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Application of a New Wavelet Denoising Method in Optical Fiber Strain Measurement

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Abstract The Brillouin distributed optical fiber sensing technology can measure the optical fiber strain, but the measurement precision is affected by noise easily. So a new method of wavelet denoising is developed to enhance the measurement precision of optical fiber strain. The new method not only takes the wavelet transform detail coefficients to threshold quantification, but also removes the noise from the approximation coefficients. So the new method can also obtain high precision Brillouin spectrum with fewer decomposition scales as the signal-to-noise ratio (SNR) of Brillouin spectrum is low. The research results show that the method can reduce the Brillouin spectral noise effectively. Compared with the conventional wavelet denoising method, the new method can decrease the wavelet transform calculation and the denoising effect is better, so the optical fiber strain measurement is more accurate.

Key words fiber optics; denoising; Levenberg-Marquardt method; optical fiber sensor

OCIS codes 060.2330; 060.2400; 060.4510

新型小波去噪法在光纤应变测量中的应用

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摘要 布里渊分布式光纤传感技术能够测量光纤的应力分布，然而测量精度易受噪声的影响。为了提高光纤应力的测量精度，提出一种新的小波去噪方法。新方法不仅把小波分解的高频系数进行阈值量化，而且也对小波分解的低频系数进行了去噪处理。因此，当布里渊谱的信噪比(SNR)较低时，新方法能够以较少的小波分解尺度获得高精度的布里渊谱。研究结果表明，新方法能够有效减小布里渊谱的噪声。与传统小波去噪方法相比，新方法不仅减少了小波变换的计算量，而且去噪效果更好，因此获得的光纤应力也更准确。

关键词 光纤光学；去噪；Levenberg-Marquardt 算法；光纤传感

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1 Introduction

Optical fiber has enormous bandwidth, so it has wide applications in high speed optical communication[1,2]. However, the performance of optical fiber transmits signal is easily affected by the optical fiber strain, caused by construction, mountain deformation and so on[3,4]. Accordingly the measurement of optical fiber strain is necessary.

The Brillouin distributed optical fiber sensing technology can be used to analyze Brillouin spectral frequency shift, which is caused when optical wave transmits in the optical fiber. And it can obtain the distribution of the optical fiber strain[5~7], which has extensive applications in the monitor of optical fiber state. However, sometimes the Brillouin spectrum inevitably interfuses a large amount of noise due to the effect of the optical fiber components in actual applications[8], which makes the conventional wavelet denoising method not well adaptive, so the measurement precision of optical fiber strain is influenced. Therefore, a new wavelet denois-

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ing method based on the characteristic of Brillouin spectrum is proposed. The new method can not only decrease the wavelet decomposition scales effectively, but also obtain the high precision Brillouin spectrum even when the signal-to-noise ratio (SNR) of Brillouin spectrum is low, so it ensures the exact measurement of optical fiber strain preferably.

2 Denoising technology

The conventional wavelet denoising process is as follows:

1) Select the wavelet series ψ and the decomposition scales, and then the wavelet transform of Brillouin spectrum $f(t)$ are given by:

$$W(a,b) = |a|^{-1/2}\int_R f(t)\psi^*\left(\frac{t-b}{a}\right)\mathrm{d}t, \qquad (1)$$

Where $*$ is the complex conjugate symbol, a is the flex factor, b is the shift factor.

2) Select the soft threshold algorithm or hard threshold algorithm to threshold quantification for wavelet decomposition detail coefficients of each scale. The soft threshold algorithm is expressed in formula (2) and the hard threshold algorithm is expressed in formula (3):

$$s = \begin{cases} \mathrm{sign}(x)(|x| - x_0), & |x| > x_0 \\ 0, & |x| \leqslant x_0 \end{cases}, \qquad (2)$$

$$s = \begin{cases} x, & |x| > x_0 \\ 0, & |x| \leqslant x_0 \end{cases}, \qquad (3)$$

Where s is the detail coefficients after threshold quantification, x_0 is the threshold, x is the detail coefficients after wavelet transform, $\mathrm{sign}(x)$ expresses the same sign as x.

