Research on Monitoring of Coal Mine Shaft Deformation Based on Fiber Grating Technology

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Abstract. As one of the most important production resources, coal has a huge demand. China is the country with the largest amount of coal mining and export in the world. Coal mines are widely distributed throughout the country. A large number of coal mines have a long service life and damage accidents occur from time to time. Affecting the daily production of the mine, not only caused a lot of economic losses, but also hidden dangers of safety accidents. The optical fiber method applied to the deformation monitoring of the mine shaft can better adapt to the complex working environment under the mine, which is the current trend of scientific and technological development and also meets the requirements of the modernization and information industry.

1. Introduction
As one of the most important production resources, coal has great demand. China is the country with the largest amount of coal mining and export in the world. Coal mines are widely distributed throughout the country. A large number of coal mines have been in service for a long time, and damage accidents occur from time to time. As the only channel of daily production of coal mine, the shaft is the "throat" part of the whole mine. With the increase of service life and mining depth, as well as the change of surrounding geological environment, it has also become one of the most damaged places. Since its own statistics, there have been more than 100 mines with shaft (shaft wall) damage accidents in China, which has affected the daily production of the mine, not only caused a lot of economic losses, but also caused potential safety accidents.

There are many methods to monitor the deformation of the shaft. At present, there are many widely used methods, such as steel wire baseline method, embedded sensor method, three-dimensional measurement, GPS monitoring, etc., which can effectively provide the data of the deformation of the shaft, but they can not prevent the disaster in advance. As a new monitoring method, optical fiber method has high precision, small volume, less electromagnetic interference, easy to combine with computer and electronic communication technology. In recent years, it has been applied to the deformation monitoring of various buildings such as mines, roads, houses, bridges and so on. Compared with the traditional method, the optical fiber sensor can continuously and real-time monitor the wellbore at the accident-prone depth, and can connect multiple sensors in series on a main cable, effectively sense the values of wellbore stress, deformation and temperature, and give an effective early warning in time, breaking the shortcomings of the traditional monitoring method of single physical measurement. In addition, optical fiber monitoring is continuous monitoring, which does not
affect the daily production work and has little economic impact. The application of optical fiber method in the deformation monitoring of mine shaft can better adapt to the complex working environment under the mine. It is the current trend of science and technology development, and also in line with the requirements of the construction of modern and information industry.

2. Principle and development of light grating sensor

2.1. Development of Fiber Grating Technology

In 1978, Hill, a Canadian scholar, first observed the photon induced grating in Germanium Doped Fiber and used the argon ion laser to increase or extend the light irradiation time injected into the fiber core, thus forming the grating in the fiber core, opening the door of the fiber grating for human beings [1]. Later, Meltz and others used the method of side exposure of interference fringes of ultraviolet light source to produce refractive index modulation or phase grating in the fiber core, which promoted the research and application of fiber. In 1989, American Morey first carried out the research of FBG temperature and strain sensor, and achieved great success, opening the research discipline of FBG sensor [2]. In the same year, Mendez of Brown University proposed to embed FBG sensor into concrete building beam to achieve the monitoring purpose, and described the possible problems and basic ideas in practical application. Since then, countries have increased efforts to carry out the application of FBG sensor in concrete structure.

In the past ten years, great progress has been made in the field of fiber Bragg grating sensing. In practical applications, key technical issues such as sensor packaging have been well resolved, and have been obtained in aerospace, civil construction, composite materials and other fields. Widely used.

2.2. Theoretical model of fiber grating

The principle of fiber grating can be understood as the change of the fiber waveguide conditions caused by the periodic change of the refractive index of the fiber core region, which results in corresponding mode coupling at a certain wavelength, which makes its projection spectrum and reflection spectrum appear singular [2]. We take the uniform period sinusoidal fiber grating as an example to explain its coupling model, and the structure is shown in Figure 1.

