Analysis on Structural Health Monitoring System of High-Pile Wharf Based on Optical Fiber Sensor

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Abstract. With the continuous development of my country's economy, the demand for various high-tech products has also increased. Therefore, as an important detection tool for industrial production, optical fiber sensors have become one of the important tools for the development of the Internet of Things industry. Real-time monitoring and diagnosis of structural performance of main engineering structures, timely perception of structural damage, safety evaluation, structural performance changes and remaining life predictions. Make maintenance decisions to improve, improve and ensure the operational efficiency of engineering structures and protect people’s lives and property. The structural health monitoring system collects data about the status of structural services in real time, uses specific damage recognition algorithms to determine the location and scope of damage, evaluates structural safety in a timely and effective manner, predicts structural performance changes, and provides early warning for emergencies. In recent years, structural health monitoring systems have become one of the hot topics in international academic research. In response to the needs of large-scale civil engineering health monitoring systems at home and abroad for monitoring methods, a method for structural health monitoring of high-piled wharves based on optical fiber sensor technology is studied. The structural health monitoring system of the high-piled wharf includes an intelligent monitoring system and a signal demodulation system.

Keywords: Optical Fiber Sensor; High Pile Wharf; Structural Health Monitoring; Damage Mechanism

1. Introduction
Since the beginning of the 21st century, my country’s economy has developed more rapidly, the country’s investment in infrastructure has increased, and extraordinary achievements have been made in the construction of civil engineering [1]. However, due to environmental erosion, material aging, fatigue effects of building materials, and mutation effects, the terminal inevitably suffers from damage and reduced carrying capacity during operation, and it is more prone to major accidents when encountering special road conditions (2) ]. Recently, the structural health monitoring of wharf buildings has gradually attracted the attention of the engineering community. Disaster warning, post-
disaster evaluation and survival life prediction of wharf buildings have become the current research hotspots of scholars in many countries. Most high-piled wharves operate within a certain period of time, and structural damage and damage will occur due to factors such as corrosion, aging, and overload, which threaten the structural safety of the high-piled wharf and affect the service life of the high-piled wharf[3]. However, due to the low operating frequency of the existing high-piled wharf structure health inspection, it cannot meet the requirements of safe operation, maintenance, and enhanced upgrade of the high-piled wharf. Therefore, it is necessary to conduct health monitoring work on the high-piled wharf.

Compared with electronic sensing technology, optical fiber sensing technology is based on various types of optical fiber devices and inherent sensing mechanisms, as well as many characteristics that do not exist in electronic sensing elements, and can provide existing electronic sensors [4]. Achieved indicators and results. Due to its small size, high precision, strong resistance to electronic interference, water resistance, corrosion resistance and excellent durability, optical fiber sensors have gradually replaced existing electrical sensors. They are used in buildings, bridges, reservoirs and It is widely used in the health test of marine and other civil engineering structures [5]. The development of high-piled wharf structural health monitoring technology is relatively late. As a direct component to perceive changes in the bridge, optical fiber sensors, its performance, sensitivity and response time, output signal stability and other factors will directly affect the performance of the entire monitoring system[6]. In the past monitoring systems, traditional mechanical and electrical sensors are often used as components to obtain information, and their performance is easily affected by the working environment. It is not very good for high-piled wharf structures that require long-term monitoring. The traditional sensing element still has many flaws[7].

The structural health monitoring of the high-piled wharf is through the destruction monitoring of the physical and mechanical characteristics of the building, the real-time monitoring of the overall movement of the building, the diagnosis of the damage and location of the building, the service status, reliability, and durability of the building and land fertility evaluation. Trigger early warning signals of structural emergencies or serious abnormalities in use, and provide basis and guidance for maintenance of high-piled wharf structures, maintenance and management decisions [8]. At present, fiber optic sensors are widely used in perimeter security systems due to their multiple unique transmission advantages. Fiber optic sensors can be used as conduction and sensing elements at the same time. Compared with other sensors, they can achieve long-distance transmission without adding any external media [9]. In practical applications, the temperature value of the temperature compensation fiber can be used to compensate the wind speed value to eliminate the influence of the environmental temperature change and the air cooling effect during the wind speed measurement process, and effectively improve the accuracy of the optical fiber sensor detection [10].

2. Optical Fiber Sensor Algorithm

2.1. Optical Fiber Sensor Theory

In order to change the state of the light wave, the refractive index of the core scene changes periodically, the light generation response mode of the specific wavelength is combined, and the transmission and reflection spectrum of the wavelength are abnormal. The refractive index distribution is determined by the intensity of the input light. The refractive index distribution characteristics can be expressed in the following ways.

\[
n(r,\varphi,z) = \begin{cases} 
n_1[1 + F(r,\varphi,z)] & |r| \leq a_1 \\
n_2 & a_1 \leq |r| \leq a_2 \\
n_3 & |r| \geq a_2 
\end{cases}
\]  

(1)

