Chapter 41
A Novel Phase Demodulation Method and Simulation for Fiber-Optic Distributed Acoustic Sensor

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Abstract Fiber-optic distributed acoustic sensors (DASs) can be used for various applications, such as seismic wave detection, geological exploration, and large-scale structural health monitoring. Phase-sensitive optical time-domain reflectometer (Φ-OTDR) is one of DAS's most common technical schemes. In this paper, a novel phase demodulation method for DAS is proposed. In this proposed method, four pairs of probing pulses are used to construct in-phase and quadrature (IQ) components for phase demodulation. Compared to the conventional quadrature demodulation method, this method simplifies the system. The scaler model of Φ-OTDR and phase demodulation algorithm are revealed in theory and simulation. Simulations confirm the validity of the proposed method. The demonstrated phase demodulation method achieves ~ 80 dB of SNR, capable of vibroacoustic perturbations along the same line. It has good potential in low-cost and long-distance health structural health monitoring.

Keywords Fiber-optic distributed acoustic sensor (FODAS) · Phase demodulation method · Phase sensitive optical time domain reflectometer (Φ-OTDR)

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41.1 Introduction

Fiber-optic distributed acoustic sensing (DAS) technology is a new sensing technology that enables continuously distributed detection of vibration and acoustic fields. It can be used for various applications, such as seismic wave detection [1–3], geological exploration [4–7], and structural health monitoring [8–13]. Using standard communication fiber cables embedded in infrastructures, DAS provides a novel monitoring solution [13]. It has the advantages of anti-electromagnetic interference, a large dynamic range, and real-time sensing capabilities.

Because of the linear relationship between phase information and fiber strain, a phase-sensitive optical time domain reflectometer (Φ-OTDR) becomes one of the threading technical solutions for DAS [14]. An accurate phase demodulation method plays an important role in waveform recovery of DAS sign Various phase extraction methods for DAS have recently been developed to improve the spatial resolution, frequency response bandwidth, noise reduction, and sensing distance. In [15] proposed a quadrature demodulation scheme using dual-pulse probe signals to extract phase information [15]. Other influential works were done by Ren et al. [16] and He et al. [17]. In [18] presented a direct detection scheme using cyclic pulse coding in Φ-OTDR-based DAS [18]. The scheme achieves ~ 9 dB signal-to-noise ratio (SNR) improvement. In [19] proposed an approach based on temporal adaptive processing of ϕ -OTDR signals to reduce the fading noise in DAS [19]. The approach achieved more than 10 dB of SNR without reducing the system bandwidth and using an additional optical amplifier. Fu et al. proposed a method to compensate for the amplitude imbalance in I/Q demodulated coherent Φ-OTDR system [20]. As an effective phase retrieval scheme, the Kramers–Kronig (KK) receiver has recently become a hot topic in fiber-optic communications for its high spectral efficiency and l continuous wave-to-signal power ratio requirement. Jiang et al. discussed the feasibility of applying the KK receiver into Φ-OTDR and analyzed the signal retrieval error with KK relation [21]. Its performance is verified through numerical simulations and experiments. In addition, the method can be extended to all existing coherent Φ-OTDR systems with no or only a few modifications. Li et al. presented an ultra-high sensitive quasi-distributed acoustic sensor based on coherent detection and a cylindrical transducer [22]. The phase sensitivity of the sensor is −112.5 dB (re 1 rad/μPa) in the field test within the flat frequency range of 500 Hz-5 kHz. In 2023, He et al. demonstrated a scheme of integrated sensing. The system communicates in an optical fiber using the same wavelength channel for simultaneous data transmission and distributed vibration sensing [23]. The scheme improves transmission performance by ~1.3 dB.

However, most of the improved phase detection schemes mentioned above increase the system's complexity. The cost of the hardware is high. In this paper, a novel phase demodulation method for DAS is proposed. In the proposed method, four pairs of probing pulses are used to construct the IQ components for phase demodulation. Compared to the conventional quadrature demodulation method in Φ-OTDR, this method simplifies the system. In addition, it can be extended to an existing

cover with a few modifications on them. The scaler model and phase demodulation algorithm are revealed to reorient Φ-OTDR systems and simulation. Simulation and experimental results confirmed the validity of the proposed method. The demonstrated phase demodulation method can vibroacoustic perturbations along the same line, which has good potential in low-cost and long-distance health structural health monitoring.