![Figure 1. Uniform fiber grating structure and refractive index distribution](image)

The refractive index perturbation of uniform fiber grating is

\[
\Delta n(r) = \Delta n \cdot \cos \left( \frac{2\pi}{\Lambda} \cdot z \right)
\]  

(1)
$\Delta n$ is the maximum change in refractive index, $\Lambda$ is the grating period. The coupled wave equation of the grating can be obtained from formula (1) as:

$$
\begin{aligned}
&\frac{dA_i^+}{dz} = k \cdot A_i^+ \cdot \exp(2i\Delta \beta z) \\
&\frac{dA_i^-}{dz} = k^* \cdot A_i^- \cdot \exp(-2i\Delta \beta z)
\end{aligned}
$$

(2)

$A_i^+ A_i^-$ is the forward and backward conduction modes, $k$ is the coupling coefficient, $\Delta \beta z$ is the phase mismatch condition. Correspondingly, the phase matching conditions of the sinusoidal grating can be obtained as:

$$
\begin{aligned}
&\Delta \beta = \frac{k_S}{2} - \beta_s = 0 \\
&\lambda_b = 2n_{eff} \Lambda
\end{aligned}
$$

(3)

$n_{eff}$ is the effective refractive index of the $s$-th mode.

In the initial region of the grating, there are $A_i^+(0) = 1, A_i^-(L) = 0$, according to this boundary condition, the decoupling wave equation is:

$$
\begin{aligned}
&A_i^+(z) = \exp(-i\Delta \beta z) \cdot \frac{-\Delta \beta \sinh[(z-l)S] + iS \cos[(z-l)S]}{\Delta \beta \sinh(Sl) + iS \cos(Sl)} \\
&A_i^-(z) = \exp(i\Delta \beta z) \cdot \frac{ik \sinh[(z-l)S]}{\Delta \beta \sinh(Sl) + iS \cos(Sl)}
\end{aligned}
$$

(4)

Where, $S = \sqrt{k^2 - (\Delta \beta)^2}$, It has nothing with the initial conditions. In this way, the reflectance of the fiber grating $R$ and transmittance $T$ can be obtained:

$$
\begin{aligned}
&R = \frac{k^2 \sinh^2[SL]}{\Delta \beta^2 \sinh^2[SL] + S^2 \cosh^2[SL]} \\
&T = \frac{S^2}{\Delta \beta^2 \sinh^2[SL] + S^2 \cosh^2[SL]}
\end{aligned}
$$

(5)

When the phase matching conditions are fully satisfied, $\Delta \beta = 0, S = k$, the peak reflectance can be obtained:

$$R = \tan^2(Sl) = \tan^2\left(\frac{\pi \cdot \Delta n}{\lambda_b} \cdot l\right)
$$

(6)

From this, an approximate expression of the bandwidth of the Bragg grating can be calculated:

$$
\frac{\Delta \lambda}{\lambda_b} = S \left(\frac{\Delta n}{2n_{eff}}\right)^2 + \left(\frac{\Lambda}{L}\right)^2
$$

(7)
In this model, changes in the period $\Lambda$ and effective reflectance of the fiber grating $n_{\text{eff}}$ cause changes in the spectral pattern. The sensing process of the fiber grating sensor is to obtain information through the modulation of the spectral pattern.

2.3. Application of fiber grating sensor

The materials used for fiber grating sensors are basically the same as ordinary optical fibers, both of which are silicon dioxide. However, in actual application process, considering its fragile material and the influence of external conditions such as temperature and humidity, it is necessary to design its package. Commonly used the package structure is shown in Figure 2.

