POLARIZATION RANDOM NOISE SUPPRESSION METHOD IN TWO-DIMENSIONAL FORCE SENSOR BASED ON RANDOM FOREST

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Abstract - The technique of distributed optical fiber sensing is very effective and applied in many different industries. Because of its benefits, including a long sensing distance and good spatial resolution, Brillouin Optical Time Domain Analysis (BOTDA) has received a lot of interest. A method for reducing the polarization random noise of a two-dimensional force sensor based on random forest is proposed in order to lessen the restriction between long sensing distance and high spatial resolution and measurement accuracy. The random forest algorithm is presented first. The polarization correlation of Stimulated Brillouin Scattering (SBS) and its impact on Brillouin time domain analysis and sensing are then examined. By studying polarization random noise, a method to suppress polarization random noise based on random forest algorithm and Brillouin phase shift spectrum (BPS) is proposed. Following that, simulation studies are used to confirm the method’s impact on enhancing sensing accuracy. Finally, an analysis is done of the impact of gray coded BOTDA system sensors on wavelet-based image threshold denoising technology. The findings demonstrate that while the wavelet threshold denoising method is excellent at denoising white noise, it is not successful at suppressing polarization random noise, which lowers the sensing accuracy. Polarization random noise is less of an issue with BPS than it is with Brillouin gain spectrum (BGS), which allows for a three-fold increase in sensing accuracy. Wavelet denoising has a denoising impact on Brillouin phase shift sensing data that is unquestionably superior to Brillouin gain, and the BFS fluctuation is unquestionably decreased after denoising. This paper offers some suggestions and guidelines for reducing polarization random noise in sensors.

Keywords: Random forest algorithm; Sensor; Polarized random noise; Brillouin optical time domain analysis; Wavelet threshold denoising technology.

1. Introduction

An object or system that can sense the given measured data and transform it into usable output signals in accordance with predetermined rules is referred to as a sensor. The field of optical fiber sensing technology detects numerous properties through optical fiber. Optical fiber sensors are superior to other types of sensors in that they are lightweight, compact, have a high transmission capacity, are immune to electromagnetic interference and chemical corrosion, and can function in challenging conditions [1]. Depending on the measuring range, optical fiber sensing technology can be single-point or disseminated. Single-point optical fiber sensors process optical fiber using the properties of light to detect local physical parameters like temperature and vibration [2]. The three basic divisions of distributed optical fiber sensors are Rayleigh scattering, Raman scattering, and Brillouin scattering. High measurement accuracy and stability are two benefits of Brillouin distributed sensors, which have a wide range of applications. Brillouin distributed optical fiber sensors have consequently become a popular area of study [3]. Brillouin Optical Time Domain Analytic (BOTDA), Brillouin Optical Correlation Domain Analysis (BOCDA), and Brillouin Optical Frequency Domain Analysis (BOFDA) are the three basic analysis techniques used with Brillouin distributed sensing technology. Although BOCDA and BOFDA have excellent spatial resolution, their sensing range is constrained [4]. BOTDA can achieve high spatial resolution and has obvious advantages in long-distance and high-precision sensing. The pulse width of pump light determines the spatial resolution in BOTDA [5].

The study of sensor polarization random noise is expanding right now. Using two polarization components that can be employed for standard totally normal dispersion fiber produced by supercontinuum, Bravo Gonzalo et al. (2018) investigated the effects of pump power, pulse length, and fiber length on coherence and relative intensity noise (RIN). The findings demonstrate that Polarization Modulational Instability (PMI) provides...
a power dependence that is not present in the scalar model, and that at an acceptable power level beyond 40kW, the coherence of fully normal distributed supercontinuum may also diminish. It has also been demonstrated that PMI shortens the pump pulse and fiber lengths, which affects the coherence of a fully normal dispersion supercontinuum. The RIN measurement of fiber-pumped totally normal dispersion fiber supercontinuum supports the numerical prediction [6]. A technique termed source-estimated-utilizing-noise-discarding (SOUND) was introduced by Mutanen et al. (2018). The anatomical details of the skull are used by SOUND to cross-verify sensor data. Simulation and application to several Electroencephalography (EEG) and Magnetoencephalography (MEG) data sets are used to validate SOUND’s performance. The performance of commonly used channel suppression and interpolation approaches is outperformed by SOUND, which significantly improves the quality of the data [7]. In the local frequency domain of Ground-Penetrating Radar (GPR) data, Bi et al. (2018) introduced a Singular Value Decomposition (SVD) approach based on the Hankel matrix. The suggested method is used to process actual GPR data as well as other numerical models. Qualitative and quantitative analysis is done based on the misleading signals that are created by various processes. By removing clutter like ground waves, the proposed technique can diminish the introduced horizontal false signal and enhance its ability to suppress random noise around non-horizontal phase reflection occurrences, according to the comparison [8]. In order to increase measurement signal-to-noise ratio and support simultaneous adjustment of Rayleigh and polarization fading, Sagues et al. (2021) introduced the usage of optical pulse compression. They did this by employing perfect periodic correlation phase code. A technique is also used to unlock the differential phase measured with a single wavelength in order to further minimize the relative noise introduced to the dual-wavelength measurement by employing the synthetic wavelength measurement. All of them are highlighted in the 1 km sensor link, which has a spatial resolution that is 67 times greater than the conventional single wavelength technique and can detect objects as small as 20 cm away [9]. In conclusion, it shows that there have been numerous studies on sensor noise suppression and some progress has been made.

