Broadening frequency response of distributed sparse-wideband vibration sensing via time-division multi-frequency sub-Nyquist sampling

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Abstract: A sub-Nyquist sampling sequence with an average repetition rate less than 5-kHz can be efficiently utilized to detect 24-kHz sparse-wideband vibration signal along 4.5-km sensing fiber and recover its frequency information via compressive sensing technique. © 2020 The Author(s)

1. Introduction

Distributed vibration sensing technology has attracted intensive attention over the past several decades due to its unique properties [1-7] due to its unique properties such as immunity to electromagnetic interference and harsh environments, high sensitivity, and low cost. In q-OTDR system, spatial resolution [2], sensing fiber length [3-4] and frequency response ranges [5-6] are main parameters for evaluating the system performance. It is crucial for the maximum frequency response and sensing fiber length to satisfy the requirements of practical applications. It is well known that the maximum frequency response is inversely related with the sensing fiber length. Higher response frequency can be obtained by decreasing the sensing distance.

A novel method is demonstrated to broaden the frequency response of the distribution vibration system using a time-division multi-frequency sub-Nyquist sampling sequence, so that a multi-frequency sub-Nyquist sampling is realized along every sensing point of the interrogation fiber. In some cases, the vibration signals are sparse in frequency domain, which provides an opportunity for the q-OTDR system to reconstruct sparse signals with low pulse repetition rates. The proposed method is able to sample the wide-band sparse signals with a sub-Nyquist sampling sequence and reconstitution signal via compressive sensing technique [7]. Experimental results verify that sparse vibration signals with frequencies up to 24-kHz can be detected along 4.5-km sensing fiber by using the sub-Nyquist sampling sequence with an average pulse repetition rate less than 5-kHz. The proposed method can break through the theoretical maximum detection frequency of traditional q-OTDR system without any hardware modification compared to conventional method. Therefore, such a method is of great significance for broadening the frequency response range of the distributed sparse-wideband vibration sensing.

2. Tables and Figures

The experiment setup of q-OTDR system is shown in Fig.1 (a). A planar external cavity low-noise laser with 10mW output and a line-width less than 5-kHz is applied as the optical source of system. The continuous-wave light from the laser is modulated by an acoustic optical modulator (AOM) driven by an arbitrary function generator (AFG). Then the first erbium-dope fiber amplifier (EDFA) is used to amplify the modulated light for compensating a large insertion loss of the AOM. Modulated light is launched into 4.5-km sensing fiber (SF) via an optical circulator (CIR). A PZT cylinder is used as the vibration source and put at the location of 2.5-km along the sensing fiber in our q-OTDR system, which is driven by another arbitrary function generator. The backscattered Rayleigh signal is amplified by another EDFA and detected by using a balanced photo-detector. Finally, the backscattered Rayleigh signals are collected by a high-speed oscilloscope.

Uniform sampling that satisfies the traditional Nyquist sampling theorem is given in Fig.1 (b). Continuous optical pulses with constant repetition rate \( f \) are injected into the sensing fiber to detect the frequency response. The maximum sampling rate (or pulse repetition rate) \( f_{\text{max}} \) in \( q \)-OTDR system is determined by the length of sensing fiber \( f_{\text{max}} = c/2Ln_e \), where \( c \) is the speed of light in vacuum, \( L \) and \( n_e \) are the length and the effective index of the sensing fiber. Generally, the sampling rate needs to be several times larger than the frequency of the signals under test for better quality of signal reconstruction. Therefore, this method will cause heavy burdens on the information storage and signal processing. Limited by the Nyquist sampling theorem the maximum frequency of the signal under test should be band-limited within half of \( f_{\text{max}} \) to avoid frequency aliasing. In order to improve the frequency response, a time-division multi-frequency sub-Nyquist sampling method is proposed to solve the above problems by using a combination of pulse trains with different repetition rates as shown in Fig.1 (c). In the proposed method,
several optical pulse trains, each with a unique repetition frequency \( f_i \), are injected into the fiber under test. It is worth noting that \( f_i \) is much smaller than the traditional maximum sampling rate \( f_{\text{max}} \).

![Image](figure1.png)

Fig. 1. (a) \( \Phi \)-OTDR system setup. (b) Pulse train applied in traditional uniform sampling method. (c) Pulse train applied in the proposed method. Generally, \( f_i \) represents different pulse repetition rate and is far less than \( f_{\text{max}} \). \( \Delta t_i \) remains the same within the \( f_i \) pulse train

In order to prove that the presented method has the ability to detect the higher frequency response without any hardware modification compared with the conventional method, the multi-frequency sub-Nyquist sampling sequence is modulated and launched into the sensing fiber. A driving signal with a frequency of 24-kHz is applied to the PZT in our experiment. Then, the vibration signal is sampled by the multi-frequency sub-Nyquist sampling sequence and the detail of measurement result is shown in Fig. 2. The vibration position information can be identified easily by the sub-Nyquist sampling in Fig 2.(b). The spectrum of the reconstructed signal at the vibration position by the OMP algorithm based compressive sensing theory is shown in Fig 2. (b). An obvious frequency peak, which agrees well with the vibration signal applied in the \( \Phi \)-OTDR system, can be discerned in the spectrum information. Therefore, the proposed scheme is able to break through the theoretical tradeoff between maximum detectable frequency and the length of sensing fiber by using multi-frequency sub-Nyquist sampling sequence with several different repetition frequencies that are less than 5-kHz without any hardware modification compared to that of the conventional method.

![Image](figure2.png)

Fig.2. The position and spectrum information of vibration signal at vibration position obtained by the sub-Nyquist sampling. (a) shows the position information of vibration signal. (b) shows the spectrum of the reconstructed signal.

3. References

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