![Figure 2. Common Package Structure of Fiber Grating Sensor](image)

With the development of fiber grating fiber optic sensing model theory, maturation of packaging technology, and other key issues such as sensor design have been gradually solved, fiber optic sensing has begun to monitor applications from underground to ground and even aerospace engineering [3]. In 1993, Canada and the United States pioneered the application of fiber-optic sensors to monitor the health of bridges. In China, the Hulan River Bridge and the Haikou Century Bridge became the first bridge buildings to use fiber-optic sensing. In the aerospace industry, the United States uses fiber-optic sensor networks to monitor space shuttles in real time, and Germany also uses fiber-optic sensors to monitor temperature and strain on wings in flight.

In 2008, Professor Chai Jing of Xi'an University of Science and Technology proposed the use of fiber grating sensors to monitor the wellbore subsidence and deformation [4]. The method of embedding Bragg gratings at a specified depth in the loose stratum of the wellbore was used to monitor and predict the subsidence and deformation around the wellbore. Experiments show that this method is safe, reliable, simple to operate, and can be widely used.

3. Wellbore Damage Status and Mechanism Analysis

3.1. Hazards and main features of wellbore damage

Wellbore damage has occurred in various mining areas in China since the 1980s. Among them, the main mining areas such as Xuzhou, Huaibei, Yanzhou, Datun, etc. are more serious.

Once a wellbore damage accident occurs, it will greatly affect the production of the mining area. The main hazards of this type of accident are: spalling and cracking of the concrete on the wall of the well where the shaft is damaged, and damage to the reinforced structure, accompanied by water seepage, slurry and even gushing water; Safety poses a great threat; normal drainage and lifting of the wellbore will be affected, resulting in production suspension [5]. In the wellbore damage accident that has occurred, even more than ten meters of shaft wall concrete fell off, metal tanks were severely damaged, and the mine was forced to stop production for several months, resulting in economic losses of tens of millions of yuan.

Based on the analysis of more than 70 wellbores in Xuzhou, Huaibei, Datun, Yongxia, Yanzhou and other mining areas, the following characteristics were found:

1. The damage patterns are similar: Most of the damaged wellbore's morphological characteristics are approximately horizontal annular cracks, and the concrete in the well wall has spalled and dropped.
Significant internal deformation of the wellbore: Before the wellbore was damaged, especially before the well wall was ruptured, the tank tunnel was usually bent and deformed, the gap between the tank tunnel and the well wall was reduced, and the concrete was partially deformed radially.

Sinking of the surface: The surface around the mine where the wellbore is damaged will sink in different amplitudes, and the outward diffusion around the wellbore will increase.

Similarity of geological features: The damaged shafts all pass through the thicker Quaternary surface soil layer. Part of the location of the damage accident is concentrated near the interface between the Quaternary surface soil layer and the bedrock, and part of it is concentrated in the upper specific range. In the aquifer or clay layer, the water level drops significantly when damaged.

Concentration of time: The time of wellbore damage is basically in April-October each year, concentrated in July-August, and all are several years after the mine is put into production.

3.2. Mechanism analysis of wellbore damage

The characteristics of the damage are only a summary of the performance of the accident after the accident, and the reasons behind the characteristics need to be summarized and analyzed. First of all, the time concentration of the damage accident tells us that the rupture of the well wall is related to the loss of the lower water and the rise in temperature. The loss of the lower water is gradually accumulated with the production of the mine, so the occurrence of the damage of the well wall is after the mine is put into production. For several years, the specific time of damage depends on the rate of groundwater loss [6]. Secondly, from the similarity of geological characteristics, it can be seen that the vertical stress distribution of the wellbore has a certain regularity, which is determined by the external force acting on the wellbore. Third, surface subsidence indicates that the damage of the wellbore is related to the hydrophobic settlement of the topsoil. Therefore, the deformation and settlement mechanism caused by the hydrophobicity of the topsoil is also the key to the wellbore damage. The similarity of the final damage patterns indicates that the causes of most wellbore damages are consistent.

