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Advancements in Optical Fiber Sensing Systems for Pipeline and Tunnel Safety Inspection: A Comprehensive Review and Analysis

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Abstract: In modern engineering construction, the complexity and variability of soil conditions pose huge challenges to the safety of engineering structures. Soil conditions and the safety of these structures are critical considerations in engineering projects. The interaction between natural geological conditions and human engineering activities makes real-time monitoring and precise evaluation of geological-soil systems particularly important, especially for predicting and preventing geological disasters and ensuring the safe operation of pipelines and railways. Optical fiber sensing technology plays a pivotal role in modern monitoring systems, particularly in the realm of pipeline and railway safety inspections. This paper provides a thorough discussion of the technical architecture and process, basic detection principles, and application categories of fiber optic sensors in soil settlement monitoring and pipeline and tunnel safety assessments. It also analyzes the types of sensors suitable for different soil monitoring parameters and their integrated application in real-world scenarios to achieve precise monitoring and safety assessment of pipelines and tunnels.

Keywords: Fiber optic sensor technology, soil settlement monitoring, geological environment monitoring, sensor technology

1. Introduction

Fiber optic sensor technology, with its unique advantages such as wide coverage, high sensitivity, resistance to electromagnetic interference, easy deployment and minimal environmental impact, is increasingly becoming a key technology in soil monitoring and engineering safety assessments [1-3]. This technology can be broadly categorized into three types: point sensing, quasi-distributed sensing, and distributed sensing. The foundational elements of these systems include Fiber Bragg Grating (FBG) and Distributed Optical Fiber Sensing (DOFS) systems. FBG sensors, which collect point-specific data through a Bragg grating embedded in the optical fiber, offer high-resolution detection at specific locations. When densely distributed along a fiber, they approximate a quasi-distributed sensing method, striking a balance between precision and coverage [4]. Conversely, DOFS technology leverages light scattering phenomena within optical fibers for real-time transmission of light signals influenced by ambient conditions. The method, analyzed through principles like Rayleigh, Brillouin, and Raman scattering, provides wide coverage and contiguous detection points, making it well-suited for distributed sensing applications. Despite their widespread application in soil and engineering monitoring, the selection between FBG and DOFS technologies hinges on critical

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factors such as spatial resolution, coverage range, and cost. Understanding the strengths and limitations of these technologies is essential for optimizing their use in various monitoring scenarios. The primary objective of this study is to provide a comprehensive analysis of the application of different optical fiber sensing systems in pipeline and tunnel safety inspection systems. By examining their fundamental principles and technical characteristics, this research aims to identify the optimal sensing strategies for various inspection scenarios.

2. Optical Fibre Sensors

Optical fiber sensors operate by modulating light waves transmitted through the fiber in response to external environmental changes. Based on the modulation principle, they are broadly categorized into two major types: Bragg grating optical fiber detectors and distributed optical fiber detectors.

2.1. Bragg Grating Optical Fiber Sensors

Bragg grating optical fiber detectors function by etching a periodic refractive index modulation structure—known as a Bragg grating—into the fiber core using ultraviolet laser exposure. This grating reflects light at a specific wavelength (Bragg wavelength) while allowing other wavelengths to pass through. The mechanism is illustrated in Figure 1. i, r and t stand for input light, reflected light and transmitted light respectively. n refers to the refractive index. (a) Refractive index profile along the fibre (b) Input spectrum, reflection spectrum with a peak and transmission spectrum with a notch [4]. Therefore, by monitoring changes in the reflected light wavelength, the variation of the corresponding environmental parameters can be detected [4].

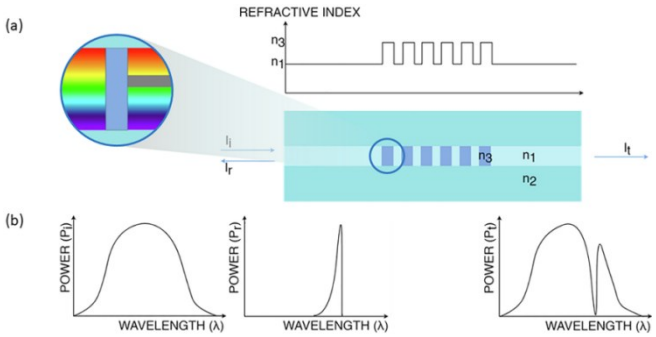

Figure 1: The structure of an FBG and its Spectral Response

The Bragg wavelength λ_B is related to the grating period Λ_G and the effective refractive index n_{eff} of the fiber core, given by:

$$\lambda_B = 2n_{eff}\Lambda_G \tag{1}$$

When external environmental factors (e.g., temperature or strain) affect the optical fiber, they induce changes in the grating period or refractive index, resulting in a Bragg wavelength shift, expressed as:

