Method of widening dynamic range of measurable vibration in FDM-based sampling-rate-enhanced Φ-OTDR

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Abstract: We propose and demonstrate a method to suppress the infidelity effect in FDM-based sampling-rate-enhanced Φ-OTDR vibration sensing; it extends the dynamic range without increase of the system complexity or prior knowledge of the vibration.

1. Introduction

Distributed vibration sensing (DVS) enables the acquisition of various environmental information surrounding an optical sensing fiber. Phase-sensitive OTDR (Φ-OTDR) is a powerful DVS technique that can measure vibrations quantitatively and sensitively. Because the simple Φ-OTDR configuration that utilizes an optical pulse of a single frequency suffers from several problems, many studies have attempted improvements. By using frequnecy-division-multiplexing (FDM), we can tackle two important ones – fading noise and the tradeoff between sampling rate and fiber length. Fading noise can be suppressed by injecting different optical frequency components at the same time and averaging their signals, while sampling rate can be enhanced by launching different frequency components at different timings and concatenating their phases. For FDM-based sampling rate enhancement, various configurations are possible including uniform [1] /nonuniform [2] sampling base on different detection principles such as dual-pulse configuration [3], coherent detection [1], and TGD-OFDR [4]. A common problem with many of them is that the vibration waveform to be measured is distorted unless phase offets of different frequencies are corrected. Recently, direct compensation of the distortion was proposed [5], in which the phase offsets are evaluated by using the complementary frequency concept. This method is useful for fully characterizing a vibration based on the waveform pattern (not only the vibration frequency but also the waveform amplitude and the shape). However, there is the other crucial problem that also distorts the measured waveform, infidelity effect [6-8] (also known as nonlinear response to a strain). Because of the infidelity effect, different optical frequnecies respond to the strain differently, which generates undesired spurious vibration peaks that do not really exist on the sensing fiber. This lowers the spurious free dynamic range of the measurable vibration severely. Although this problem is common among many methods in FDM-based sampling-rate-enhanced (SRE) Φ-OTDR, this problem has not been fully considered up to now. In this work, we propose a method to suppress the infidelity effect without changing the system complexity that does not need prior knowledge of the vibration. By the proposal, we experimentaly demonstate the suppression of the spurious peaks and the improvement of the dynamic range with the use of the sensing fiber over 10 km and the vibration with the amplitude of nε-level.

2. Principle

2.1. Impact of infidelity effect in FDM-based sampling-rate-enhanced (SRE) Φ-OTDR

In FDM-based SRE Φ-OTDR, different optical frequency components monitor a vibration at different timings. By concatenating their phases, we can increase the sampling rate. When the sampling rate is enhanced by N (= the number of multiplexed frequencies), the concatenated phase is calculated in the uniform sampling case as

$$\theta\left(nt,z\right)=\theta_i\left(\left(i+mN\right)t,z\right)=A_i(z)\cdot s\left(\left(i+mN\right)t,z\right)+B_i(z)\left(n,m\in\mathbb{Z}\right)\text{when } n\equiv i\left(\operatorname{mod}N\right), \tag{1}$$

where t is time interval between adjacent pulses, z is fiber length from the input end, θ_i is phase of frequency f_i. Integer m is chosen such that the equation holds. Function $s(nt, z)$ expresses the vibration in units of strain [ε], A_i is conversion coefficient from stain [ε] to phase [rad], and B_i is the phase offset. Since B_i has random value, it yields distortion (frequency is $1/Nt$). The countermeasure of previous work [5] adds the complematary frequency f_c to the main frequnecies f_i. By using both signals, θ_i is replaced by $\theta_i + B_c - B_i$, where B_c is the offset of f_c. As a result, all main frequencies offsets are corrected, as visualized in Fig. 1 (a). If the infidelity effect did not exist, A_i can be considered independent of f_i in practice, so the correct waveform can be obtained by the offset compensation. However, in real measurements, the infidelity effect is significant. Here, the infidelity effect means a nonlinear response of the phase to a strain; it is caused by interference between scattered lights within the pulse width. Due

