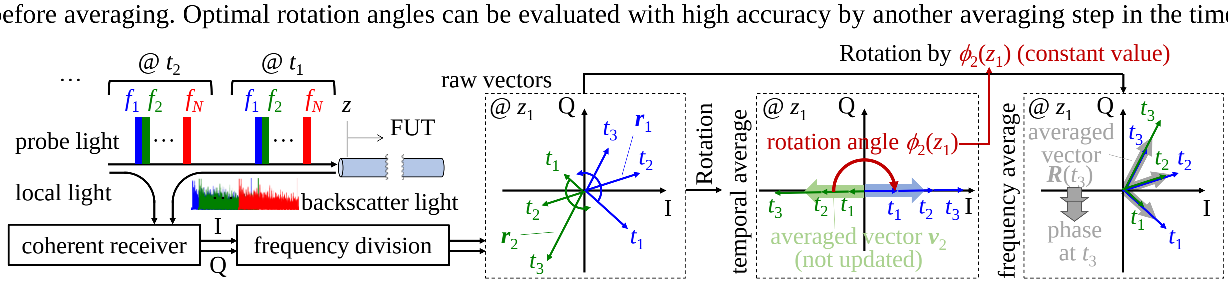

Fig. 1. Basic schematic of the frequency-multiplexed phase OTDR with the vector-based averaging in both frequency and time domain.

domain [7]. This algorithm enables high sensitivity measurements. The vector-based frequency averaging methods considered so far use a constant rotation angle. This is valid as long as the strain change is small because the phase (angle) variations of the multiplexed frequency vectors are almost the same over time. Thus, constant values can be used for frequency averaging regardless of time.

However, this is not the case when the FUT experiences a large strain change. As the large strain alters the fiber state greatly, the nonlinearity of the phase response to the strain becomes significant [4, 8]. Nonlinearity is a phenomenon in which the phase variation (units of radian (rad)) does not match the exact vibration waveform in the units of strain (ε). For example, when measuring the sine vibration waveform with the frequency f_v, this discrepancy distorts the phase variation and generates harmonics mf_v ($m > 1$). Since the origin of this phenomenon is the interference between scattered lights from many scatterers (similar to fading), how the phase waveform is distorted depends on the optical frequency. This means that, from the viewpoint of measurement sensitivity, the rotation angle suitable at one time may not be optimal at other times. Non-optimal rotation angles decrease the length of the frequency-averaged vector, and SNR becomes smaller than the ideal value. When the sensitivity degradation is large, noise-induced phase unwrapping failures happen frequently. As a result, undesired phase jumps occur, making the phase variation quite different from the actual waveform. In this sense, the method is not well-suited to measure large strain changes, with its current procedures.

This issue hasn't been reported and investigated yet, so no direct countermeasure has been proposed to date. In this work, we propose a procedure that effectively counters this issue. The proposed method tracks the optimal rotation angle for each measurement time by setting and moving a time window in performing the time-domain vector-based averaging. Fig. 2 shows the concept. Raw vector of each frequency f_n ($n = 1, 2, \ldots, N$) after frequency division is denoted as $\boldsymbol{r}_n(z, t_j)$, where N is the number of the utilized frequencies, z is the distance from the input end of the FUT and t_j is the monitor time. The rotation angle $\phi_n(z, t_j)$ for frequency f_n is calculated as

$$\phi_n\left(z,t_j\right) = -\arg\left[\boldsymbol{v}_n\left(z,t_j\right)\right] = -\arg\left[\frac{1}{2T+1}\sum_{k=j-T}^{j+T}\exp\left[-i\frac{\boldsymbol{r}_1\left(z,t_k\right)}{\left|\boldsymbol{r}_1\left(z,t_k\right)\right|}\boldsymbol{r}_n\left(z,t_k\right)\right]\right], \tag{1}$$

where $\boldsymbol{v}_n(z, t_j)$ is the time-domain averaged vector, $2T+1$ is the time window, the arg operator calculates the argument of the complex vectors. As in (1), the proposed method continuously updates $\phi_n(z, t_j)$ corresponding to the fiber state. By using the obtained $\phi_n(z, t_j)$, frequency averaging is performed as