The gray pulse coding technology used in BOTDA has a significant traction impact that will somewhat degrade the signal-to-noise ratio of sensing signals. The Brillouin gain time domain curve measurement’s stability will be decreased even though the strong polarization traction effect can be completely minimized by employing random interference technology.

The stability of Brillouin time-domain curve measurement is mostly impacted by polarization random noise. Based on this, a technique to reduce polarization random noise using the Brillouin phase shift spectrum (BPS) is suggested in an effort to increase measurement accuracy through testing.

2. Analysis of Polarization Random Noise and its Suppression Method based on Random Forest Algorithm

2.1 Random Forest Algorithm

In the robot learning algorithm, ensemble learning is to complete the learning task by building multiple basic learning models and fusing them to make decisions together, which is also called the learning multi-classifier system based on committee. The basic learners that make up the ensemble learning algorithm can be of the same category or different categories. Multiple basic learning models are combined to obtain integrated learning, and the integrated learning formed by combination has higher generalization ability than a single learner [10].

According to the construction method of single learner, the current integrated learning algorithms are classified. First is that each learner has a strong dependence, and the operation must be performed in series during the training process. The classification process is a serialization method that is carried out step by step. Secondly, there is no great dependence among the basic learners, and the training process can be carried out at the same time and the operation process can be realized in parallel. The representative algorithms of serial operation and parallel algorithm are Boosting, random forest and Bagging respectively.

Bagging is an integrated learning algorithm with parallel operation. Its main step is to sample the training set to get the sample set, then train the basic learners by using each sample subset, and then fuse the basic learners to make a joint decision to get the final result. Random forest algorithm is a typical parallel integrated learning algorithm, which extracts a variety of feature attributes, combines multiple decision trees, and randomly selects base learners to learn in the process of training the model, thus ensuring the stability of the system and preventing over-fitting phenomenon to a certain extent [11]. The construction steps of random forest model are shown in Figure 1:
Polarization Random Noise Suppression Method in Two-Dimensional Force Sensor Based on Random Forest

2.1 Polarization-dependent Stimulated Brillouin Scattering Effect

Stimulated Brillouin effect is related to polarization, which makes BOTDA sensor with single-mode fiber as sensing medium have polarization-related fading and polarization traction problems. At present, the existing polarization control technologies are mainly orthogonal polarization control and random polarization control, and the above two polarization control methods cannot solve the polarization-related fading and strong polarization traction effect in BOTDA at the same time.

2.1.1 The Polarization-dependent Fading

The polarization parallelism between the pump light and the probe light has a certain influence on the efficiency of SBS, which means that SBS is polarization-dependent [12]. When the polarization states of pump light and probe light are parallel, SBS has the strongest effect, and the maximum SBS efficiency $\gamma = 1$ is obtained. When the polarization states of pump light and probe light are perpendicular, there is no SBS effect $\gamma = 0$. The expression of efficiency coefficient $\gamma$ through SBS is as follows:

$$\gamma = \frac{1}{2} (1 + \hat{p} \cdot \hat{s}) = \frac{1}{2} (1 + s_1 p_1 + s_2 p_2 + s_3 p_3) \quad (1)$$