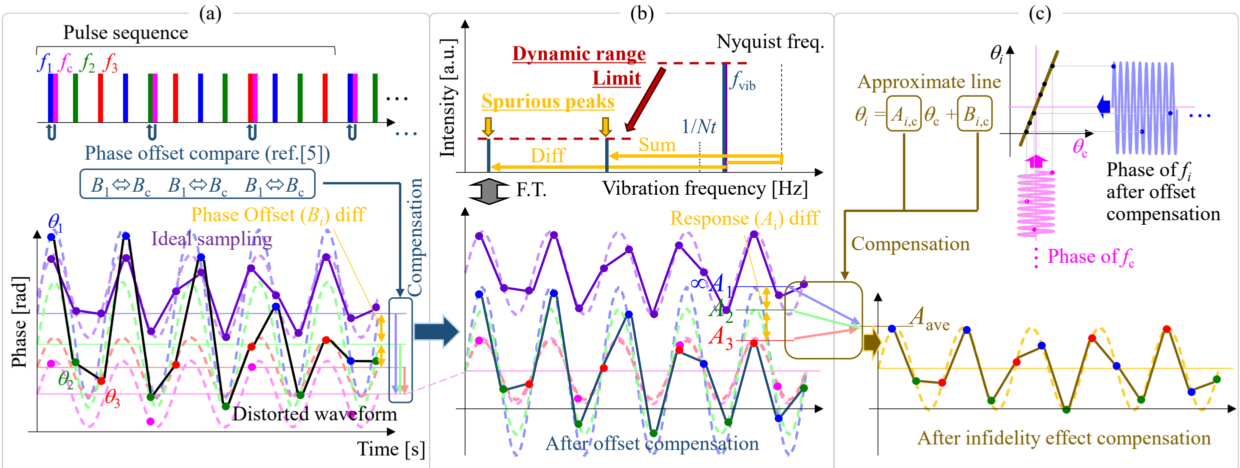

Fig. 1. (a) Phase offset compensation. (b) Impact of infidelity effect. (c) Simplified procedure of the proposal

to the infidelity effect, the responses of the different optical frequencies to a strain are not the same [6-8]. This effect can be taken into consideration by using different values of A_i (but indepent of s) as a first approximation. Depndence of A_i on f_i leads to another distortion, which cannot be eliminated by the phase offset compensation. For example, when detecting sinusoidal waveform having the frequency of f_{vib}, the difference in A_i can generate undesired spurious components with the frequencies of the sum and the difference of f_{vib} and $1/Nt$, as illustrated in Fig. 1 (b). These undesired spurious peaks, which do not really exist, degrade the spurious free dynamic range of measurable vibration. Up to now, this problem has not been adequately addresed in FDM-based SRE Φ-OTDR studies. Therefore, a sophisticated infidelity effect suppression technique is needed for FDM-based SRE Φ-OTDR that does not alter system complexity.

2.2. Suppressing the infidelity effect by post signal processing

The essence of the phase offset compensation is to relate the phase offsets of the main frequencies through comparison between the phase offsets of each main frequnency and the complementary one. With the same analogy, our proposal suppresses the infidelity effect by comparing the responses of each frequency and the complementary one. Such comparison is possible without changing the system configuration based on the key fact that f_c component also trackes the vibration. While this phase information of f_c is not fully utilized in the previous work [5], this paper takes full advantage of it. At the time of $T_i(k) = [i+(i-1)N+N(N+1)k]t$ (k is an arbitrary integer), f_i and f_c components are simultaneously launched, so they capture the same strain $s(T_i(k))$. If we denote $\theta_c = A_c s + B_c$ as in (1), θ_i is expressed after phase offset comensation as

$$\theta_i\left(T_i\left(k\right),z\right)=\frac{A_i(z)}{A_c(z)}\theta_c\left(T_i\left(k\right),z\right)-\frac{A_i(z)}{A_c(z)}B_c(z)+B_c(z)=A_{i,c}(z)\cdot\theta_c+B_{i,c}(z), \tag{2}$$

where $A_{i,c}$ is response ratio and $B_{i,c}$ is relative offset. In (2), f_c component doesn't need to sample the vibration above the Nyquist frequnecy, so no additional arrangement is necessary. The vibration, through the variation of s, changes both θ_i and θ_c. Therefore, by plotting (θ_c, θ_i) of different times in 2D plane and calculating the approximate line, we get $A_{i,c}$ and $B_{i,c}$. By using them and the mean of $A_{i,c}$ as to i (denoted as $A_{ave,c}$), we modify θ_i as

$$\alpha_i\left(\left(i+mN\right)t,z\right)=\frac{\theta_i\left(\left(i+mN\right)t,z\right)-B_{i,c}(z)}{A_{i,c}(z)}A_{ave,c}(z)=A_{ave}\cdot s\left(\left(i+mN\right)t,z\right)+A_{ave}\cdot B_c, \tag{3}$$

where α_i is the modified phase and A_{ave} is the mean value of A_i. The simplified schematic is shown in Fig. 1 (c). This procedure is simple but effective in compensating the infidelity effect as shown in the rightmost side of (3). The response A_{ave} no longer depends on i, so the problem of the response difference is solved. Furthermore, A_{ave} is the average response of main frequnecies, so α changes are a more realiable indicator of strain. In addition, the offset of $A_{ave}B_c$ does not depend on i, causing no further distortion. Therefore, the proposal can compensate the impact of the infidelity effect. Since the proposal doesn't need the prior knowledge of vibrations beforehand, it is applicapable to measuring unknown vibrations.