$$\boldsymbol{R}\left(z,t_j\right) = \frac{1}{N}\sum_{n=1}^{N}\left[\exp\left[i\phi_n\left(z,t_j\right)\right]\cdot\boldsymbol{r}_n\left(z,t_j\right)\right], \tag{2}$$

where $\boldsymbol{R}(z, t_j)$ is the frequency-averaged vector. By calculating the phase difference between $\boldsymbol{R}(z \pm D/2, t_j)$ separated by a gauge length D and performing the unwrapping, we get the phase variation representing the vibration at z. By setting T to an appropriate value, it is possible to obtain the rotation angle with enough precision and increase the vector length of $\boldsymbol{R}$ compared with the conventional method over the entire measurement time. Thus, it enhances tolerance to large strain changes. The proposed method has a unique feature in that it provides high sensitivity while permitting the nonlinear distortion itself to remain to some extent. The rotation angle tracking used here is a kind of moving average, but it does not obscure high-frequency vibrations. This is because the rotation angle is only a parameter used in frequency averaging step, and the final phase change is not subject to moving average. Thus, the measureable frequency range is maintained.

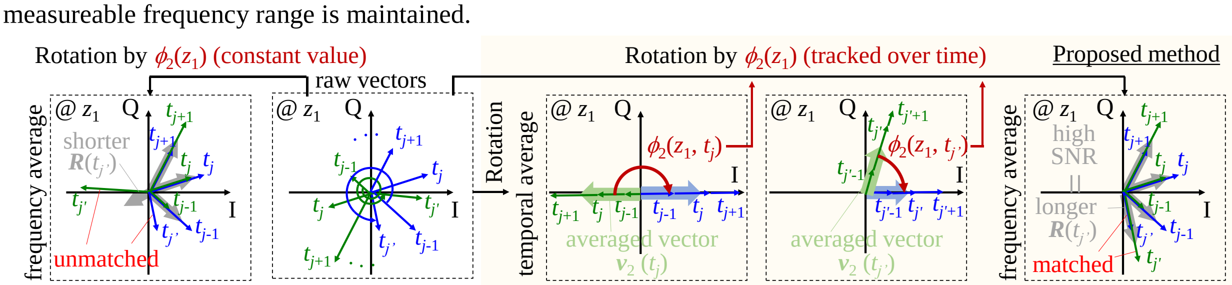

Fig. 2. Frequency averaging with the optimal rotation angle tracking technique, compared with the conventional method. Example of $T = 1$.

3. Experiment

Fig. 3 (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 shape the probe light into multi-frequency pulses. Pulse width of each component was 50 ns. A 60-m-long optical fiber stretcher (OFS) was placed at 10 km from the input end of the FUT. Sine vibration (3 Hz, 0.35 με) was applied to the OFS, first. Phase variation was calculated by the conventional method and the proposed method. Gauge length D

was set to 5 m. In the proposed method, parameter T was set to 25. In the conventional method, for fair comparison, the rotation angles were calculated and fixed by temporal averaging by using the first 51 sampling points. Thus, in the conventional method and the proposed method, the accuracy of the rotation angles against the measurement noises was statistically the same. Fig. 3 (b) shows the phase variation obtained by using two multiplexed frequencies signals and applying the conventional method at position z_1 on the OFS. Abrupt phase changes occurred when phase unwrapping did not work correctly. The waveform was quite different from the actual one, which was not easily compensated by post signal processing. Fig. 3 (c) shows the phase variation obtained by using the proposed method at the same position. The abrupt changes were significantly decreased. Fig. 3 (d) shows the change in the rotation angles ϕ_2 ($z_1 \pm D/2$) used in the frequency averaging. The rotation angles used in the proposed method had the same period as the vibration frequency, indicating that the optimal value actually changed according to the fiber state from the viewpoint of the sensitivity. It should be noted that phase unwrapping was not necessary for determining the rotation angles. The variation fully ranged from $-\pi$ to π, so this was not negligible. This directly indicates the importance of tracking the optimal values. Fig. 3 (e) shows the waterfall graphs around the OFS. Undesired abrupt phase jumps on the OFS were successfully decreased with the proposed method, which enhanced the signal visibility. Fig. 3 (f) shows the waterfall graphs obtained by increasing the multiplexed frequencies signals up to four, while (g) shows the result of the other vibration-frequency case. These results confirm the validity of the proposal.