3) Submit the detail coefficients and approximation coefficients to inverse wavelet transform, then the denoising Brillouin spectrum can be obtained by the following formula:

$$f(t) = \frac{1}{C_\psi}\iint_{RR}\frac{1}{a^2}W(a,b)\psi\left(\frac{t-b}{a}\right)\mathrm{d}a\mathrm{d}b, \qquad (4)$$

Where $C_\Psi < \infty$ is the wavelet transform admissible condition.

In practical applications it can be found that the conventional wavelet denoising method can remove the noise effectively and only need few wavelet decomposition scales when the SNR of Brillouin spectrum is high. However, although the wavelet decomposition detail coefficients of each scale after threshold quantification can remove some noise, as the SNR becomes low, the noise which also included in the approximation coefficients can't be ignored when the decomposition scales is less, so the threshold quantification of detail coefficients can only remove part of the noise. As a result, the conventional wavelet denoising method needs more wavelet decomposition scales in order to eliminate more noise. The calculation of the conventional method becomes large. At the same time, the decomposition scales can't be too much owing to the reconstruction error[9]. In conclusion, the conventional method can't meet the need of real time signal processing in many engineering applications.

The wavelet decomposition approximation coefficients describe the signal approximation portion and the Brillouin spectrum is the Lorentz curve, so the wavelet decomposition approximation coefficients of Brillouin spectrum have the trait of Lorentz curve. Based on the trait, as the SNR of Brillouin spectrum is low, the new method not only applies threshold quantification to wavelet decomposition detail coefficients, but also adopts the curve fitting algorithm to fit the wavelet decomposition approximation coefficients in order to reduce the noise in the approximation coefficients. This step can decrease the wavelet decomposition scales, and consequently, cut down the wavelet transform calculation effectively.

Owing to the nonlinear Lorentzian characteristic of Brillouin spectrum, the Levenberg-Marquardt (L-M) method which has small mean square error and good convergence performance is used to eliminate the noise contained in the approximation coefficients. The L-M algorithm can be expressed as follows:

$$x^2 = \sum_{i=0}^{N-1}\left[\frac{y_i - f(x_i, a_1, a_2, \cdots, a_M)}{\sigma_i}\right]^2, \qquad (5)$$

$$\hat{y}_i = f(x_i, a_1, \cdots, a_M), \qquad (6)$$

Where (x_i, y_i) are the data to be fitted, σ_i is the standard deviation of point i, and $a_1, \cdots, a_M$ are the parameters of function f which are results when x^2 is smallest, $\hat{y}_i$ is the fitted results.

3 Characteristic extraction of Brillouin spectrum

In Fig. 1, the line '-' represents the perfect Brillouin spectrum through Matlab simulation and its center frequency is 11.2 GHz; the line '…' represents the Brillouin spectrum which contains Gaussian white noise. By using the db1 wavelet function, the Brillouin spectrum is decomposed into three scales. Then the new method utilizes the heursure to calculate the threshold of detail coefficients of each scale and applies threshold quantification to detail coefficients of each scale via soft threshold. At the same time, it uses the L-M algorithm to fit the approximation coefficients. Finally, the new method takes the detail coefficients and approximation coefficients to inverse wavelet transform. In order to verify the advantage of the new method, the article eliminates the noise of Brillouin spectrum using the conventional method and the new method respectively, based on same decomposition scales. In Fig.1, the line '+' and line '-.' represent the Brillouin spectrum obtained through the conventional wavelet denoising method and the new method respectively. It can be seen that the new method can remove the

