Signal-to-noise ratio enhancement of Φ-OTDR based on Block-matching and 3D filtering

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***Abstract*—Aiming at successful vibration extraction of Φ-OTDR under the condition of low signal-to-noise ratio (SNR), a differential intensity image denoising scheme based on Block-matching and 3D filtering (BM3D) is proposed. The correlation of data in time domain and space domain was utilized for denoising, which reduces noise significantly while retaining rich details. Distributed vibration sensing with a spatial resolution of 20 m over a 50 km distance was realized in the experiment. The SNR at the end of the optical fiber was increased from close to 0 dB to 37.2 dB.**

Keywords— Φ-OTDR, BM3D, signal denoising

I. INTRODUCTION

Phase-sensitive optical time-domain reflectometer (Φ-OTDR) has attracted extensive attention due to its capability of detecting weak disturbances along optical fibers. To investigate the performance of Φ-OTDR, signal to noise ratio (SNR) is a key factor which determines the sensing distance, the sensitivity and accuracy. In recent years, researchers have proposed a number of ways to improve the SNR. The straightforward method is to increase the signal power at the receiver. Ways like second-order Raman amplification[1], RP-EDFA [2], etc. have been proposed based on this. On the other hand, reducing the system noise can also improve the SNR, such as using PMFs [3] or auxiliary weak reflection points in the fiber [4]. But all of these methods add more devices to the traditional Φ-OTDR, increasing the cost and complexity of the system.

In recent years, with the continuous upgrading of noise reduction algorithms, more and more algorithms have been proposed to improve the SNR of φ-OTDR in the digital domain. A method based on two-dimensional edge detection was proposed. The value of each pixel of gray image is calculated by the convolution of Sobel operator, and the SNR is increased to 8.4 dB [5]. Two-dimensional bilateral filtering (BLF) whose adaptive parameter algorithm has stronger robustness, was also applied in Φ-OTDR to successfully improve the SNR by 14 dB [6]. As a classical image denoising algorithm, the parameter optimization of Non-Local Means (NLM) in Φ-OTDR was also investigated, which effectively improves the accuracy of measurement and positioning [7]. Deep learning algorithm is also widely used in this aspect. Adaptability deep learning temporal-spatial detection (DL-TSD) algorithm was proposed to improve the SNR of vibration signal to 38.49 dB [8]. Another deep learning algorithm based on image semantic segmentation is used to extract vibration signals, which successfully improves the vibration SNR to 32.17 dB at 40 km in [9]. Although the performance of deep learning based denoising is better than that of traditional algorithms, deep learning requires a large number of data sets for its training and the training model will change for different sensing scenarios, which increases the complexity of digital signal processing (DSP).

In this paper, we apply BM3D algorithm to image denoising Φ-OTDR signals for the first time. The vibration sensing over 50 km with 20 m spatial resolution is realized without using any additional equipment. Comparing with other traditional image processing algorithms, this algorithm performs better than others especially in extremely low SNR environment. Moreover, it can reach the same denoise performance as deep learning does but its operation is easier.

II. PRINCIPLE

BM3D is one of the most effective image denoising algorithms, which was first proposed in 2006 [10]. It is a denoising algorithm based on block matching to realize grouping and realize cooperative filtering by shrinking in the 3D transform domain. The flowchart of denoising Φ-OTDR using BM3D in this work is shown in Fig. 1. In the use of BM3D for denoising Φ-OTDR, we take the 2D map of consecutive differential Φ-OTDR traces after intensity demodulation as the input image. The longitudinal axis and horizontal axis are the trace number and position of differential Φ-OTDR signals, respectively. BM3D image denoising has two stages, each of which consists of three steps: grouping, collaborative filtering and aggregation. First, matching blocks M, which are similar to the reference block R, are found in the image and integrated into 3D array. After 3D transformation, hard threshold filtering (Wiener filtering in the second stage) and anti-3D transformation of the 3D array are applied. The processed blocks are returned to their original position in the image. Finally, the real image is estimated by a weighted average of all the obtained overlapping block estimates (the estimated result of the first stage and the original noise image as the input of the second stage).