where $\hat{p}$ refers to the unit vector representation of the polarization state of pump light in Stoke space. $\hat{s}$ refers to the unit vector representation of the polarization state of the probe light in Stoke space. When considering the influence of polarization, the signal light $p_g$ after SBS can be expressed as:

$$\begin{align*}
\{ p_g(z, \nu) &= \mu_{g0} \exp[-\alpha(L-z)] \exp[\nu(z)G(z, \nu)] \\
G(z, \nu) &= g_{SBS}(z, \nu) + i\phi_{SBS}(z, \nu)
\end{align*} \quad (2)$$

where $\nu$ refers to the pump-probe optical frequency difference. $\mu_{g0}$ refers to the initial intensity of the probe light. $\alpha$ refers to the attenuation coefficient of optical fiber. $L$ refers to the total length of sensor fiber. $z$ takes the incident position of pump light as zero. $G(z, \nu)$ refers to the change of probe light caused by SBS, and $g_{SBS}(z, \nu)$ and $\phi_{SBS}(z, \nu)$ refer to the change of amplitude and phase respectively. $g_{SBS}(z, \nu)$ refers to the Brillouin gain coefficient. $I_p(z)$ refers to the light intensity of the pump light after it is transmitted by $z$ meters. $\Delta z$ is the spatial resolution.

Influenced by the uneven shape, refractive index and stress distribution of ordinary single-mode fiber, it is easy to appear birefringence, which leads to the random change of polarization state when light propagates in single-mode fiber, which makes the efficiency of SBS action in different positions of fiber inconsistent, so the polarization-related fading problem occurs.

2.1.2 Polarization Traction Effect

The polarization states of the pump light and the probe light are influenced by the birefringence of the fiber and the SBS effect. In the process of SBS, the pump light will not only produce Brillouin amplification, but also change the polarization state of the probe light [13]. The expression of polarization state of probe light in SBS process is as follows:

$$\frac{d}{dz} \hat{S}_p(z) = \hat{\beta}(z) \times \hat{S}_p(z) + \frac{\gamma_2}{2} \left[ \hat{S}_p(z) - \left( \hat{S}_p(z) \cdot \hat{S}_p(z) \right) \right] \frac{\partial}{\partial \nu} \hat{S}_p(z) \quad (3)$$

where $\hat{\beta}(z)$ refers to the birefringence of the optical fiber. $\hat{S}_p(z)$ refers to the polarization direction of the probe light. $\hat{S}_p(z)$ refers to the polarization direction of the pump light. $p_p(z)$ refers to the power of pump light.
Because orthogonal polarization control technology is very sensitive to polarization traction effect, Brillouin gain time domain curve is distorted and measurement stability is reduced. Because the Brillouin gain is small and the polarization traction is weak in the single-pulse BOTDA sensor, the birefringence of the fiber is the main factor that affects the detection light, so the traction will have a significant impact on the sensor at the end of the fiber only when sensing for a long distance. However, the effect of polarization traction in the coded BOTDA sensor is different, which will seriously deteriorate in the Signal to Noise Ratio (SNR) of Brillouin time domain curve at the front end of the optical fiber, reducing the stability of the test. The strong polarization traction effect in coding destroys the orthogonality of the polarization direction of the probe light measured twice, which leads to the failure of the orthogonal polarization control technology, and thus cannot suppress the polarization-related fading.

2.2 Theoretical Analysis of Polarization Random Noise in Gray Coded BOTDA

The system response of gray pulse light sequence A and B after SBS interaction with probe light in optical fiber can be expressed as:

\[
H_A(z,v) = A \Theta [1 + \Delta_e(z,v)] h_k(v) + [e_{A1}(z) - e_{A2}(z)]
\]

\[
H_B(z,v) = B \Theta [1 + \Delta_e(z,v)] h_k(v) + [e_{B1}(z) - e_{B2}(z)]
\]

where \(\Delta_e(z,v)\) is a single pulse polarization random fluctuation. \(e_{A1}(z), e_{A2}(z), e_{B1}(z), e_{B2}(z)\) refer to the white noise caused by \(A_1, A_2, B_1, B_2\) passing through the sensor fiber respectively, \(\Delta_e(z,v) h_k(v)\) is monopulse random polarization noise.