3. Experimental demonstration

The experimental setup was the same as used in the previous work [5]. Pulse sequence and fiber-under-test (FUT) are shown in Fig. 2 (a). Optical fiber stretcher (OFS) was placed (10 km from the input end) on the FUT, which experienced the sinusoidal vibration (7 kHz, 30 nε). Fading-suppressed signals were first calculated, then the phases were concatenated to increase the sampling rate by three (N = 3). Gauge length was set to 10 m. Fig. 2 (b) shows PSD of a measured waveform after the phase offset compensation without the proposal at a position on the FUT as an example. In Fig. 2 (b), undesired non-negligible peaks of the diff- and sum- frequencies between 7 kHz (= f_{vib}) and 6.66 kHz (= $1/Nt$) appeared at 0.33 kHz and 6.33 kHz. In the proposal, (θ_c, θ_i) were plotted, from which the approximate lines were calculated, as shown in Fig. 2 (c). Difference in the slopes and the intecepts are manifestation of the difference in the responces of f_i to the strain. Based on (3), the modified phase α was calculated. Fig. 2 (d) shows PSD of the waveform as determined by α; the undesired peaks were successfully suppressed by ~ 7 dB to almost the noise floor. Fig. 2 (e) shows PSD maps around OFS with/without the proposal. As shown in Fig. 2 (e), the proposed scheme was effective over the entire section of OFS, which shows the robustness of the proposal.

4. Conclusions

For the first time, we proposed a simple but effective method for compensating the infidelity effect, which is a common problem in FDM-based SRE Φ-OTDR. Key procedure is to relate and average the responses of the main frequencies without increasing the system complexity by fully utilizing the complementary frequency phase information. We demonstrated the validity of the proposal along the FUT with the length over 10 km. Proposal doesn't need prior knowledge of the vibations, so it may further broaden the measurable waveforms of Φ-OTDR.

5. References

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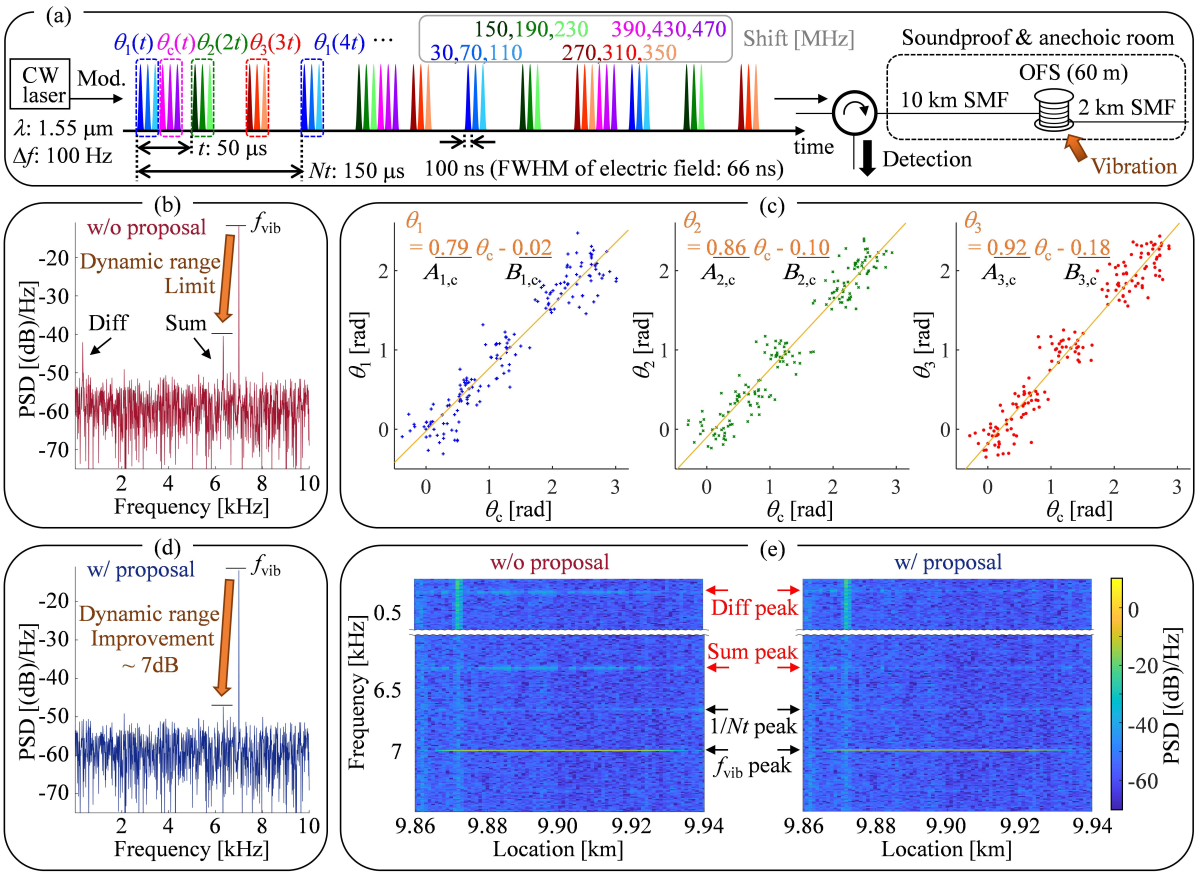

Fig. 2 (a) Pulse setting and FUT. (b) PSD at the place on OFS without the proposal. (c) Linear fitting process in the proposal. (d) PSD of the modified phase by the proposal. (e) PSD maps around OFS.