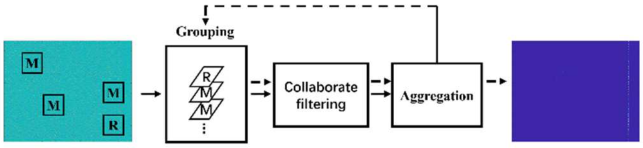

Fig. 1 Flowchart of the proposed BM3D denoising for Φ-OTDR

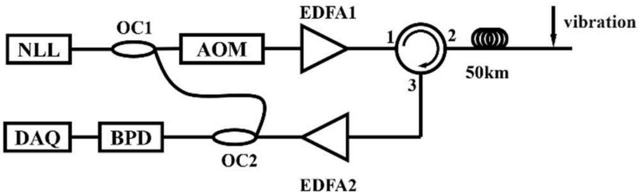

Fig. 2 Φ-OTDR experiment setup. EDFA: erbium-doped fiber amplifier, NLL: Narrow linewidth laser, OC: Optical coupler, AOM: Acousto-optic modulator, BPD: Balanced photodetector, DAQ: Data acquisition.

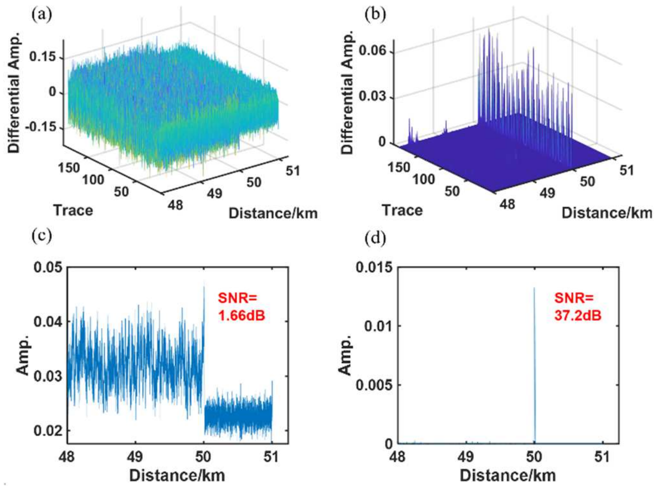

Fig. 3 Raw differential data and BM3D processing results. (a)Three dimensional differential amplitude image after demodulation. (b)Three dimensional differential amplitude image after denoising. (c)Localization curve of original signal. (d)Localization curve of denoising signal.

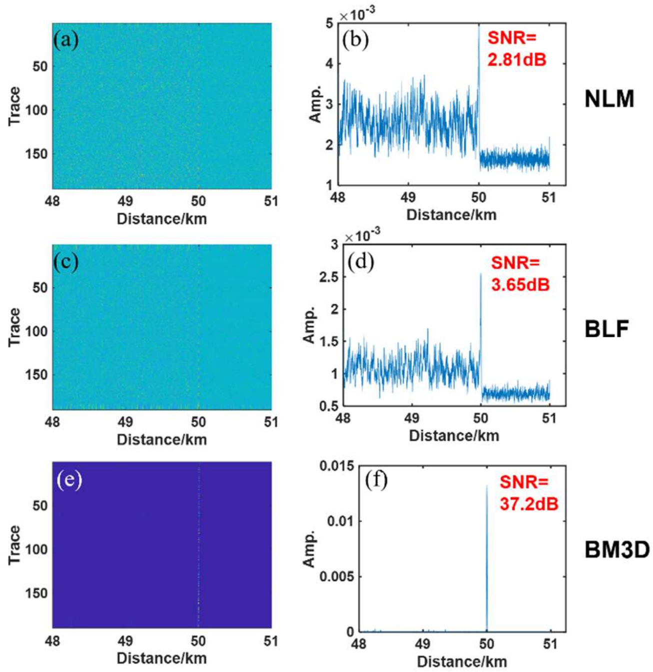

Fig. 4 Comparison of noise reduction performance of different algorithms. (a) Two-dimensional amplitude image after NLM denoising. (b)Localization curve after NLM denoising. (c)Two-dimensional amplitude image after BLF denoising. (d)Localization curve after BLF denoising. (e)Two-dimensional amplitude image after BM3D denoising. (f)Localization curve after BM3D denoising.