The estimated signal of Brillouin eigen spectrum can be expressed as:

\[
\Delta_{\text{prn}}(z,v) = g_{2bs}(v)\Delta_e(z,v)
\]

\[
\Delta_{\text{prn}}(z,v) = \frac{g_{2bs}(v)\Delta_e(z,v)}{2g_{2bs}(v)\Delta_e(z,v)}
\]

where \(\Delta_{\text{prn}}(z,v)\) is the decoded polarization random noise on BGS. \(\Delta_{\text{prn}}(z,v)\) is polarization random noise at BPS. \(g_{2bs}(v)\) is the BGS. \(g_{2bs}(v)\) is BPS. \(g_{2bs}(v)\) is the Brillouin gain spectrum (BGS) and Brillouin phase shift spectrum (BPS) have experienced the same polarization random fluctuation, and the polarization random noise of BPS and BGS is as follows:

\[
\Delta_{\text{prn}}(z,v) = g_{2bs}(v)\Delta_e(z,v)
\]

\[
\Delta_{\text{prn}}(z,v) = \frac{g_{2bs}(v)\Delta_e(z,v)}{2g_{2bs}(v)\Delta_e(z,v)}
\]

The simulation results are shown in Figure 2:

Figure 2. Influence of random fluctuation of the same polarization on BGS and BPS
Figure 2 shows that under the premise of the same random fluctuation of polarization, the distortion of BPS is much less than that of BGS in the range of full width at half maximum $\Delta V_g$. In the vicinity Brillouin Frequency Shift (BFS), BPS is insensitive to polarization random fluctuation, which makes the BFS estimated by BPS through fitting algorithm more accurate.

Under different pump-probe light frequency differences, the suppression degree of BPS to polarization random noise is as follows:

$$R(v) = \frac{2_{\text{prm}, \phi}(z,v)}{2_{\text{prn}, \phi}(z,v)} = \frac{2(v-v_p)}{\Delta V_g}$$  \hspace{1cm} (8)

Among them, the frequency difference between pump and probe light is $v_p$, and the smaller $R(v)$ the better the suppression effect of polarization random noise. When $v_p$ is closer to BFS $V_g$, the larger the linewidth $\Delta V_g$ of BGS, the better the suppression effect of BPS.

2.3 Simulation Analysis of Polarization Random Noise in Sensor

2.3.1 IQ demodulation Analysis in Coherent Detection BOTDA Sensing System

Based on the analysis of the extraction process of Brillouin gain and phase shift in coherent detection BOTDA sensing system and as the basis of simulation experiment, the extraction methods mainly include coherent receiver technology and In-phase quadrature (IQ) demodulation technology [14]. IQ demodulation technology is widely used because of its simple equipment and easy implementation. Its main principle is shown in Figure 3:

The probe light is optically filtered by a programmable optical processor Wave Shaper (WS). The $v_p - v_z - v_{LO}$ and $v_p - v_z$ in the optical frequency component are sent to the photodetector (PD) 2, and the optical frequency components $v_p + v_z + v_{LO}$ and $v_p + v_z$ are sent to the PD1 [15]. Since only the frequency component of the probe light frequency is $v_p - v_z - v_{LO}$ can SBS with the pulse pump light, the optical signals entering PD1 and PD2 can be expressed as:

$$E_{\text{PD2}} = P_s(t)\exp\left[i2\pi(v_p - v_z)t + i\theta_1\right] + P_s(t)\exp[ig_{\text{SBS}}(t)]\exp\left[i2\pi(v_p - v_z - V_{LO})t + \varphi_{\text{SBS}}(t)\right] + i(\theta_1 + \theta_2)$$  \hspace{1cm} (9)

$$E_{\text{PD1}} = P_s(t)\exp\left[i2\pi(v_p + v_z)t - i\theta_1\right] + P_s(t)\exp[ig_{\text{SBS}}(t)]\exp\left[i2\pi(v_p + v_z + V_{LO})t - i(\theta_1 + \theta_2)\right]$$  \hspace{1cm} (10)

The electrical signal $E_{RF}$ output by PD2 and the electrical signal $E_{LO}$ output by PD1 can be expressed as:

$$E_{RF} = A_1\exp[g_{\text{SBS}}(t)]\cos[2\pi V_{LO}t + \theta_2 - \varphi_{\text{SBS}}(t)]$$ \hspace{1cm} (11)

$$E_{LO} = A_2\cos[2\pi V_{LO}t + \theta_2]$$  \hspace{1cm} (12)

