Wavelet Denoising Applied in Optical Fiber Raman Temperature Sensor System

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Abstract　The distributed optical fiber Raman temperature sensor system (DTS) uses optical fiber Raman scattering effect to measure temperature. However, the spontaneous Raman scattering signals are particularly weak, completely submerge in the noise, and affect the system's temperature measurement accuracy. To solve this problem, this paper proposes to use wavelet transform, which has been widely used in engineering field, for signal processing. By using Matlab and VC combined programming, wavelet denoising is applied to the system actually. The results show that this method can eliminate signal noise effectively. The average error of the measured temperature is reduced from 3.1 ℃ to 1.1 ℃. And then, both the resolution and precision of the measured temperature of the system are improved.

Key words　fiber optics; denoising; wavelet transform; Raman scattering; temperature sensor

小波去噪用于光纤拉曼温度传感系统

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摘要　分布式光纤拉曼温度传感系统(DTS)可采用光纤拉曼散射效应测量温度,但由于光纤中产生的自发拉曼散射信号特别微弱,完全被淹没在噪声中,影响了系统的测温精度。针对存在的噪声问题,提出了将工程领域中广泛应用的小波变换用于系统的信号处理,并利用 Matlab 与 VC 进行联合编程的方法,将小波去噪实际地应用于系统中。实验结果表明该方法能够有效去除信号中的噪声,使系统的平均温度测量误差由 3.1 ℃降低到 1.1 ℃,进而可以提高系统的温度分辨率以及温度测量精度。

关键词　光纤光学；去噪；小波变换；拉曼散射；温度传感器
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1　Introduction

Distributed optical fiber Raman temperature sensor system (DTS) can realize the real-time, continuous measurement of temperature in a distance of thousands of meters. And the system has reliable temperature resolution and temperature measurement precision. Due to the inherent advantages of the system, such as small volume, low cost, anti-electromagnetic radiation, resistance to corrosion, quick response and so on, it has been widely used on many occasions[1,2].

The traditional theory of signal processing is based on the Fourier analysis. However, the Fourier transform, as a global change, has some limitations. In practical applications, people began to improve the Fourier transform by various ways. As a result, wavelet analysis yielded. Compared with the Fourier transform, wavelet transform is a local change in time domain and frequency domain, so that it can effectively extract information from the signal. With expansion and translation or other operation functions, it makes a multiscale detailed analysis

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of the signal. Wavelet transform solves many difficult problems which the Fourier transform cannot treat with. It has been widely used in many engineering fields[3~5].

Signal denoising is one of the typical problems in signal processing field. DTS also cannot avoid the noise problem. Traditional denoising methods mainly include averaging methods and filtering methods such as the median filter and the Wiener filter. The defect of traditional denoising methods lies in that the entropy is increased after transformation and it cannot describe the instability of the signal and signal correlation. In order to overcome the above disadvantages, people begin to use wavelet transform to solve the signal denoising problem. Wavelet transform has many good characteristics, such as low entropy, multi-resolution, removal of correlation and so on[6].

Wavelet transform for signal processing is used in this paper. By using Matlab and VC combined programming, wavelet denoising is applied to the system actually. As a result, it improves signal to noise ratio (SNR). The average error of the measured temperature is reduced from 3.1 ℃ to 1.1 ℃. And then, both the resolution and precision of the measured temperature of the system are improved.

2 Principle

2.1 Principle of temperature measurement of DTS

When light propagates in the fiber, photons collide SiO_2 molecules and exchange energy. Raman backscattering light is generated, including Stokes photons and anti-Stokes photon. The scattering intensities of Stokes and anti-Stokes photon after rigorous theoretical derivation are calculated by the expressions[7,8]:

$$i_s = \frac{N_0}{\gamma_s^4\{1-\exp[hc\Delta\gamma/(kT)]\}}, \tag{1}$$

$$i_{as} = \frac{N_0}{\gamma_{as}^4\{\exp[hc\Delta\gamma/(kT)]-1\}}, \tag{2}$$

where N_0 is temperature independent and depends on the fiber structure, physical properties and incident intensity. γ_{as} is the wavenumber of anti-Stokes light. γ_s is the wavenumber of Stokes light. c is light speed in vacuum. $\Delta\gamma$ is Raman frequency-shift. h is Planck constant. k is Boltzmann constant. T is the temperature. The ratio of above two formulas is

$$R(T) = \left(\frac{\gamma_s}{\gamma_{as}}\right)^4 \exp\left(-\frac{hc\Delta\gamma}{kT}\right), \tag{3}$$

where $R(T)$ is the ratio of anti-Stokes to Stokes beam in spontaneous Raman scattering, and only depends on the measured temperature.

