Optik 125 (2014) 6287–6290

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Design and experiments on a wide range fiber Bragg grating sensor for health monitoring of coal mines

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ARTICLE INFO

Article history:
Received 13 November 2013
Accepted 16 June 2014

Keywords:
Fiber Bragg grating sensor
Coal mine tunnel collapse
Spring
Bolt
Displacement sensors

ABSTRACT

The tunnel collapse problem of coal mine is very common and its damage is very serious. It also seriously endangers people's lives and property safety. At present, a variety of instruments are used for tunnel roof structure health monitoring in most of the coal mines at home and abroad. In this paper, a displacement sensor using optical fiber grating technology was designed, which could be used to prevent the problem of coal mine tunnel collapse by monitoring the coal mine tunnel roof displacement. Firstly, finite element analysis was demonstrated to simulate the stress and displacement of coal mine tunnel roof to determine where to install the sensor. Then the characteristics of the fiber Bragg grating sensor were analyzed in detail and the sensor structure was designed according to the actual requirements in the coal mine. At last, the feasibility of the whole system was experimentally verified. The cross-sensitivity of the temperature and displacement issue with FBG sensors could be eliminated by using matched pairs of FBG. The measuring range of 50 mm and the measurement resolution up to 0.06 mm could be obtained with the proposed sensor.

1. Introduction

The coal mine tunnel collapse problem is an extremely common disaster in the process of coal mining. The frequency of its occurrence is significantly improved with extraction and mining depth increases. The coal mine tunnel collapse problem is very serious which seriously endangers people's lives and property safety. So it is necessary for the health monitoring of coal mine tunnel roof to early warning and reduces the loss of life and property [1].

Traditional health monitoring for the tunnel roof is often completed by a manual operator. But it is more difficult to analyze the stress condition of the tunnel roof because of the complexity of the coal formation. Manual operation is not easy to grasp the situation of the tunnel roof displacement and force. Therefore, it is very necessary to establish a real-time monitoring system with automatic monitoring function which can monitor the tunnel roof displacement and stress state. We can keep the tunnel roof deformation and stress situation to ensure the tunnel roof security through analyzed the representative data.

In recent years, electronic sensors frequently appear in people's daily life and production activities with the development of electronic information technology. As the electronic sensor technology becomes more and more matures, it is gradually applied to the health monitoring on large-scale projects. To a certain extent, the application of electronic sensors solves the drawbacks of traditional methods. However, electronic sensors for the health monitoring on large-scale projects cannot be achieved for long-term stability due to the characteristics of the electronic device itself that it will be affected by the environmental impact [2].

FBG sensor is the novel sensor technology recently developed in the past few years, which has advantages in comparison with traditional electric detection technology such as intrinsic safety, corrosion proof, small shift, high sensitivity, anti-electromagnetic interference, long service life and easy for integrating fiber network communication system, etc. It has several incomparable advantages in comparison with other sensing element. It has been wildly used in special monitoring fields such as petroleum chemical engineering, electric engineering, aviation, aerospace and construction business, etc. As the sensing element, FBG can be used to measure pressure, temperature, displacement, acceleration, humidity

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http://dx.doi.org/10.1016/j.ijleo.2014.08.015

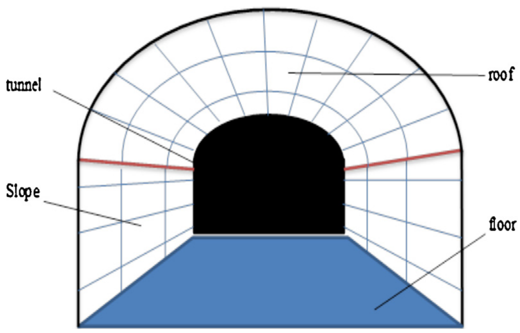

Fig. 1. The front view of mine tunnel.

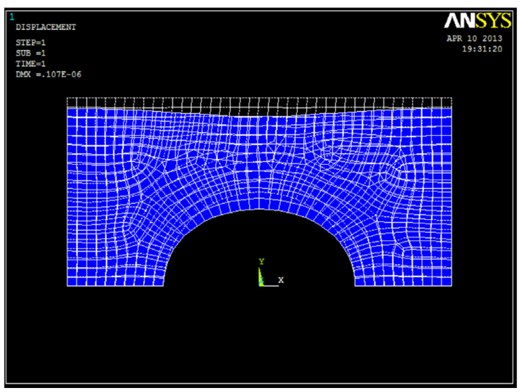

Fig. 2. The displacement of the vertical roof.

and other physical quantities [3]. Its innate advantage also makes it more suitable for safety monitoring of coal mine and it has drawn more and more attentions in coal mine safety monitoring field.