The above equation shows that the phase between RF signal $E_{RF}$ and intrinsic signal $E_{LO}$ is synchronous without SBS, and the output signal after I/Q demodulator is collected by oscilloscope, and the amplitude of I and Q signals is normalized to obtain:

$$I_W = \exp[g_{\text{SBS}}(t)]\sin[\varphi_{\text{SBS}}(t) + \theta]$$

$$Q_W = \exp[g_{\text{SBS}}(t)]\cos[\varphi_{\text{SBS}}(t) + \theta]$$  \hspace{1cm} (13)

where $g_{\text{SBS}}(t)$ is the Brillouin gain curve. $\varphi_{\text{SBS}}(t)$ is a BPS curve. $I_W$ and $Q_W$ are I-path and Q-path time-domain curves. The Brillouin phase is solved by:

$$\varphi_{\text{SBS}}(z) = \arctan\left(\frac{I_W}{Q_W}\right)$$  \hspace{1cm} (14)

The equation for solving the Brillouin gain is:

$$g_{\text{SBS}}(z) = \ln\left(\sqrt{I_W^2 + Q_W^2}\right)$$  \hspace{1cm} (15)

The Brillouin gain of Gray coded BOTDA is as follows:

$$g_{\text{SBS}}(z, v) = \sum_{m=1}^{N} g_{\text{SBS}}(z, v_m) = g_{\text{SBS}}(z, v) + g_{\text{SBS}}(z - L_0, v) + \cdots + g_{\text{SBS}}(z - (M-1)L_0, v)$$  \hspace{1cm} (16)

Among them, $g_{\text{SBS}}(z, v)$ represents the cumulative Brillouin gain when detecting the frequency difference $v$ between light and pump light at the sensing fiber $z$. $N$ is the number of coded bits.
$g_{SBS}(x, r)$ is Brillouin produced by the interaction between the $i$-th pump light and the probe light SBS in the coding sequence. $L_a$ is the code width of a single pulse code [16].

2.3.2 Image Denoising Technology

Image denoising algorithms are divided into spatial domain algorithms and variable domain algorithms. Spatial domain algorithms mainly include nonlocal averaging, mean filtering, Gaussian smoothing and low-pass filtering, etc., which mainly take the pixel values in the image to be processed as the data processing object of the algorithm. Image denoising in the change domain is mainly through transforming the information in the spatial domain into the change domain, and the obvious coefficient characteristics after the change make the denoising effect better [17]. In the image change denoising algorithm, wavelet analysis is widely used in various fields because of its perfect reconstruction ability, which makes no information loss in the process of signal decomposition [18].

The basic principle of wavelet threshold denoising is that after the signal with noise is transformed by wavelet, the signal energy is mainly concentrated on a few wavelet coefficients with large amplitude, and the noise energy will be evenly distributed on most wavelet systems with small amplitude [19]. The noise can be eliminated by setting an appropriate threshold to filter the noise wavelet coefficients in high-frequency components [20].

2.3.3 Matlab Simulation Experiment Design

This simulation experiment is carried out using Matlab R2021a software, and the experimental parameters include:

1. Pump light frequency: 10.684GHz
2. Probe light frequency: 10.684GHz different from pump light frequency.
3. Response time of detection light: 10ps
4. Noise types: white noise, polarization random noise, etc.

Based on this, firstly, according to the working principle of gray coded BOTDA sensor, the mathematical model is established and the parameters of pump light and probe light are set. Secondly, according to the experimental requirements, different types and intensities of noise are generated and added to the simulation model.

In addition, BPS technology is introduced into the simulation model, and its suppression effect on polarization random noise is observed by adjusting the parameters of orthogonal polarization state. Finally, according to the established simulation model, the simulation experiment is run. The experimental results are recorded and analyzed, including statistical analysis and curve fitting to evaluate the influence of different noise types and intensities on the sensor performance and the suppression effect of BPS technology.

3. Suppression Analysis of Polarization Random Noise

3.1 The Influence of Polarization Random Noise and its Suppression Effect Analysis

In Matlab environment, this paper simulates the performance of gray coded BOTDA sensor under different noise influences [21]. Firstly, this paper constructs a mathematical model for simulation, which considers the case that the frequency difference between pump light and probe light is 10.684GHz. Then, by changing the input noise type and intensity, this paper observes and records the influence of noise on the sensor performance. In the simulation experiment of this paper, this paper mainly pays attention to the characteristics and influence of polarization random noise [22].

