Investigation of Tolerance of OFDR-Based DAS to Vibration-induced Beat Frequency Offset

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Abstract: We investigate the statistical property of Rayleigh backscattered light to confirm the tolerance to vibration-induced beat frequency offset, which forces us to interrogate an unintentionally-positioned sensor. A long sensor is capable of measuring vibrations correctly.

1. Introduction

Distributed acoustic sensing (DAS) based on optical fiber reflectometry of Rayleigh backscattering is highly sensitive to vibration. The high sensitivity allows us to utilize a deployed optical fiber inside the cable, which receives attenuated vibration thanks to a protective outer sheath, as an array of virtual vibration sensors and specify locations of inappropriate optical cable deployments by distinguishing normal and distinctive vibration waveforms [1]. Different kinds of optical fiber reflectometry exist that can interrogate virtual vibration sensors, and several methods have been studied [2,3]. Optical frequency domain reflectometry (OFDR) can measure the optical spectrum of Rayleigh backscattered light from a local section of the fiber and can provide spectroscopic vibration measurements in which the local optical spectrum, whose spectral shift is proportional to strain, is utilized for vibration sensing [4,5]. However, the fine frequency resolution of OFDR, given by the reciprocal of measurement time for beat signal, degrades distributed measurement performance. Vibration that occurs at a preceding location provides a slight frequency modulation to the light propagating in the following segment, and the mapping between beat frequency and distance at that segment fluctuates in a way similar to that found in the distance measurement of a moving target in FMCW [6]. The fluctuation in beat frequency–distance mapping forces us to interrogate an unintentionally-positioned sensor whose optical spectrum is not correlated to that of the target sensor, and the spectrum shift between the uncorrelated spectra, which is calculated by cross-correlation, results in measurement error in DAS. A deployed optical fiber cable has many vibration sources along its length making application of OFDR to a deployed cable would suffer from the vibration-dependent unintentional interrogation. For interrogating the target sensor even when the beat frequency – distance mapping fluctuates, distance tracking of the target sensor by digital signal processing has been demonstrated [7], but the signal processing load is heavy and an obstacle to realizing real-time measurement.

In this work we investigate numerically the statistical property of the local optical spectrum to confirm the tolerance to the beat frequency offset, and verify OFDR-based DAS measurements with the tolerance. A long sensor length has the tolerance and measures correctly vibrations along the fiber. The beat frequency offset caused by intermediate vibration is inevitable in practical applications, and this investigation of the tolerance is useful for optimizing the design methodology for OFDR-based DAS.

2. Simulation of tolerance to vibration-induced beat frequency offset

We discuss the statistical property of the optical spectrum of Rayleigh backscattered light from a local section of an optical fiber. Vibration in the intermediate section frequency-modulates the light propagating through the section, and a frequency-swept light is frequency-shifted when the frequency sweep time of the light is much shorter than the vibration period. Thus, the beat frequency–distance mapping in following section deviates from the mapping predefined in the OFDR measurement setup [7].

$$z = \frac{c}{2\gamma}(f_{\mathrm{beat}} + \nu_{\mathrm{offset}}), \quad z_{\mathrm{offset}} = \frac{c}{2\gamma}\nu_{\mathrm{offset}}, \tag{1}$$

where z is the distance measured with OFDR, c is the speed of light in the optical fiber, γ is the frequency sweep rate, f_{beat} is the beat frequency between a local light and backscattered light without vibration-induced frequency modulation, and ν_{offset} is the instantaneous frequency modulation by the vibration (source of the vibration-induced beat frequency offset). The first and second terms in (1) are the mapping predefined in the measurement setup and the distance offset caused by vibration, respectively. Since a vibration analysis of the optical spectrum of Rayleigh backscattered light utilizes the optical spectrum at a certain distance, which is defined by (1), the distance offset changes the spectrum analysis section. The optical spectrum of the Rayleigh backscattered light is analysed by using

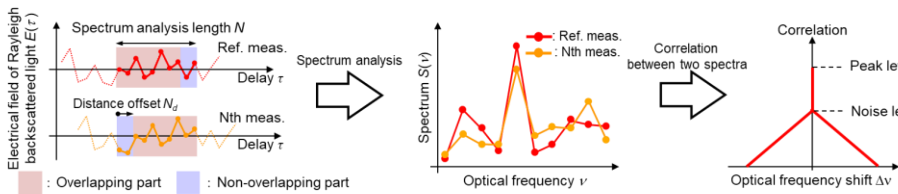

Fig. 1. Correlation between optical spectra with and without the distance offset.