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = (1-\rho_\alpha)\Delta\varepsilon+(\alpha+\xi)\Delta T \tag{2}$$

$$\rho_\alpha = (\frac{n_{eff}-2}{2})[p_{12}-\nu\,(p_{11}-p_{12})] \tag{3}$$

In equation 2, λ_{B0} is the Bragg wavelength at 0°C and no strain, α is the thermal expansion coefficient of the fiber, ξ is the thermo-optic coefficient, and ρ is the strain-optic coefficient. Equation

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3 provides the method for obtaining the strain-optic coefficient, where v is the Poisson's ratio, and p_{ij} (i, j = 1/2) are the Pockel's coefficients [2].

2.2. Distributed Optical Fiber Sensors

Distributed optical fiber sensors are mainly based on three primary scattering mechanisms: Rayleigh scattering, Brillouin scattering, and Raman scattering. These arise from the interaction of photons with the fiber's local properties, such as density, temperature, and strain. Additionally, acoustic or mechanical waves can dynamically modulate these interactions, further influencing the scattering process [5]. Scattering can be classified as either elastic and inelastic, depending on whether energy is exchanged between the incident light wave and the medium. This classification determines whether the scattered wave undergoes a frequency shift relative to the incident wave. Inelastic scattering can further be divided into Stokes and anti-Stokes scattering. Stokes wave refers to the process where the photon energy decreases and the molecule transitions from a lower energy level to a higher one, while an anti-Stokes wave refers to the opposite effect. Due to their intensities and frequencies being closely related to environmental parameters, they are often used for quantitative environmental detection [5]. Figure 2shows the intensity and frequency characteristics of the three types of scattering.

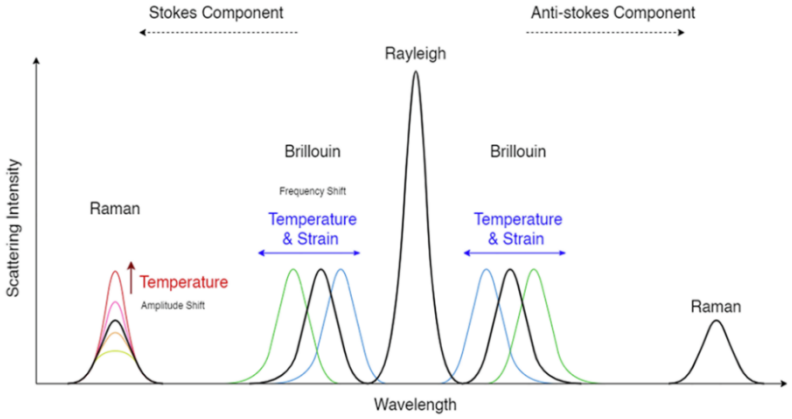

Figure 2: Rayleigh, Raman and Brillouin scattering intensity in optical fibres [4]

The following sections provide a detailed explanation of the three scattering mechanisms.

2.2.1. Rayleigh Scattering

Rayleigh scattering is caused by the interaction between light waves and microscopic density fluctuations in a medium, making it an elastic scattering process. The electric field of the incident light wave induces instantaneous dipoles in the medium's particles, which subsequently radiate secondary electric fields. These secondary fields interferes with the original wave, producing scattered light without a frequency shift. The formation of backscattered Rayleigh signals can be regarded as the spatial statistical response of the medium's random inhomogeneities along the direction of light propagation. The intensity distribution of the scattered signal encapsulates the spectral characteristics of the medium's density fluctuations. Through frequency-domain analysis methods such as Fourier transform, key parameters such as correlation length and amplitude distribution can be extracted, thereby establishing a quantitative relationship between scattering characteristics and the microscopic state of the medium [5].

Additionally, the forward-propagating light wave experiences energy loss due to scattering, which follows an inverse fourth-power dependence on wavelength. This energy loss is further modulated by

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environmental disturbances, serving as complementary sensing information to the backscattered signal. By analyzing both the backscattered Rayleigh signal and the degree of energy loss, fiber damage points or density discontinuities can be effectively detected.