Polarization random noise is a kind of noise caused by random process in physical system, and its characteristics include Gaussian distribution, autocorrelation, and ergodicity. This kind of noise shows random fluctuation in time domain, which affects the sensing performance. Meanwhile, this paper also studies the suppression effect of BPS technology on polarization random noise [23]. By introducing two orthogonal polarization states into the system, BPS technology disperses the influence of polarization random noise into two channels, thus reducing its influence on the overall sensing performance. In the simulation experiment of this paper, it is found that BPS technology can effectively suppress the influence of polarization random noise, thus improving the performance of the sensor [24].

In order to show the discovery of this paper intuitively, Brillouin time domain curve is drawn in Matlab. These curves show the performance changes of the sensor under the action of white noise and polarization random noise, and after adopting BPS technology. Figure 4 can clearly show the influence of polarization random noise and the suppression effect of BPS technology on this noise [25].
The above figure shows that at the same sensing position, the Brillouin gain time domain curve value is larger than the Brillouin phase shift time domain curve value. In Figure 4(a), under the action of white noise, the curve fluctuates uniformly along the optical fiber, and it is found that the Brillouin phase shift curve and Brillouin gain time domain curve fluctuate similarly. The white noise passing through the sensor system has the same influence on the two curves, which shows that the fluctuation of time domain curve is determined by the noise. In Figure 4(b), under the action of polarization random noise, the fluctuation of Brillouin time-domain curve decreases with the increase of sensing distance, and the sensing signal is affected by fiber attenuation, which decreases with the increase of sensing distance, indicating that the magnitude of polarization random noise is proportional to the signal. Moreover, the overall fluctuation of Brillouin phase shift curve is obviously smaller than that of Brillouin gain curve, which further proves that polarization random noise is multiplicative noise related to signal.

Figure 5 shows that the Brillouin gain time-domain curve fluctuates the most due to polarization random noise, and the maximum value of uncertainty STD is 0.09. The uncertainty of time-domain curve produced by Brillouin phase-shifted polarization random noise and white noise is very small, and the maximum is only about 0.03. Therefore, it is polarization noise that seriously reduces the stability of curve measurement in Brillouin gain. The estimation curve of BFS is shown in Figure 6:
Figure 6. BFS estimation curve (a) White noise; (b) Polarization random noise

Figure 6(a) shows that with the increase of sensing distance, the sensing SNR weakens, and the fluctuation of BFS is gradually increasing. In Figure 6(b), the BFS estimation curve fluctuates approximately uniformly along the fiber, and the SNR under fluctuating random noise is inversely proportional to the polarization random fluctuation \( \Delta_\varphi \) and the sensing signal weakens with the attenuation of the fiber, but the polarization random fluctuation is similar at different positions of the fiber.

It shows that the fluctuation of BFS estimation curve has nothing to do with sensing distance. At the same time, because the fluctuation of BFS estimation curve of BPS is obviously smaller than Brillouin gain, it shows that phase shift spectrum analysis has higher tolerance to random fluctuation of the same polarization.

The BFS estimation error can fully reflect the level of sensing accuracy, and the greater the BFS error, the lower the sensing accuracy. Repetitive simulation of BFS is shown in Figure 7:

Figure 7. Simulation diagram of sensor BFS estimation error (a) White noise; (b) Polarization random noise

In Figure 7(a), as the sensing distance increases, the sensing signal weakens and the sensing accuracy gradually decreases. It shows that the sensing accuracy obtained by Brillouin gain and BPS analysis is the same under the condition of constant system noise, indicating that the sensing accuracy will not be affected in the process of data processing. Figure 7(b) shows that the sensing accuracy based on BPS analysis and gain spectrum analysis is 0.05MHz and 1.5MHz respectively. Combined with the previous analysis, it shows that the sensing accuracy of BPS analysis is obviously higher than that of BGS under the same polarization random fluctuation, and the sensing accuracy of BPS analysis is improved by nearly three times compared with BGS. The simulation curve of BFS estimation error under the combined action of white noise and polarization random noise is shown in Figure 8:

Figure 8. Simulation curve of BFS estimation error under the combined action of white noise and polarization random noise

Figure 8 shows that with the increase of sensing distance, the influence of polarization random noise on sensing degree becomes smaller and smaller. According to the previous analysis, polarization
random noise is a multiplicative noise. The sensing SNR at the front end of the sensing fiber is high, but it can still have a great impact on the Brillouin time domain curve, thus reducing the sensing accuracy. It shows that Brillouin phase shift spectrum analysis can suppress the random noise of polarization and effectively improve the sensing accuracy.