In formula (1), \(F(r,\varphi,z)\) is the photoinduced refractive index change function, which has the following characteristics:
\[
F(r, \varphi, z) = \frac{\Delta n(r, \varphi, z)}{n_1} \tag{2}
\]

\[
|F(r, \varphi, z)| = \frac{\Delta n_{\text{max}}}{n_1} \quad (0 < z < L) \tag{3}
\]

\[
F(r, \varphi, z) = 0 \quad (z > L) \tag{4}
\]

In order to give the general form of \(F(r, \varphi, z)\), it is necessary to analyze the light wave field that causes the refractive index change. Based on the above considerations, the following function can be used to describe the photoinduced refractive index change:

\[
F(r, \varphi, z) = \frac{\Delta n_{\text{max}}}{n_1} F_0(r, \varphi, z) \sum_{q = -\infty}^{\infty} a_q \cos[(k_g q + \varphi(z))] \tag{5}
\]

In the formula, \(F(r, \varphi, z)\) is the exposure unevenness of the fiber transverse interface caused by the ultraviolet absorption effect of the core, or the lattice reduction rate spurious non-uniformity caused by unknown factors.

\[
n(r, \varphi, z) = n_1 + \Delta n_{\text{max}} F_0(r, \varphi, z) \sum_{q = -\infty}^{\infty} a_q \cos[(k_g q + \varphi(z))] \tag{6}
\]

2.2. The principle of Optical Fiber Temperature Sensing

\[
d\lambda_B = 2(n_\text{eff} \partial \Lambda/\partial T + \partial n_{\text{eff}}/\partial T) dT \tag{7}
\]

From equation (7), the grating period change caused by the thermal expansion effect is:

\[
\frac{d\Lambda}{dT} = \alpha \cdot \Lambda \tag{8}
\]

The effective refractive index change caused by the thermo-optic effect is:

\[
\frac{dn_{\text{eff}}}{dT} = n_{\text{eff}} \cdot \xi \tag{9}
\]

The relative temperature sensitivity of the Bragg grating can be expressed as:

\[
K_T = \frac{1}{\lambda_{\text{eff}}} \frac{d\lambda}{dT} = \alpha + \xi \tag{10}
\]

Further observation of equation (10), it is not difficult to get that the temperature sensitivity of the Bragg grating is related to the thermal expansion coefficient of the material. For a material with a thermal expansion coefficient of \(\alpha_s\), the relative sensitivity of the grating can be expressed as:

\[
K_T = (\alpha + \xi) + (1 - P_e)(\alpha_s - \alpha) \tag{11}
\]

Based on (11), we can improve the temperature sensitivity of the Bragg grating by selecting appropriate materials.

2.3. Coupled-mode Equations of Fiber Bragg Gratings and Their Solutions

As long as the mode coupling in the fiber Bragg grating occurs between the forward mode and the reverse mode transmitted along the z-axis, it belongs to the coupling between the two reverse modes. Let 1 and 2 denote the forward and reverse modes propagating along the z and -z directions respectively:

\[
a_1 = A(z)e^{j\beta_1 z} \tag{12}
\]

\[
a_2 = B(z)e^{j\beta_2 z} \tag{13}
\]
Where $\beta_2=\beta_1$, only considering the coupling between these two modes can be obtained:

$$
\begin{align*}
\frac{dA}{dx} &= j(K_{11}A + K_{21}Be^{j(\beta_2-\beta_1)x}) \\
\frac{dB}{dx} &= j(K_{22}B + K_{12}Ae^{j(\beta_2-\beta_1)x})
\end{align*}
$$

The coupling coefficient $k_{\nu\mu}$ in the formula is:

$$
k_{\nu\mu} = -2\omega\varepsilon_0\frac{\iint_{+\infty}^{+\infty} h_S^2 d\delta}{\iint_{+\infty}^{+\infty} h_S^2 d\delta}
$$

It can be seen from the coupling coefficient equation that the self-coupling coefficients of the forward mode and the reverse mode are equal, which is $K_{12} = K_{21}$.

2.4. Application of Optical Fiber Sensor

Optical fiber sensor is used to convert the measured information into measurable optical signal. It consists of optical source, light source and signal processing instrument. Optical fiber sensor has the function of information modulation and demodulation. In order to change the light wave parameters, the measurement part is called the modulation region, and the photodetector and signal processing part are called the compound modulation region. The light emitted by the laser is divided into two paths of 2x2 lovers. One way is to reach Miller M1 through the standard wall, and the other is to move to Miller M2 through sensors. The main method of optical fiber sensor sensing correlation signal is to solve the interference phenomenon caused by external pressure, capture and identify the related signal. Therefore, it is difficult to use in many fields such as oil field exploration and dynamic detection.

3. Modeling Method

It shows that the basic equations of hierarchical fluid mechanics are closed. In order to prevent the equations from being closed again, the equations of turbulent motion must adopt averaging time or isolation. Therefore, a turbulence model must be adopted for new unknowns and then closed again. The main function of the turbulence model in CFD is to correlate the new unknown index with the average velocity tilt. Among them, the model widely used in engineering structural health monitoring is solved based on the Reynolds average N-S equation. $\kappa-\varepsilon$ Two-equation mode eddy viscous closed mode model.