41.2   Working Principle

The working principle of Φ-OTDR is based on coherent detection for Rayleigh backscattering (RBS) in optical fiber. A pulse modulator converts continuous light into a pulse. The probe pulse is injected into the sensing fiber. Many tiny regions of inhomogeneous refractive index exist in single mode fiber (SMF), which interact with the probe pulse to produce RBS in all spatial directions [24]. The phase change of RBS can be extracted by the proper phase demodulation method [25]. In addition, the spatial resolution of the method is determined by the delay τ_{delay} between the pulses.

$$\tau_{delay} = \frac{cW}{n} \tag{41.1}$$

where W is the probe pulse width, and n is the SMF's refractive index. And c is velocity of the light propagation (Fig. 41.1).

Consider that the sensing fiber is discretized into a series of reflectors with widths much smaller than the pulse length, as shown in Fig. 41.2. Each reflector acts as a scattering center (RC). The RBS of each RC is calculated separately. And the superposition of the RBS of all mirrors within the pulse width is used as the scattering
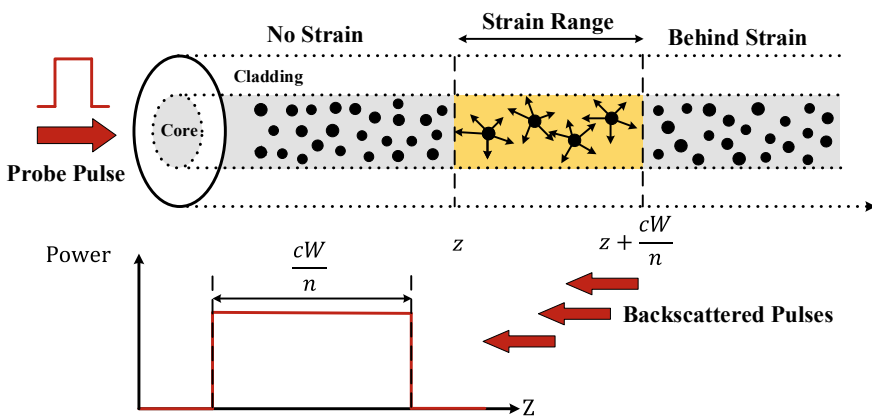

Fig. 41.1 Schematic diagram of pulsed light backward Rayleigh scattering in a fiber
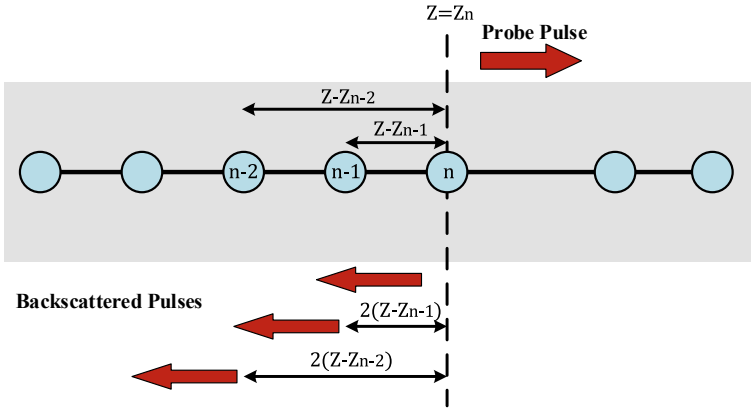
Fig. 41.2 Backscattering signal graphical model

value of a point. Its amplitude of it follows a Rayleigh distribution [26]. Neglecting losses, the sum of backscattered pulses at z_n can be expressed as follows:

$$R(z) = \sum_n^N H(2z - 2z_n) \cdot e^{2ikz_n} \tag{41.2}$$

where $H(x)$ is the expression of the RBS pulse, which has the same expression form as the probe pulse.