III. EXPERIMENT AND RESULTS

The Φ-OTDR system used in this experiment is shown in Fig. 2. A narrow linewidth laser is used as the light source which is divided by a 99:1 optical coupler. 99% of the light is modulated by AOM into an optical pulse with a repetition rate of 1kHz and pulse width of 200 ns . The other 1% is used as a reference light. The modulated pulse light is amplified by an EDFA and injected into a 50km single-mode test fiber by the circulator. To stimulate the vibration signal, the end 5 meters of the fiber is wound on the PZT which is driven by a sinusoidal wave. The Rayleigh backscattered light goes through a circulator and beats with the local oscillator light, which is then detected by a balanced photodetector, and collected by the acquisition card. After demodulation, the differential intensity image is obtained as the input of the subsequent algorithm.

Fig. 3 (a) shows the input image constituted by 200 differential Rayleigh backscattered intensity curves corresponding to the final ~3 km of FUT. It can be seen that the original SNR in this experiment is very low. The localization curve, which is obtained by averaging the absolute value of each trace at the same location, is shown in Fig. 3 (c). The SNR is 1.66 dB, which is calculated as follows [6]:

$$SNR = 10log_{10}\left(\frac{peak\ value}{RMS(noise)}\right) \qquad (1)$$

With such a low SNR, it is difficult to either accurately judge the occurrence of vibration or locate it. However, as shown in Fig. 3 (b), with the use of BM3D, the vibration position after denoising is clearly observed and consistent with the actual vibration position without deviation. The localization curve is shown in Fig 3 (d). Compared with the original signal, BM3D effectively achieves vibration signal

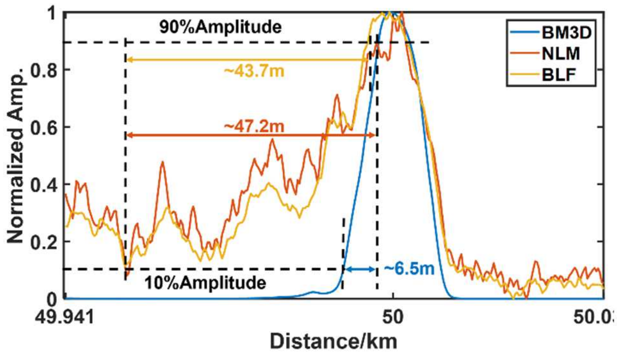

Fig. 5 Spatial resolution after processing by the three algorithms

extraction and SNR enhancement. The SNR is improved by 35.5dB.

In this work, BM3D is also compared with the classical image denoising algorithms NLM [7] and 2D bilateral filtering(2D-BLF) [6] to demonstrate the advantages of BM3D under the low SNR conditions. The results of image noise reduction performance of these three algorithms are shown in Fig. 4, where Fig. 4 (a) (c) (e) show the time and spatial image of Φ-OTDR after processed by the three algorithms and Fig. 4 (b) (d) (f) show the corresponding SNR of signal trace. The SNRs obtained by NLM, 2D-BLF and BM3D are 2.81 dB, 3.65 dB and 37.2 dB, respectively. It is obvious that under low SNR conditions, the SNR improvement of other algorithms is rather limited, but BM3D still maintains very good performance, which indicates that BM3D is significantly better than the other two algorithms.

We finally compare the performance of spatial resolution by using these three algorithms. From Fig.5, we can see NLM and BLF algorithms cause the loss of details in denoising at low SNR. This induces signal distortion and an increase in spatial resolution. The width from 10% to 90% of the peak intensity achieved by NLM and BLF are ~47.2 m and ~43.7 m. In contrast, it is only ~6.5 m for BM3D. Considering that the theoretical limit of spatial resolution determined by the pulse width in this work is 20 m, it is obvious that BM3D can effectively reduce noise while preserving image details.

IV. CONCLUSION

In this paper, we first proposed and verified an SNR enhancement technique based on BM3D for the circumstances of extremely low SNR Φ-OTDR signals. The sensor with optical fiber length of 50 km and spatial resolution of 20 m was tested without adding any hardware, and the SNR of 37.2 dB was obtained at the end of the optical fiber. We show that BM3D provides much better noise reduction performances than traditional image denoising algorithms do while the processing procedure is much simpler compared with those deep learning based methods. We believe that it can be applied to largely improve the SNR performance of Φ-OTDR, leading to the detection of minor vibrations or the extension of sensing distance.

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