2.2 Theory of wavelet transform

In wavelet analysis, scale function φ and wavelet function ψ are very important. In fact, signal analysis and processing are based on these two functions to realize signal decomposition and reconstruction[6].

Suppose $\psi(t) \in L^2(R)$ and $\hat{\psi}(\omega)$ is its Fourier transform. When $\hat{\psi}(\omega)$ meets the admissibility condition

$$C_\psi = \int_R \frac{|\hat{\psi}(\omega)|^2}{|\omega|}\mathrm{d}\omega < \infty, \tag{4}$$

$\psi(t)$ is called as a basic wavelet. After expansion and translation

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right), \quad a,b \in \mathbb{R},\ a \neq 0, \tag{5}$$

$\psi_{a,b}(t)$ is called as a wavelet sequence. Here a is expansion factor and b is translation factor.

For an arbitrary function that meets $f(t) \in L^2(R)$, its continuous wavelet transform is

$$W_f(a,b) = \langle f, \psi_{a,b} \rangle = |a|^{1/2}\int_R f(t)\overline{\psi\left(\frac{t-b}{a}\right)}\mathrm{d}t. \tag{6}$$

Its reconstruction formula is

$$f(t) = \frac{1}{C_\psi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{1}{a^2}W_f(a,b)\psi\left(\frac{t-b}{a}\right)\mathrm{d}a\mathrm{d}b. \tag{7}$$

Circuit signal inevitably contains noises. DTS also has the problem of noises. The collected signal contains many peak or mutation parts. The main components of these noises are white noise. People usually use numerical averaging algorithm for denoising. This algorithm is easy to achieve and can remove some noise. But this method has the following shortcomings: with the increase of cumulative frequency, though the improvement of the signal-to-noise ratio is getting better and better, it is not a linear relationship between the signal-to-noise ratio and the cumulative times. When the cumulative frequency reaches a certain value, even if we increase the measurement time, the improvement of the signal-to-noise ratio is also very limited and the signal still contains high frequency noise, which will affect the system measuring accuracy.

When decomposing the signal with wavelet, the noises are included mainly in the high-frequency wavelet coefficients. Thus we can use threshold or other forms to process the wavelet coefficients. The noises will be removed after reconstructing the signal. Commonly used wavelet denoising methods include wavelet decomposition and reconstruction method, nonlinear wavelet transform threshold method and wavelet transform modulus maximum value method. In this paper we use nonlinear wavelet transform threshold method.

Nonlinear wavelet transform threshold method is to set a threshold to the wavelet coefficients. The wavelet coefficients that have smaller absolute value are set to zero. The wavelet coefficients that have bigger absolute value are retained or contracted. Then we do inverse wavelet transformation for the wavelet coefficients that have been processed by threshold to reconstruct the signal. In this way, the noises can be removed. The method is mainly applied to the signal mixed with white noise. The advantage is that the noises are almost completely suppressed. The specific implementation steps are as follows.

1) The wavelet decomposition of signals: Select a wavelet and determine the number of wavelet decomposition layer N, and then do wavelet decomposition

for signals in N layers. Each layer is divided into high frequency part and the low frequency part.

2) Threshold quantization of the wavelet decomposition high frequency coefficients: Choose a soft threshold or hard threshold for each layer to process the high frequency coefficients.

3) Wavelet reconstruction: Use the low frequency coefficients in the Nth layer and the high frequency coefficients after processed by threshold in every layer to reconstruct the signals.

In the three steps above, the key is how to select the threshold and how to carry out the threshold procession. The threshold can not only remove noises, but also retain useful signals[9~11].

3 Wavelet denoising for the improvement of system performance

3.1 Wavelet denoising results and analysis

In our experiment, thermostatic water tank is used to do temperature calibration. We use the main parameters: temperature range is −5 ℃～100 ℃, temperature fluctuation is ±0.05 ℃, volume is 400 mm×325 mm×230 mm, flow of circulating pump is 13 L/min. The center wavelength of the pulse light source in DTS is 1550 nm. The repetition freguency is 10 kHz and the pulse width is 10ns. Optical fiber is 3000-m-long common multimode fiber. The spatial resolution of the system is 1 m. In the experiment, the front end 500-m-long optical fiber is placed in constant temperature water tank. The temperature is set as 30 ℃, 40 ℃, 50 ℃, 60 ℃ and 70 ℃.