Sound is a mechanical wave. Based on the photo-elastic effect [27], its effect on the optical fiber makes the fiber force and produces deformation. When an external acoustic signal is applied to the strain range, a slight change and refractive index change occur. As a result, a phase change occurs. An acoustic signal measurement model can be formed assuming a linear strain distribution, as shown in Fig. 41.3. The RBS pulses of a Φ-OTDR system overlap and interfere. The interfered pulses contain phase information at each RC of the sensing fiber with a length of L. The phase delay is $\psi_d = \beta L$. The phase change $\Delta\psi_d$ is expressed as follows [28]

$$\Delta\psi_d = \beta \cdot \Delta L + L \cdot \Delta\beta = \beta L \cdot \frac{\Delta L}{L} + L \cdot \left(\frac{\partial\beta}{\partial n}\right)\Delta n + L \cdot \left(\frac{\partial\beta}{\partial\alpha}\right)\Delta\alpha \tag{41.3}$$
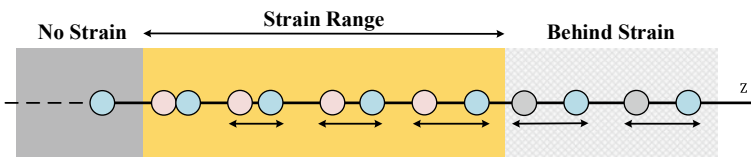

Fig. 41.3 Linear strain measurement model of the optical fiber
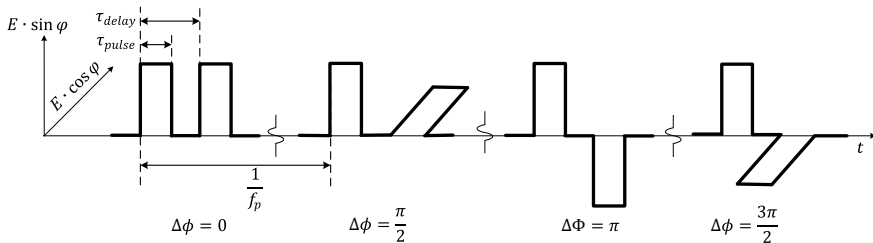
Fig. 41.4 Probe pulse sequence

A novel phase demodulation method using a sequence of four pairs of probe pulses is proposed to extract the phase information efficiently, as shown in Fig. 41.4.

The amplitude of the four pairs of probe pulses can be express as follows

$$E_z = A\left(z + \tau_{delay}\frac{c}{n}\right) + A(z) \cdot e^{i\Delta\Phi_k} \tag{41.4}$$

where $\Delta\Phi_k$ changes with four period OTDR-trace, which equal to $(k-1)\frac{\pi}{2}, k = 1, 2, 3, 4$. Then, four intensities I_1, I_2, I_3 and I_4 can be obtained

$$I_{1,3} = \left|R(t) \pm R\left(t - \tau_{delay}\right)\right|^2$$
$$= \left|R^2(t)\right| + \left|R^2\left(t - \tau_{delay}\right)\right| \pm \left\{R(t)R^*\left(t - \tau_{delay}\right) + R^*(t)R\left(t - \tau_{delay}\right)\right\} \tag{41.5}$$

$$I_{2,4} = \left|R(t) \pm i R\left(t - \tau_{delay}\right)\right|^2$$
$$= \left|R^2(t)\right| + \left|R^2\left(t - \tau_{delay}\right)\right| \mp i\left\{R(t)R^*\left(t - \tau_{delay}\right) + R^*(t)R\left(t - \tau_{delay}\right)\right\} \tag{41.6}$$

where $R(t)$ is RBS amplitude, which has the same expression form as the single pulse. Then, the in-phase and the quadrature (IQ) components containing phase difference $\psi_d = \psi(t) - \psi(t - \tau_d)$ can be obtained