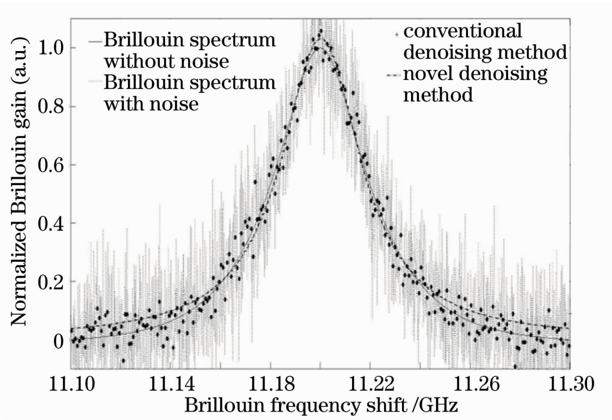

Fig.1. Simulated Brillouin spectrum

Brillouin spectral noise effectively, and has better denoising effect than the conventional wavelet denoising method.

The article utilizes standard deviation to describe the difference between the denoising Brillouin spectrum and the perfect Brillouin spectrum in order to evaluate the performance of the new method objectively[10]. The expression is shown in formula:

$$E = \sqrt{\frac{\sum_{n=1}^{N} [B(n) - B'(n)]^2}{N-1}}, \tag{7}$$

Where N is the point number of Brillouin spectrum, $B(n)$ is the perfect Brillouin spectrum, $B'(n)$ is the denoising Brillouin spectrum.

Using the new method, the Brillouin spectrum is decomposed into three scales and the standard deviation is shown in Table 1. In addition, in order to research the influence of denoising effect caused by different wavelet decomposition scales, the Brillouin spectrum is decomposed into three scales, four scales and five scales using the conventional method respectively, and the corresponding standard deviations are shown in Table 1. From the Table 1, it can be seen that the denoising effect becomes better and better with the increase of decomposition scales. In order to gain the same standard deviation as the new denoising method based on three decomposition scales, the Brillouin spectrum must be decomposed into five scales when using the conventional wavelet denoising method. Compared with the conventional wavelet denoising method, the new denoising method not only decreases the wavelet decomposition scales, but also reduces the Brillouin spectral distortion obviously.

Table 1 Comparison between the conventional wavelet denoising method and the new denoising method

	Three scales	Four scales	Five scales	New method
Standard deviation	0.0513	0.0356	0.0292	0.0307
Center frequency /GHz	11.2010	11.2008	11.2003	11.1999
Center frequency error	0.0010	0.0008	0.0003	0.0001

The optical fiber strain distribution is obtained by analyzing the Brillouin spectral frequency shift. And the precision of Brillouin spectrum is extremely critical to acquire the precise Brillouin spectral frequency shift. The better the denoising Brillouin spectrum coincides with the real spectrum shape, the more accurate the obtained optical fiber strain distribution is. The Brillouin spectrum feature extraction is achiered by using the General Regression Neural Network, and the results are shown in Table 1. From the Table 1, it can be seen that the center frequency error between the Brillouin spectrum obtained through the new denoising method and the perfect Brillouin spectrum is the smallest. Accordingly, the feasibility and advantage of the new denoising method are also validated.

The experimental platform is set up to verity the feasibility and effectiveness of the novel denoising method. The experimental system is shown in Fig. 2. The coherent light produced by the ultra-narrow line width fiber laser is divided into probe light and reference light. The probe light is injected into the measured optical fiber after pulse modulation and erbium doped fiber amplifer (EDFA). The coherent results of optical fiber scattered light and the reference light can produce the beat frequency optical signal, which can be converted into the electrical signal by the photoelectric detector. Then the Brillouin spectral frequency shift can be got by analyzing the Brillouin spectral distribution of optical fiber which is obtained by the microwave heterodyne frequency sweep test.