2.2.2. Brillouin Scattering

Brillouin scattering is an inelastic scattering process resulting from the interaction between light waves and acoustic propagating within an optical fiber. The incident light wave's electric field couples with the medium's elastic properties, generating periodic density changes in the form of acoustic waves. These density fluctuations act as a moving refractive index grating that propagates at the speed of sound. Incident photons interact with this dynamic grating, exchanging energy and causing a frequency shift known as the Brillouin frequency shift. The Brillouin frequency shift is jointly determined by the medium's refractive index and the speed of sound:

$$\Delta\nu = \frac{2nV_a}{\lambda} \tag{4}$$

where the speed of sound further depends on the medium's elastic modulus and density:

$$V_a = \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \tag{5}$$

Changes in refractive index directly affects the coupling efficiency between light waves and acoustic waves, while the change in elastic modulus indirectly affects the frequency shift by modulating the speed of sound [5]. Therefore, environmental parameters such as temperature and strain can dynamically modulate the Brillouin frequency shift by altering the medium's elastic modulus and refractive index. The specific mathematical relationship is as follows:

$$\Delta\nu = C_\varepsilon \Delta\varepsilon + C_T \Delta T \tag{6}$$

The linear relationship between the Brillouin frequency shift and temperature/strain is significant and easy to demodulate, making the Brillouin frequency shift a core parameter. By precisely measuring the Brillouin frequency shift and its spatial distribution, the dynamic influence of external environmental parameters on the mechanical and optical properties of the medium can be inverted, providing a physical basis for distributed sensing. Of course, other parameters such as the intensity of Brillouin scattering can also be considered to some extent.

2.2.3. Raman Scattering

Raman scattering is another inelastic scattering phenomenon, resulting from the interaction between photons and the vibrational or rotational energy levels of molecules. At a microscopic level, incident photons excite molecules to virtual energy states. When the molecules relax to a different vibrational or rotational state, they emit scattered photons with altered energy, leading to a frequency shift known as the Raman shift.

From the perspective of wave optics, Raman scattering is the coupling of the incident light wave with the vibrational or rotational modes of molecules. The periodic changes in the polarizability of molecules due to their vibration or rotation modulate the electric field of the incident light wave, thereby generating scattered light waves with frequency shifts [5]. The efficiency of this coupling depends on the polarizability tensor of the molecule and its sensitivity to the external environment.

Therefore, environmental factors such as temperature and strain modulate the Raman shift and scattering intensity by altering the vibrational or rotational energy levels of molecules and their polarizability. The intensities of Stokes and anti-Stokes scattering are directly related to the population distribution of molecular vibrational energy levels. According to the Boltzmann

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distribution, the ratio of the intensity of anti-Stokes scattering to that of Stokes scattering can be expressed as:

$$\frac{I_{AS}}{I_S} = \left(\frac{\lambda_S}{\lambda_{AS}}\right)^4 \exp\left(-\frac{h\omega_M}{2\pi K_B T}\right) \quad (7)$$

Where $\frac{I_{AS}}{I_S}$ is the intensity ratio of anti-stokes and stokes line, $\left(\frac{\lambda_S}{\lambda_{AS}}\right)$ is the wavelength ratio of anti-stokes and stokes line, h is the Planck constant, ω_M is the frequency of the incident light, K_B is the Boltzmann constant, and T is the absolute temperature. By measuring the intensity ratio of I_{AS} to I_S, the temperature change can be precisely inverted [5]. This method offers high spatial resolution and real-time capabilities, making it highly suitable for monitoring temperature distribution and thermal stress changes in building structures.

3. Application of Different Optical Fiber Sensing Systems in Pipeline and Tunnel Safety Inspection Systems

Various optical fiber sensing technologies are utilized for pipeline and tunnel safety monitoring, each with distinct advantages and limitations. In this section, the author first briefly summarize the advantages and disadvantages of different detection technologies and then describe the existing applications of static parameter monitoring technologies and the development status of dynamic parameter measurement systems.

At present, the most widely used optical fiber sensing technologies include FBG sensing and sensing technologies based on three types of scattering phenomena. FBG sensing technology is preferred due to its low cost and simple principle, but it has limited measurement range and low sensitivity to environmental changes. Rayleigh scattering-based φ-OTDR is highly sensitive to stress changes but is affected by fiber bending loss. Brillouin scattering BOTDA and BOTDR can monitor both temperature and pressure changes. BOTDA offers superior performance and higher spatial resolution but requires dual-end access, limiting its application, whereas BOTDR is more versatile but has slightly lower resolution [3]. Raman scattering-based ROTDR is solely used for temperature monitoring, as it calculates temperature through the intensity ratio of positive and negative Stokes waves, eliminating errors caused by absolute attenuation [6]. However, this technology is costly, and the demodulator's complexity makes it challenging to operate [5].

However, the cost of using this technology is high and the demodulator principle is complex and difficult to operate.