Figure 1 is the temperature data calculated by DTS under each experiment temperature, in which Fig. 1(a) is the temperature data calculated with the original signals and Fig. 1(b) is the temperature data calculated with the signals after wavelet denoising. The horizontal axis is the optical fiber position, and the vertical axis is the temperature value. Comparing those two figures, we can see that the noises are removed effectively after wavelet denoising. The average temperature measurement error is reduced from 3.1 ℃ in Fig. 1(a) to 1.1 ℃ in Fig. 1(b). And then, the temperature resolution and precision of temperature measurement of the system can be both improved.

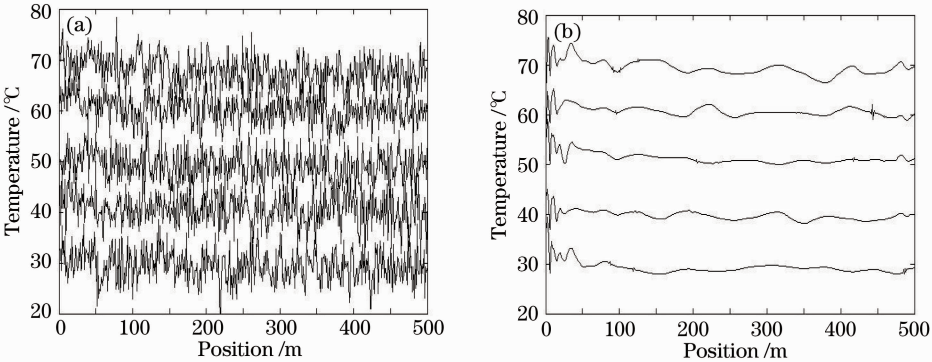

Fig. 1 Data before and after denoising at different temperatures. (a) Before wavelet denoising; (b) after wavelet denoising

Here, we take anti-Stokes signal as the example to tell about the process of wavelet denoising. Wavelet analysis toolbox in Matlab provides many wavelet analysis functions. We can use these functions to realize various wavelet transform. The first step is the wavelet decomposition of signals. Figure 2(a) is an anti-Stokes signal that acquired at 30 ℃. 2-m-long optical fiber is placed in a thermostatic water tank whose temperature is 50 ℃. We select wavelet "sym5" and use discrete wavelet transform function "wavedec" to do wavelet decomposing

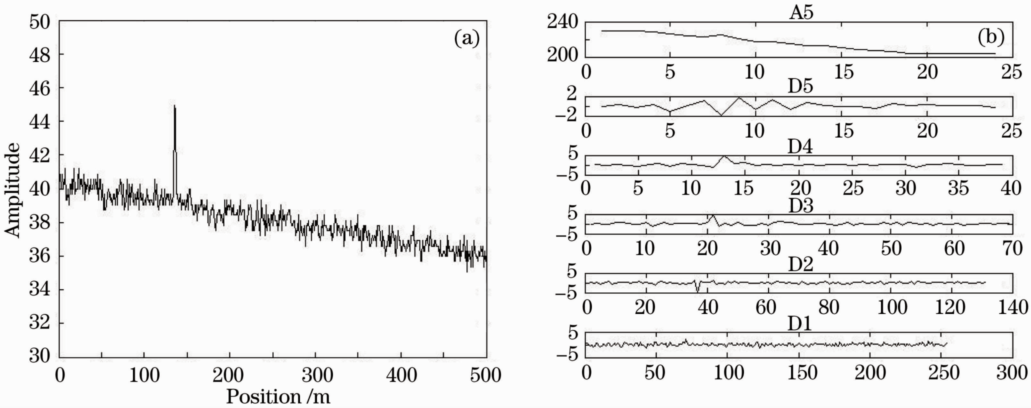

Fig. 2 (a) Anti-Stokes signal and (b) wavelet coefficients after wavelet decomposition with 5 scale. Figure 2(b) shows the low frequency coefficients (A5) and high frequency coefficients (D5, D4, D3, D2, D1) after wavelet decomposition in each layer. The second step is threshold quantization of the wavelet decomposition high frequency coefficients. We select function "thselect" to acquire signal threshold. The choice of threshold meets $T = \sigma_n \sqrt{2\ln N'}$, in which σ_n is noise standard deviation and N' is signal length. We select function "wden" to do threshold denoising for signal. Figure 3(b) is the wavelet coefficients after threshold denoising. The third step is wavelet reconstruction. We select function "waverec" to do signal reconstructing. Figure 3(a) is the reconstruction signal that uses wavelet coefficients after threshold denoising.