In this model, the eddy viscosity model of Reynolds stress is:

$$
\tau_{ij} = 2\mu\left(S_{ij} - \frac{S_{\omega\delta j}}{3}\right) - \frac{2\mu k\delta_{ij}}{3}
$$

The definition of eddy viscosity is the function of turbulent flow energy $k$ and turbulent dissipation rate $\varepsilon$ as:

$$
\mu_i = \frac{c_{f}\rho k^2}{\varepsilon}
$$

The energy transfer equation and energy dispersion transfer equation of warm current are as follows.

$$
\frac{\partial \rho k}{\partial t} + \frac{\partial }{\partial x_i}\left(\rho u_i \frac{\partial k}{\partial x_j} - \left(\mu + \frac{\mu_j}{\sigma_{ij}}\right)\frac{\partial k}{\partial x_j}\right) = \tau_{ij}S_{ij} - \rho \varepsilon + \Phi_k
$$

$$
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial }{\partial x_i}\left(\rho u_i \varepsilon - \left(\mu + \frac{\mu_j}{\sigma_{ij}}\right)\frac{\partial \varepsilon}{\partial x_j}\right) = c_{\varepsilon} \frac{\varepsilon}{k} \tau_{ij}S_{ij} - c_{\varepsilon} f_2 \rho \varepsilon \frac{\varepsilon^2}{k} + \Phi_\varepsilon
$$
In the above two formulas, the first port on the right is the generative port, the second port is Susheng port, and the third port is bigang.

Attenuation function:

\[
f_\mu = \exp\left(-\frac{3.4}{(1 + 0.02R_e)^2}\right) \quad (20)
\]

\[
f_2 = 1 - 0.3\exp(-R_e^2) \quad (21)
\]

\[
R_e = \frac{\rho k^2}{\mu \varepsilon} \quad (22)
\]

4. Evaluation Results and Research

Through the above analysis and description, the basic functions required by the structural health monitoring system of high-piled wharf are: structure measuring point vibration collection, vibration signal modeling, parameter identification, modal parameter extraction and vibration shape display have been basically realized in the software. Considering that most of the actual high-piled wharf structure monitoring is in the field, vibration sensors are installed in various parts of the structure, and it is difficult to directly connect with the data acquisition system. Generally speaking, it is more common to transmit vibration signals through optical fibers, which requires the addition of long-distance optical fiber communication modules and photoelectric conversion devices in the actual hardware system. In software processing, it is necessary to add processing functions such as digital filtering and detrending to enhance the signal-to-noise ratio.

**Table 1.** Hardware used in the structural health monitoring system of high-piled wharf

| Name                        | Model           | Quantity |
|-----------------------------|-----------------|----------|
| PXI controller              | NI PXI 8176     | 1        |
| Dynamic Data Acquisition Card | NI DSA 4472   | 1        |
| Acceleration fiber sensor   | Lance           | 8        |

**Table 2.** Tools required for software development

| Name                                    | Version |
|-----------------------------------------|---------|
| Lab VIEW                                | 7.1     |
| Lab VIEW Advanced Model Processing      | 7.1     |
| Package                                 |         |
| NI DAQ mx                               | 7.4     |

Based on the vibration signals before and after the damage of the concrete beam in the high-piled wharf, the modal modes before and after the damage are calculated. Figure 1 shows the changes before and after damage to the first-order mode of the structure.
Figure 1. Comparison of the first-order mode shape before and after damage

It can be seen from Figure 1 that the data measured by the optical fiber sensor shows that the mode shape of the high-piled wharf structure has a tendency to increase near the structural damage, but the relative change of the mode shape before and after the damage is not obvious.

According to the calculation formula of the modal curvature in the method of extracting the health damage criterion of the high-piled wharf, the modal curvature changes before and after the structural damage are further obtained, as shown in picture 2.

Figure 2. Comparison of first-order mode shape curvature before and after damage

The results show that the relative change of the healthy mode curvature of the high-piled wharf structure has a good indication of the damage of the high-piled wharf structure. The modal curvature before and after structural damage is suitable as the health damage criterion of high-piled wharf.

5. Conclusion
At present, there is almost no research on the structure monitoring technology of coastal port high mountain wharf. According to the structure and environmental characteristics of the high file Wharf in the coastal harbor, this paper analyzes the pressure characteristics of the high document wharf along the coast, and puts forward the structural integrity monitoring index of the high file wharf, and establishes the monitoring enterprise of the structural integrity of the high file wharf along the coast. Wharf In order to ensure the safety and reliability of passenger stations, many passenger stations should take effective measures as soon as possible, and use the structural monitoring system of high wharf to evaluate the safety status of high terminal. In this paper, the structure condition monitoring method of high wharf based on optical fiber sensing technology is deeply studied. On the basis of thorough
investigation, the structure condition monitoring function of high wharf and the application of optical fiber sensor are understood. The sensor used for measuring strip is designed in standard grid mode, and a complete set of structural condition monitoring methods for high file wharf is developed. Considering all aspects, the integrity monitoring method of high wharf structure can sense the information of high wharf, and the core parameters and wavelength modulation system can meet the requirements. This method can correctly realize the condition monitoring of wharf structure with high accumulation.

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