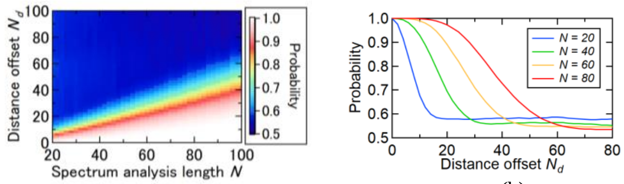

Fig. 2. (a) Simulation of tolerance to vibration-induced distance offset and (b) tolerance function of distance offset for various spectrum analysis lengths.

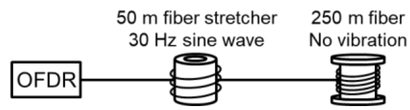

Fig. 3. Experimental setup.

the square of the absolute value of the Fourier transform [4].

$$S_{\mathrm{ref}}(\nu) = \frac{1}{N}\left|\sum_{n=1}^{N} E(\tau_n)\exp(-j2\pi\nu\tau_n)\right|^2,\;\; S_{\mathrm{sig}}(\nu) = \frac{1}{N}\left|\sum_{n=N_d+1}^{N_d+N} E(\tau_n)\exp(-j2\pi\nu\tau_n)\right|^2, \quad (2)$$

where $S_{\mathrm{ref}}(\nu)$ is the optical spectrum of the target sensor as determined by reference measurement, $S_{\mathrm{sig}}(\nu)$ is the optical spectrum of the sensor as measured in the Nth measurement, ν is the optical frequency, $E(\tau_n)$ is the electrical field of the Rayleigh backscattered light, τ_n is the delay related to the distance z_n by $\tau_n = 2z_n/c$, N is the spectrum analysis length (the window length of the Fourier transform), and N_d is the distance offset caused by vibration. The analysis sections with and without the distance offset overlap which permits construction of the correlated spectrum, and the non-overlapping parts yield the uncorrelated spectrum. The uncorrelated spectrum generated by the distance offset decreases the peak of the cross-correlation between the two spectra as shown in Fig. 1. When the peak level falls to the noise level due to the distance offset, the correct frequency shift caused by strain cannot be obtained and a false frequency shift occurs, which leads to measurement error. To evaluate the tolerance to the distance offset, we simulated the probability of the peak level being higher than the noise level by the Monte-Carlo technique in which the electrical field of the Rayleigh backscattered light is a random variable that follows a zero-mean Gaussian distribution [8,9]. The simulation has two parameters: spectrum analysis length N and distance offset N_d.

Figure 2 shows a simulation result. Note that the probability clarifies how many sections the distance offset is acceptable; it does not clarify where the non-acceptable sections are. The probability value of 1 is necessary to suppress the measurement error caused by the distance offset and obtain reliable measurement results along the fiber being measured. A larger spectrum analysis length increases the tolerance since it increases the length of overlap section, which yields the correlated optical spectrum. There is a trade-off between the tolerance and spectrum analysis length, or spatial resolution for vibration measurements. The simulation results give us a design understanding of the distance offset tolerance. For example, if the design goal is the distance offset tolerance of 10 cm, which corresponds to the beat frequency offset of 5 kHz by a measurement setup with OFDR spatial resolution of 1 cm (10 GHz frequency sweeping) and 5 GHz/ms frequency-sweep rate, the length of minimum spectrum analysis with acceptable tolerance is 80 cm. Although degradation in the spatial resolution from the original resolution of OFDR due the vibration is inevitable for ensuring adequate tolerance, shortening the measurement time of the beat signal which ameliorates beat frequency sensitivity [7], mitigates the degradation.

3. Experiment

To validate the tolerance indicated by the simulation we conducted a distributed acoustic measurement. Figure 3 shows the experiment setup. The fiber was composed of an intermediate vibration section (vibration frequency of 30 Hz) and a following section with no vibration. The vibration imposed distance offset on the measurements of the following section, and the distance offset measured by the signal processing technique of distance tracking [7] was 26 cm amplitude with 30 Hz; this distance offset corresponds to $N_d = 17$. The OFDR setup was almost the same as in [7]. The frequency-sweep rate was 8 GHz/ms, measurement time of the beat signal was 0.8 ms, and repetition rate of the frequency-sweep light was 900 Hz. The vibrations along the fiber were analysed by calculating frequency shifts relative to the reference optical spectra measured in the non-vibrated state. The spatial resolutions for vibration were 47 and 141 cm, which correspond to spectrum analysis lengths N of 30 and 90, respectively. We evaluated the tolerance by counting the number of following sections that had cross-correlation peaks with frequency shift of 0 Hz.