4. Conclusion

In this work, we clarified the sensitivity degradation issue specific to the frequency-multiplexed phase OTDR in measuring large strain change for the first time. We proposed the countermeasure based on the tracking of the optimal rotation angles used for the frequency averaging. We demonstrated that the proposed method was effective to suppress the undesired effects such as the failure of the phase unwrapping caused by the issue in the proof-of-concept experiments using vibrations of a few Hz frequencies and a sub-με amplitude. The proposed method contributes to enlarging the strain dynamic range of phase-OTDR-based DAS, so it will be useful to capture large-scale vibrations over sub-με with the high sensitivity.

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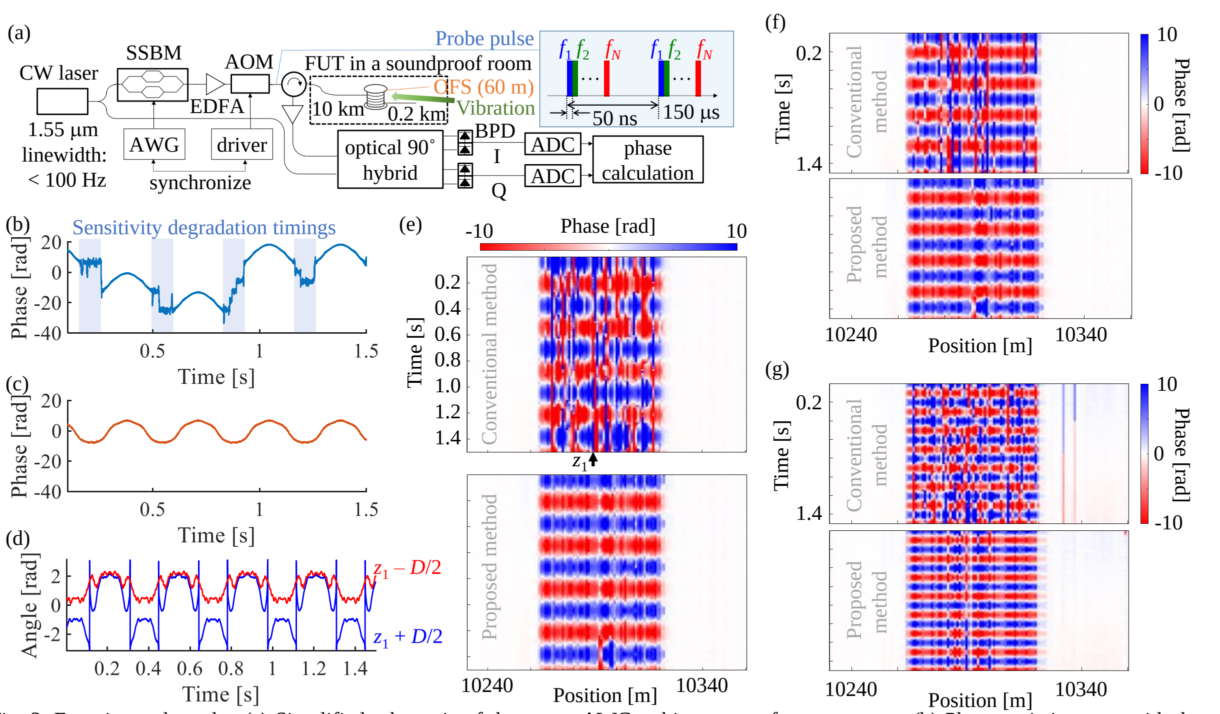

Fig. 3. Experimental results. (a) Simplified schematic of the setup. AWG: arbitrary waveform generator. (b) Phase variation at z_1 with the conventional method. (c) Phase variation at z_1 with the proposed method. (d) Rotation angles obtained by the proposed method. (e) Waterfall graphs for the sine wave vibration (3 Hz, 0.35 με) with two optical-frequencies signals. (f) Waterfall graphs for the sine wave vibration (3 Hz, 0.35 με) by using four frequencies signals. (g) Case of the sine wave vibration (5 Hz, 0.35 με) with two frequencies signals.