Based on the above discussion and analysis, this paper design a displacement sensor using fiber grating technology, which could be used to prevent the problem of coal mine tunnel collapse by monitoring the coal mine tunnel roof displacement.

2. Design and theoretical analysis of the sensor

2.1. The force and displacement analysis of tunnel roof

In this paper, the force and displacement simulation of coal mine tunnel is analyzed by using ANSYS software. The front analysis of the intramural tunnel of mine is shown in Fig. 1. By ANSYS simulation, the total displacement of the vertical roof supporting is shown in Fig. 2. As can be seen from Fig. 2, the maximum displacement is located at the middle of the roof. The stress contours of the roof

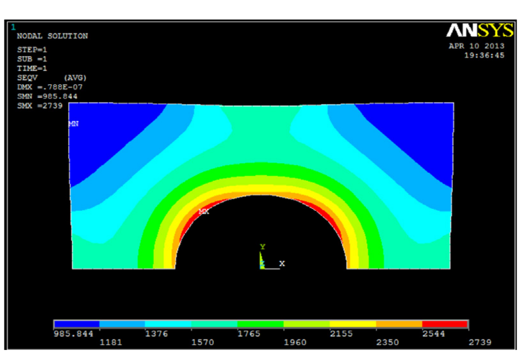

Fig. 3. The stress contours of the roof.

shown in Fig. 3. As can be seen from Fig. 3, the maximum stress of roof support is located at the top of the roof and near the center.

Integrated Figs. 2 and 3, we can see that the maximum displacement and the greatest stress of the roof are all located in the top of the tunnel roof, which is where the tunnel collapse easiest happen and is the place where mostly need to be focused on monitoring. In addition, in the coal mine, the strain is very large when the tunnel cracks or leaks, in particular a large strain on the structure will occur when tunnel collapses, then the maximum displacement of the tunnel roof can reach about 20 mm. At this time, small strain has been far from sufficient to describe the severity of deformation. This requires a corresponding enormous strain sensor or sensing device adapted to modern industrial demand for large strain measurement.

Currently the widely used method for large strain measurement is the resistance strain gauge, which is a special kind of resistance strain gauges using the ductility of the metal material and compensated to achieve strain measurement. But its application is strictly limited. Although other methods can be used to measure larger strain, but all are at the laboratory stage and cannot be used in engineering. The FBG sensing measurement method is very promising, especially in the field of structural health monitoring. The FBG sensing measurement method can be utilized in a variety of ways such as clamp two ends type, surface mount type, submerged type. It can achieve non-destructive measurement of the structure, and can be composed of distributed measurement network. It has great practical significance using fiber grating for large strain measurement [4].

2.2. Sensor structure design

Fiber Bragg gratings are periodic alterations in the index of refraction of the fiber core, which can be produced by exposing the optical fiber to the intense UV light. Lengths of FBG are normally within the region from several millimeters to tens of millimeters and grating reflectivity can approach 100%. Only the specified wavelength (Bragg wavelength) related to its grating period is reflected in an input light wave from a broadband source. FBG sensing is based on the detection of the shifted Bragg wavelength of the light reflected by a fiber grating which is sensitive to strain and temperature. A Bragg grating with an effective refractive index of n_{eff} and a period of Λ will reflect the light of the so-called Bragg wavelength λ_B. The relationship is given by $\lambda_B = 2n_{eff}\Lambda$. From this equation, we know that when the period or the effective refractive index changes, the Bragg wavelength changes. Both the fiber refractive index and the grating period vary with changes in strain and temperature. Photo elastic effect under stress will change the effective refractive index and strain will change the grating period. Thermo-optic effect due to temperature will change the refractive index and the thermal expansion effect will change the grating period. Strain and temperature can make grating Bragg wavelength shifted, so FBG has cross sensitivity problem for strain and temperature [5].

Based on the above analysis and discussion, we use two FBG, two springs and bolt structure to achieve large strain measurement. And we can resolve the cross-sensitivity problem for strain and temperature skillfully. Specific sensor is designed as shown in Fig. 4.

The sensor design idea comes from ZhouZhi large strain FBG sensor with composite structure [6]. The sensor is mainly composed of following parts: polyethylene fibers, FBG, thermoplastic pipe; spring; metallic pipe; metallic bracket; optical fiber jumper, connecting rods and anchors. Here, FBG is used as sensing element which was stuck in polyethylene fibers. And the thermoplastic pipe is used to connect polyethylene fibers and spring, spring and metallic bracket, respectively. The metallic pipe is used to protect FBG and spring to avoid external impact damage. Because bare FBG can