Indirect coefficients are derived from direct coefficients, and research efforts focus on developing accurate models to minimize derivation errors. In civil engineering structures, the most common indirect coefficient is the equivalent displacement calculated from stress. The three most frequently used methods to obtain this are empirical formulas, integration methods, or machine learning methods. Empirical formulas are simple to use, but their adaptability to different scenarios is limited. Peng et al. proposed a quasi-distributed land subsidence monitoring method based on pulsed pre-pumped Brillouin Optical time domain analysis (PPP-BOTDA). The method arranges optical fibers in a zigzag patern on monitoring rods and derives a formula for converting fiber strain into support displacement using geometric principles [7]. Experimental results show that this method achieves an accuracy of less than 1 mm and can simultaneously monitor settlement at 100 points, offering high spatial resolution and efficiency, making it suitable for remote and large-scale ground settlement monitoring. The integration of stress data allows for high-precision prediction of distance change, delivering good performance effect. However, in practical applications, the selection of fixed points has a certain impact on accuracy and will increase the calculation amount of layout to a certain extent [8].

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Another developing trend is the application of machine learning, which makes the model-building process more reliable, efficient and portable, achieving better results and performance than the first two. Cheng et al. studied the effectiveness of distributed fiber strain sensing technology in monitoring ground settlement caused by underground pipeline leakage through laboratory model experiments [9]. They proposed a strain-to-displacement transformation method based on the Seq2Seq model, which was validated through experimental data. The results show that this method can effectively convert the strain monitored by optical fiber into ground settlement, and the conversion accuracy is higher than that of the traditional method.

Humidity and velocity are also important indirect parameters in pipeline and tunnel monitoring [10]. Humidity is an indirect parameter that can be obtained by stress conversion. The cladding film of optical fiber uses humidity-sensitive material. When the humidity changes, the stress exerted on the optical fiber by the hygroscopic expansion or dehumidification contraction characteristics of the cladding film can be converted into a representation of humidity [11]. Air velocity, on the other hand, is an indirect parameter calculated based on temperature-sensitive and displacement changes. Optical fiber detectors uses temperature sensitive elements in the optical fiber to monitor temperature changes caused by air flow, while capturing tiny dislocations caused by air flow through the displacement sensing characteristics of the optical fiber itself. After processing, these temperature and displacement data can be converted into an accurate representation of the air flow rate, to achieve real-time monitoring and analysis of the air flow rate.

To better cope with sudden dynamic changes such as vibration and collapse, the performance of dynamic parameter monitoring system is gradually improving. φ-OTDR breaks through traditional fiber length limitations on spatial resolution, expanding the frequency monitoring range without compromising detection distance or signal-to-noise ratio. The combination of φ-OTDR and BOTDR addresses both low frequency and large strain monitoring demands, making vibration monitoring more comprehensive and effective [6]. He et al. proposed a collapse monitoring method based on distributed fiber strain and vibration sensing, employing φ-OTDR and BOTDR for joint monitoring [12]. By designing a multi-parameter distributed fiber optic sensor, they achieved simultaneous measurement of strain and vibration during collapses. Laboratory and field experiments show that this method can effectively identify collapse events and distinguish collapse types.

Pipelines and tunnels share similar structural characteristics, as both can be regarded as connected ring components. Consequently, their optical fiber layouts are also similar. Points are placed in the original ring horizontally to monitor the deformation of the ring configuration, and each ring is connected longitudinally to monitor the change of the configuration between the rings [13]. The selection of detector types depends mainly on the application scenario, the measurement range meets the needs, the matching degree between the environment of the fiber and the fiber shell such as temperature tolerance, strain tolerance. Additionally, the detector's placement must align with its intended function; for example, in pipeline leakage detection, fibers can be arranged on the outside of the pipeline to sense the temperature, and the liquid corrosion inside the pipeline [4].

4. Conclusion

This article analyzes the basic principles of different types of optical fiber sensors and their usability in practical scenarios. By integrating the latest developments of different optical fiber detection technologies in pipelines and tunnels, it summarizes the applications of optical fiber detection technology in the field of structural health monitoring for two similar structures. Due to the similarities in the construction process and final structure of these two types of large-scale projects, the article conducts a comprehensive analysis of both, organizing recent research directions and achievements in different monitoring indicators. It not only includes strategies for improving the monitoring performance of basic indicators but also points out the future development direction of

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this field. Additionally, it provides guidance on the selection and performance evaluation of optical fiber detectors in actual operations, comprehensively outlining the basic requirements for two application scenarios of optical fiber detectors in structural health monitoring. However, this article does not summarize the performance of commercial optical fiber detection systems and other products that are currently in use on the market. Therefore, relevant companies and technicians may need to further evaluate and select product quality and performance in future research. In the future, the integration of optical fiber detection technology with fields such as machine learning will become increasingly profound. In this article, relevant recent achievements have already utilized machine learning models to improve accuracy. With the rapid development of algorithm models, more innovative developments and performance improvements of large-scale optical fiber detection systems driven by algorithms will emerge in the future.

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