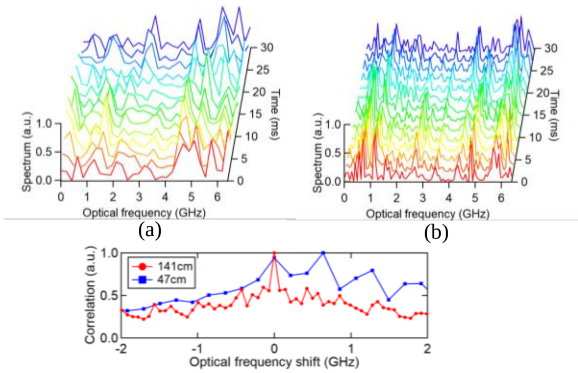

Fig. 4 Typical measurement result at 150 m with spatial resolutions of 47 cm and 141 cm. Spectrograms of Rayleigh backscattered light with (a) 47 cm and (b) 141cm lengths. (c) Cross correlation between reference and 11th measurement (12 ms) with 47 cm and 141 cm lengths.

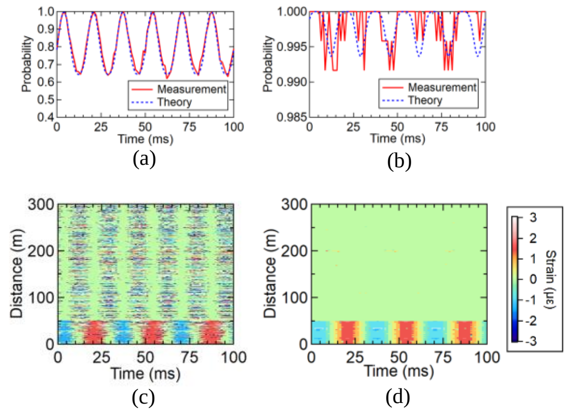

Fig. 5. Frequency of correct measurement results being obtained with spatial resolutions of (a) 47 cm and (b) 141 cm. DAS measurement result with spatial resolutions of (c) 47 cm and (d) 141 cm.

Figure 4 shows an example of the vibration measurement results from the non-vibrated 150 m section. The spectrogram analysed with 47 cm spatial resolution exhibits temporally unstable spectra and this temporal evolution of the spectrum differs from the actual state. The cross correlation with the unstable spectra is useless in terms of calculating the frequency shift and leads to measurement error. On the other hand, the spatial resolution of 141 cm shows a stable spectrum for each measurement and the cross correlation with the reference spectrum shows a clear correlation peak whose frequency shift is in accordance with the actual state. Figure 5 shows the frequency with which the cross correlation peak level at frequency shift of 0 Hz was larger than the noise level as well as the vibration measurement results along the fiber, which were obtained using a conversion coefficient from optical frequency shift to strain of 152 MHz/με [10]. Since the distance offset, or beat frequency offset, is an instantaneous frequency induced by the preceding vibration, the theoretical value varies sinusoidally with time. When the amplitude of the preceding vibration is around zero that induces the maximum instantaneous frequency, the occurrence frequency has a minimum value. The occurrence frequency in each spatial resolution is in good accordance with the theoretical curves and shows that longer spatial resolution values yield more tolerance to the distance offset. Good agreement was also obtained in other experiments such as different distance offsets and analysis lengths. The agreement between the simulation and experiment confirms that the tolerance value given by the simulation is useful in system design. In this experiment, the spectrum analysis length of 141 cm is needed to ensure adequate tolerance because the vibration of the unit lengths on the fiber stretcher is synchronous and the vibration-induced frequency offset accumulates along the fiber. In practical applications, the vibration is assumed to be asynchronous along the fiber, and this mitigates the required tolerance. For instance, the vibration measurement of an aerial cable vibrating with the wind was demonstrated to be a practical application for outside plant monitoring [1]. The vibration spatial resolution achieved was 66 cm and the measurement result showed sufficient tolerance to suppress the measurement error caused by the preceding vibration. A long spatial resolution is needed to achieve adequate tolerance but we can apply OFDR-based DAS to outside plant monitoring without losing the good spatial resolution of OFDR.

4. Conclusion

We have investigated numerically and experimentally the tolerance to the distance offset induced by preceding vibration in OFDR-based DAS. Increasing the optical spectrum analysis length of Rayleigh backscattered light yields a longer analysis section overlap which ensures adequate tolerance. Numerical results well supported the experimental results. Since the distance offset induced by vibration is inevitable, especially when applied to deployed telecom optical cable that has many vibration sources along the cable, this investigation provides the basis for a design methodology of system tolerance.

5. References

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