$$\cos\psi_d = \frac{(I_1 - I_3)}{4|R(t)||R(t-\tau_{delay})|} \tag{41.7}$$

$$\sin\psi_d = \frac{(I_2 - I_4)}{4|R(t)||R(t-\tau_{delay})|} \tag{41.8}$$

Using arctangent operation from Eqs. (41.7) and (41.8), ψ_d can be retrieved

$$\psi_d = \tan^{-1}\left(\frac{I_2 - I_4}{I_1 - I_3}\right) \tag{41.9}$$
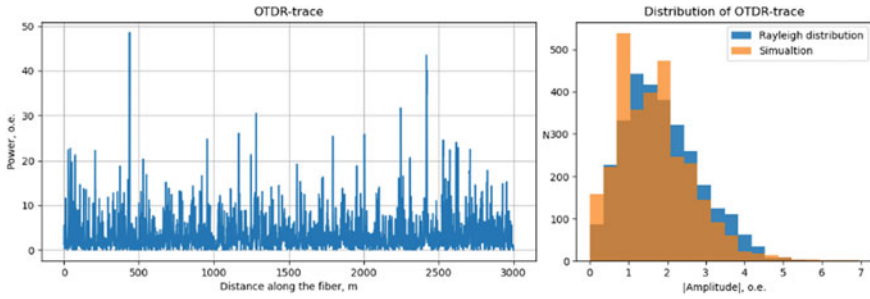
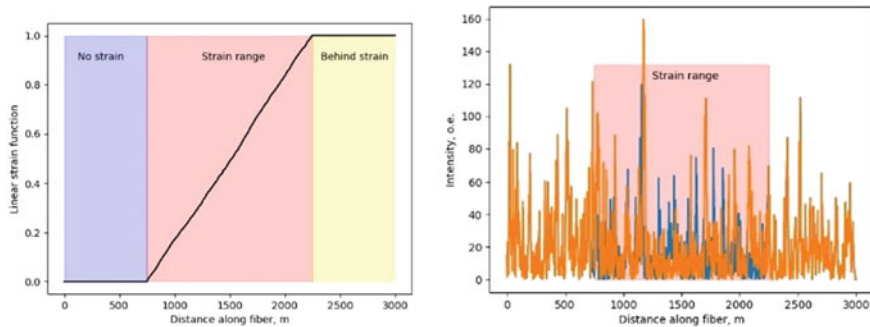**Fig. 41.5** Backscattering model is formed in a 3 km range

Fig. 41.6 Schematic diagram of linear strain distribution and OTDR-trace in the time domain

41.3   Simulation Results

To verify the proposed algorithm, a series of simulations are conducted. A graphical fiber scalar model with a random distribution of RC along the Z-axis is built. And the backscattering model is formed in the 3 km range. The working wavelength of the fiber is 1550 nm with a loss factor of 0.0410517 /km. The refractive index is 1.47. Simulation results of OTDR-trace are shown in Fig. 41.5.

When the acoustic signal is applied to the strain range of the sensing fiber, the simulated OTDR trace is shown in Fig. 41.6. The 3 km sensing fiber is probed using four pairs of 200 ns pulses with a relative delay of 300 ns. The repetition frequency is 1 kHz. The simulation results of intensity and phase changes are shown in Fig. 41.7.