3.1 Random Noise Suppression based on Wavelet Threshold Denoising Technology

For Brillouin gain and Brillouin phase shift data, wavelet denoising is carried out. According to the denoising effect, sym7 is selected as the wavelet basis function, and the decomposition level is 5. The comparison of Brillouin gain time domain curves before and after wavelet denoising is shown in Figure 9:

Figure 9 shows that the effect of wavelet denoising is better at the position where there is no SBS effect. At the position where the fiber is pre-strained, the Brillouin gain curve suddenly changes, and the curve after wavelet denoising keeps the same trend, which proves that wavelet denoising can maintain the resolution of the sensing space. In the position of SBS fiber, the Brillouin curve after denoising fluctuates greatly at the front end of the fiber, and is similar to the fiber without SBS at the end of the fiber.

The comparison of Brillouin gain and phase shift time-domain curve uncertainty before and after wavelet denoising is shown in Figure 10:

Figure 10 show that wavelet denoising has a high denoising effect on white noise, but the effect on random noise can be ignored. The reason is that polarization random noise and signal are decomposed into low-frequency components in the process of wavelet decomposition, and the threshold of wavelet denoising is measured according to high-frequency components, so wavelet denoising has a weak effect on polarization random noise suppression. The comparison of BFS before and after wavelet denoising is shown in Figure 11:
Figure 11 shows that the spatial resolution of the system is maintained after wavelet denoising at 39.98km-40km in Figures a and b. By comparing the two images, it can be found that the denoising effect of wavelet denoising on BPS sensing data is obviously better than Brillouin gain, and the fluctuation of BFS is obviously reduced after denoising. The comparison of BFS estimation errors before and after wavelet denoising is shown in Figure 12:

![Figure 12. Comparison of BFS estimation errors before and after wavelet denoising (a) Brillouin gain; (b) Brillouin phase shift](image)

Figure 12 shows that the wavelet denoising technology at the front end of the optical fiber has a small improvement on the sensing accuracy, but a great improvement at the end of the optical fiber. The maximum BFS estimation error of the original data in Figure 12(a) is about 1.3MHz, and the maximum BFS estimation error after denoising is 1MHz, and the sensing accuracy is improved by about 17%. The maximum BFS estimation error of the original experimental data in Figure 12(b) is about 0.8MHz, while the maximum BFS estimation error after denoising is 0.45MHz, and the sensing accuracy is improved by nearly 100%. Wavelet threshold denoising technology can effectively improve the accuracy of gray BOTDA sensing system, and it is better for improving Brillouin phase shift sensing signal. However, wavelet de-noising will increase the time of data processing. After de-noising, it is necessary to extract the BFS sensor information through a long-time fitting algorithm, thus reducing the response speed of the sensor signal to some extent.

4. Conclusions

Based on BOTDA sensing technology, the sensing performance of gray coded BOTDA is studied. The measurement instability caused by polarization random noise is studied, and then Brillouin phase shift spectrum is used to suppress polarization random noise. Firstly, the polarization dependence of SBS and its influence on BOTDA sensing are analyzed. Then, according to the analysis results, a method to suppress polarization random noise based on Brillouin phase shift spectrum is proposed, and the improvement of sensing accuracy is studied through simulation experiments.

Finally, the denoising effect in Gray BOTDA system is discussed by analyzing wavelet image threshold denoising technology. The results show that the accuracy of the sensor is improved slightly by wavelet denoising technology at the front end of the fiber, but it is improved greatly at the end of the fiber. On the one hand, the maximum BFS estimation error of the original data is about 1.3MHz, and the maximum BFS estimation error after denoising is 1MHz, and the sensing accuracy is improved by about 17%. On the other hand, the maximum BFS estimation error of the original experimental data is about 0.8MHz, while the maximum BFS estimation error after denoising is 0.45MHz, and the sensing accuracy is improved by nearly 100%. This means that the wavelet threshold denoising technology is weak in suppressing polarization random noise, but it reduces the influence on sensing and improves the sensing accuracy by suppressing white noise. However, due to the long time-consuming fitting algorithm in the data processing process of wavelet threshold denoising technology, the noise suppression effect is limited, and it is expected that the rapid extraction of sensing information and the improvement of high-precision sensing performance can be realized in the follow-up research.

References


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