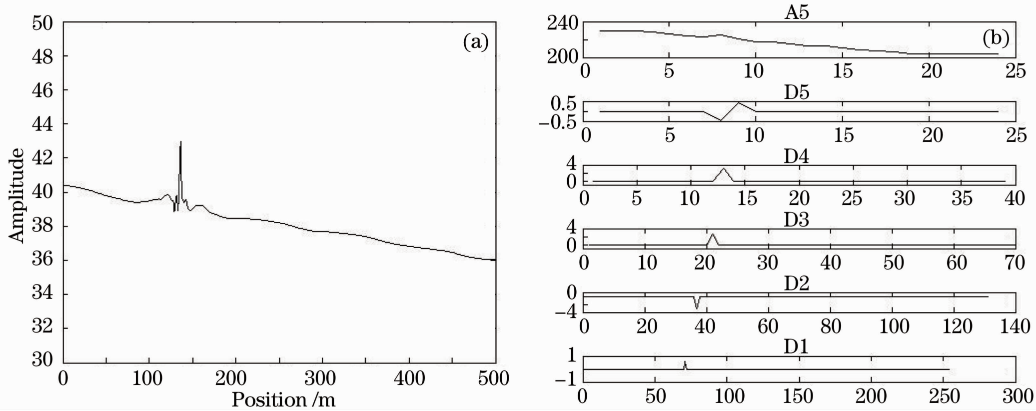

Fig. 3 (a) Signal after reconstruction and (b) wavelet coefficients after threshold denoising

Comparing Fig. 3(a) with Fig. 2(a), we can find that the signal amplitude of temperature mutation part is reduced after wavelet denoising. But it does not influence the temperature measurement. This is because the reduction degree caused by wavelet denoising for signal amplitude under any temperature is the same. When we do temperature calibration, it has no need to consider the effect caused by wavelet denoising for signal amplitude as long as we use the relative variation of signal amplitude. Figure 4(a) is the temperature data calculated with the original signal shown in Fig. 2(a). Figure 4(b) is the temperature data calculated with the signal after wavelet denoising shown in Fig. 3(a). Comparing Fig. 4(b) with Fig. 4(a), we can find that the temperature measurement is accurate after wavelet denoising.

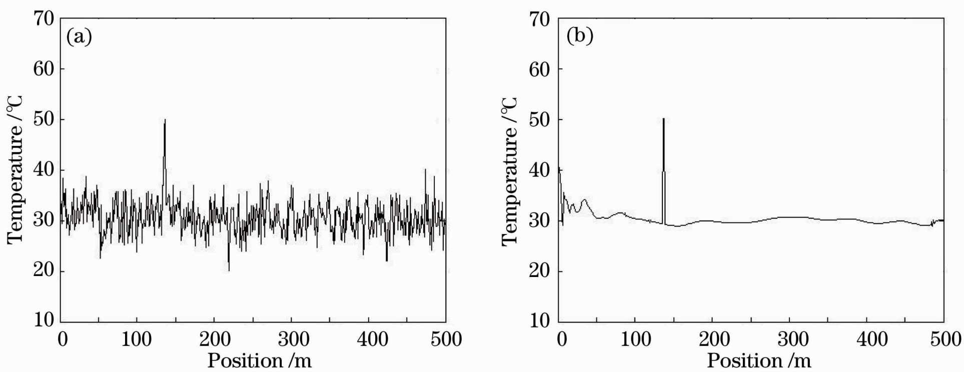

Fig. 4 Temperature data calculated with (a) original signal and (b) signal after wavelength denoising

We realize the wavelet denoising process told above by programming with Matlab. And then the program is converted into a shared library file for C++. The shared library file is added to the VC engineering environment. Thus, we can call the shared library file by system software written with VC and use it to do wavelet denoising for the signal acquired.

4 Conclusion

To solve the noises problem in the distributed optical fiber Raman temperature sensor system, this paper proposes to use wavelet transform for signal processing. By using Matlab and VC combined programming, wavelet denoising is applied to the system actually. The results show that this method can eliminate signal noise effectively. The average error of the measured temperature is reduced from 3.1 ℃ to 1.1 ℃. And then, both the resolution and precision of the measured temperature of the system can be improved.

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