Usually, a piezoelectric (PZT) cylinder is inserted into the sensing fiber to allow the injection of testing signals. The length of the PZT is 30 m. A 10 Hz sinusoidal signal is applied to the PZT. Carrier frequency drift of laser can cause decorrelation of OTDR-traces, which can be described by the $sinc(x)$ function [29]. In the simulation, a 1 kHz laser carrier frequency drift is introduced. The retrieved phase results are shown in Figs. 41.8 and 41.9. The simulation of demodulation results proves that the proposed method is effective and stable, especially when perturbation and disturbance occur
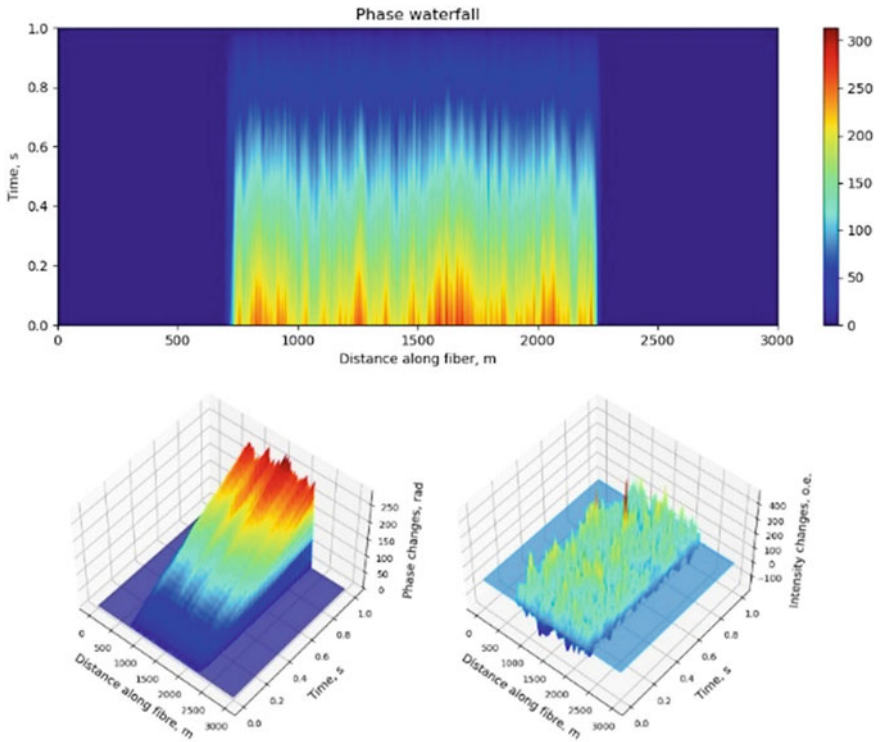
Fig. 41.7 The 2D and 3D plots of intensity and phase change with four pairs of probe pulses
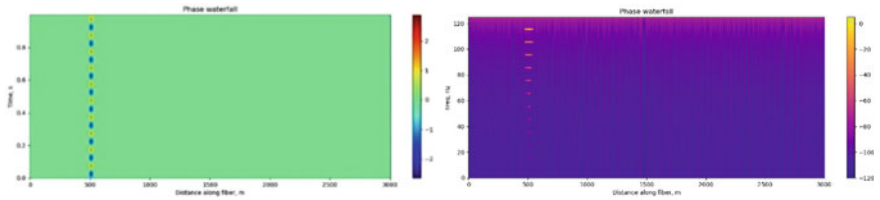

Fig. 41.8 The 2D plot of retrieved phase result from 0 to 3000 m

to laser frequency. The method can achieve a high SNR of 80 dB, which is valuable for phase extraction.
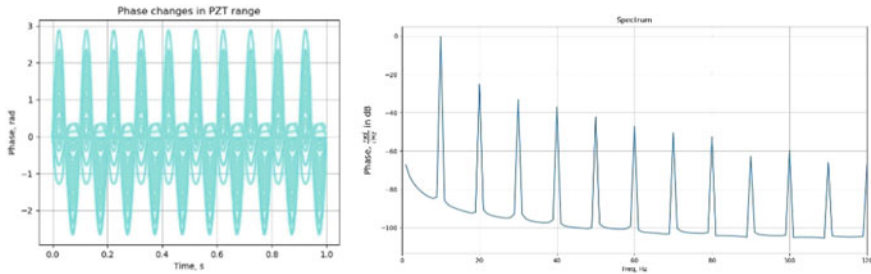
Fig. 41.9 Retrieved phase changes in the PZT range

41.4   Conclusion

A cost-efficient phase demodulation method for DAS is proposed in this paper. Four pairs of pulses are utilized to obtain IQ components for phase extraction. Theory and simulation verify the effectiveness of the demonstrated technique. It simplifies the system's hardware and offers a reliable alternative to other methods for Φ-OTDR-based DAS. The method has good potential in low-cost and long-distance health structural health monitoring. Further works will focus on experimental validation and modulation-related optimization.

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