Xu Yanchun of the Chinese Academy of Coal Science used the Sondex observation system to conduct field tests on the top soil layers of Xinglongzhuang Coal Mine Industrial Plaza in Yanzhou Mining Area. The results showed that the compression of the aquifer below the top soil reached the maximum. Outer diffusion gradually decreases, that is, the soil layer undergoes bending deformation. The lower compartment has a large compressive deformation, and the amount of deformation varies from time to time, but the overall deformation is basically stable at a certain level [7].

As the mining time increases, the water in the loose stratum gradually infiltrates, the water level in the bottom aquifer drops, and the surface sinks under pressure, and the wellbore and the surrounding stratum are relatively displaced, causing vertical negative friction. In summer, the temperature of the wellbore rises, and the increase of the thermal stress itself also aggravates the change of the stress state of the wellbore near the boundary between the bedrock and the topsoil. After several years of production of the wellbore, related damage occurred after accumulation. [8]

4. Application of fiber grating technology in wellbore monitoring

After the wellbore damage event, monitoring methods for the special terrain of the wellbore have also developed. There are many traditional methods. The most widely used method is the steel wire baseline construction method. The reference coordinates of the steel wire are obtained by conducting wires, etc., and then the position information of the feature points on the inner wall is obtained, and the deformation variables are obtained by comparing the changes of the feature points. Although this method is easy to operate and requires less investment, it takes up time in the production channel, the measurement accuracy is not high, and the information cannot be updated in a timely manner.

In 2008, Chai Jing of Xi'an University of Science and Technology proposed a fiber grating sensor monitoring system and distribution design using a Bragg grating. The plan is to specify the depth of drilling in the loose bottom and embed the Bragg grating to form the target for monitoring the
deformation of the wellbore, and summarize the technical parameters and construction requirements during implementation [9].

At this stage, the application of fiber gratings has begun to spread. The application of light gratings in wellbore monitoring systems is becoming more and more mature. The entire system consists of a sensor part, a data acquisition and transmission part, and a data processing and monitoring part [10]. The sensor part can set up different sensors according to actual requirements. Common sensors include temperature sensors, stress strain sensors and displacement sensors. As shown in Figure 3.

![Figure 3. Temperature sensor, displacement sensor and strain sensor](image)

The layout of the sensors needs to be designed according to the actual application. When designing a wellbore without damage to the wellbore, the geological conditions around the mine should be the main factor. The layout should be on the same horizontal plane at different depths of the wellbore. At least one. The temperature sensor and a displacement sensor must be selected at the interface between the topsoil and the bedrock layer in terms of depth. From the existing observation data, the location of the deformation should also be listed as the monitoring object [11]. Because most wellbore damage is repetitive, the depth of damage that has occurred in wellbores that have been damaged should be monitored.

Because the signal transmission method of the sensor is fiber transmission, the data transmission can be selected in series. When more monitoring points are deployed, it can be combined in series and parallel. The demodulator is used for fiber signal reception and data processing. When the coupler meets the incident conditions, the fiber grating sensor will transmit the reflected wavelength back to the coupler, and after processing by the demodulator, the wavelength data will be converted into monitoring point observations. In order to achieve monitoring purposes [12].

Through the data of the monitoring system, corresponding thresholds can be set. When the values of stress and strain at a monitoring point change beyond the early warning threshold, an early warning signal can be issued to play an excellent preventive role.

5. Conclusion
As a new technology, optical fiber method, with its strong anti-interference ability, continuous monitoring, high precision and high reliability, can be perfectly applied to wellbore monitoring. Compared with other traditional means, its biggest advantage is that it can realize continuous monitoring and play an early warning and prediction role. Through the analysis of the existing accidents or geological conditions around the wellbore, select the appropriate depth to arrange the sensor, transmit the signals received by the sensor to the ground through the main cable for demodulation analysis, so as to meet the requirements of the detection of the wellbore. In practical application, it can play a great role in protecting the safety of the shaft, effectively avoid other hazards caused by shaft damage, and also meet the requirements of modern industrial information construction.

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