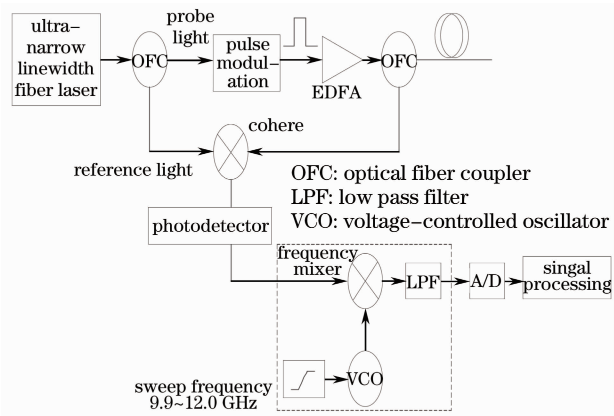

Fig.2. Experimental system which tests the optical fiber strain

Optical gratings are embedded in the optical fiber. The optical fiber strain is imposed on the optical fiber grating by utilizing the electric displacement table. The optical fiber strain on grating position can be measured by using the optical fiber grating demodulation instrument which has been corrected. On the same condition, the Brillouin spectrum can be measured by the experimental platform. The conventional wavelet denoising method and the new method are adopted to deal with the measured Brillouin spectrum, and then the distribution of optical fiber strain is obtained in the end. The denoising effects of conventional method and the new method can be verified by comparing the processed results with the measured results of the optical fiber grating demodulation instrument.

In the experiment, the optical fiber refractive index is 1.4720; the experimental temperature is 25 ℃; the pulse width is 50 ns, measuring range is 2 km, the sweeping range is 10.55～11.25 GHz, and interval is 5 MHz. The Brillouin spectrum measured in 0.08656 km, which is the position of fiber Bragg grating, is shown in Fig.3. The optical fiber stain is 1650 $\mu\varepsilon$ measured by the optical fiber grating demodulation instrument. Brillouin spectral noises are remored by utilizing the conventional denoising method and the novel denoising method respectively, and the wavelet decomposition scale is three. At last, it can be obtained that the optical fiber strain is 1728 $\mu\varepsilon$ and 1663 $\mu\varepsilon$, respectively. Table 2 shows the measured results of optical fiber strain at different grating positions. From the Table 2, it can be seen that the novel denoising method is better and can gain the more accurate optical fiber strain.

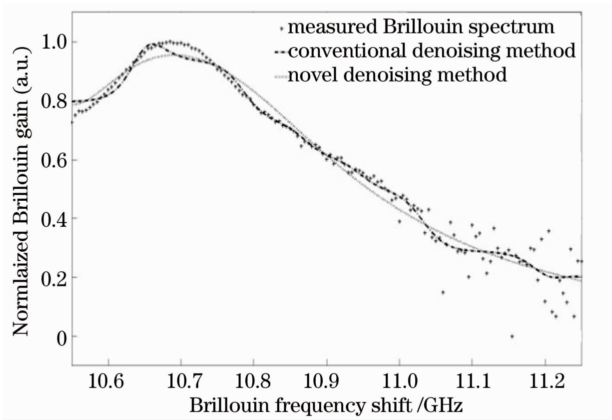

Fig.3. Measured Brillouin spectrum

Table 2 Optical fiber strains at different positions

Position /km	0.04073	0.08656	0.76628
Conventional method /$\mu\varepsilon$	1720	1728	1781
New method /$\mu\varepsilon$	1659	1663	1676
Optical fiber grating demodulation instrument /$\mu\varepsilon$	1649	1650	1652

4 Conclusion

In conclusion, the denoising method of Brillouin spectrum is researched based on the performance of the Brillouin distributed optical fiber sensing technology. From the results of simulation and experiment, it can be deduced that the new denoising method is more effective and has better denoising effect in the Brillouin spectrum than the conventional wavelet denoising method, especially when the SNR of Brillouin spectrum is low, the precision measurement of optical fiber strain can be guaranteed. So it will have a wide application prospects in the optical fiber cable state monitor.

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