Investigation of the BOTDA Technology for Structural Condition Monitoring of Urban Tunnel

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Abstract. Structural condition monitoring of actual tunnels always needs many measured points of structural response as much as possible. The Brillouin optical time domain analysis (BOTDA) technology has obvious advantages in supplying amounts of measured points of strain along the sensing optical fibre. Therefore, the application of BOTDA technique for structural health monitoring (SHM) of an actual urban tunnel was investigated in this study. The SHM system based on BOTDA technique is designed for an actual tunnel, so this system realizes the long-distance and high spatial resolution of measured strain and temperature field of tunnel structure. And then the placement of long-distance sensing optical fibre of the actual tunnel was introduced in detail. The software system is described in the following aspects such as the function of collection, display and security diagnosis and early warning. Finally the effectiveness of the BOTDA technique for condition monitoring of actual tunnel is discussed.

1. Introduction

During the construction and operation of the tunnel, the geological conditions are relatively complex, which brings many hidden dangers to the tunnel safety. Deterioration of the geological conditions of the tunnel, structural damage, degradation and instability can cause tunnel accidents. Therefore, it is necessary to real-time monitoring and evaluation of the condition of tunnel engineering. At present, the health monitoring of tunnel structure mainly focuses on structural deformation, internal force and joint connection stiffness etc. Yoshimura et al. [1] studied the deformation law of surrounding rock in tunnel construction, and verify the correctness of the finite element simulation by comparing the actual monitoring measurement data with the results calculated by the finite element software. Sulem [2] fully considered the rheological characteristics of the surrounding rock, the propulsion distance of the tunnel construction face, and the interaction between the surrounding rock and the support, and proposed a prediction method for the displacement of the tunnel sidewall.

BOTDA (Brillouin optical fibre time domain analysis) is a distributed optical sensing technique based on stimulated Brillouin scattering. The Brillouin gain spectrum has high signal strength and high measurement accuracy. In 1989, the BOTDA technology was proposed by T. Horigunchi et al [3]. And then the linear relation between the strain and the fibre Brillouin frequency shift was proved through the means of experimental verification. The sensing unit of BOTDA is optical fibre which can be distributed on large geotechnical structures. It is suitable for long-distance transmission or
monitoring with high spatial resolution and comprehensive monitoring information. Enckell et al. [4] obtained the monitoring data of strain and temperature of continuous steel bridge using a health monitoring system consisting of distributed fibre. At present, tunnel structure health monitoring mainly uses traditional point sensors, which can only measure discrete points. The monitoring space is not continuous, and there is a possibility of missing of measurement. Distributed optical fibre sensing uses ordinary single-mode optical fibre used in optical fibre communication as the sensing medium. Since the optical fibre itself is a sensor, it can realize spatial continuous measurement. Its monitoring points can reach million level; the distance of monitoring can reach 100 kilometers. So it is especially suitable for large-scale, long-distance, long-term overall monitoring of large-scale infrastructure, large-scale structural equipment and geological disasters.

2. Brief introduction of the actual tunnel
The main line of Liuchangshan Tunnel is K0+200–K1+400. This tunnel is divided into two parts: a U-shaped groove and a box. The U-shaped groove on the west side is 167m, the U-shaped groove on the east side is 97.5m, and the length of the open-buried section is 935.5m. The undercutting section is K0+450–K0+914.5, and the structure of this section is under the railway track and has long been affected by the vibration of the train. The open-excavation section of this tunnel is adjacent to Baima Mountain. With the continuous change of geological conditions of Baima Mountain, the risk of geological disasters during the operation of Liuchangshan Tunnel is relatively large. This project takes the entire structure of Liuchangshan Tunnel as the engineering object, and establishes a tunnel structure safety operation monitoring and early warning system.

3. Principle of BOTDA fibre sensing technology
The fibre is deformed by external force or ambient temperature, which causes the speed of sound and the refractive index of the fibre to change. It can be obtained from the formula (1) that the frequency of the incident pulse light wave is constant, and the Brillouin frequency of the fibre deformation section will change.

The schematic diagram of BOTDA fibre sensing is shown in Figure 2. A specific Brillouin frequency shift occurs in each small segment of the fibre due to external forces or temperature. The lasers on both sides of the fibre respectively emit pump pulse light (fixed frequency) and continuous detection light into the fibre, and the pump light scans the detected light in the Brillouin spectrum. When the frequency difference falls within the Brillouin spectrum (near 10 GHz), stimulated Brillouin scattering will occur. At the moment, the pump light energy is turned to the probe light, and the probe light get the gain. Then, when the frequency difference falls within the Brillouin spectrum (near 10 GHz), that is, when the frequency difference of a section is equal to the Brillouin frequency shift, stimulated Brillouin scattering will be generated, and the pump light energy is turned to the probe light, and the probe light obtains gain. Then, by detecting the continuous optical power obtained, the frequency of each segment of the fibre can be determined when energy transfer is maximized. Combining the Brillouin gain spectrum fitted by Lorentz method, the Brillouin center frequency $\nu_B$ of each measuring point can be confirmed. The strain or temperature can be measured by using the
Brillouin center frequency difference $\Delta v_B$ and the linear relationship between strain and temperature. The Brillouin frequency can be calculated by Equation (1):

$$v_B = \frac{2n v_a}{\lambda_p}$$

where $v_B$ is the Brillouin frequency; $n$ is the refractive index of the fibre; $v_a$ is the speed of sound; $\lambda_p$ is the wavelength of the incident pulse light.

![Figure 2. Schematic of BOTDA fiber sensing technology](image)

4. Design of the structural health monitoring system

4.1. System overview

The system for structural health monitoring takes Liu Changshan Tunnel (about 980m in length) as the research object to establish a tunnel structure safety operation monitoring and early warning system. According to the functional requirements, the system architecture includes the following subsystems: (1) automated sensing subsystem (sensing layer); (2) structural safety diagnosis and early warning subsystem; (3) central database subsystem; (4) user interface Subsystem. The sensing subsystem is based on high-performance distributed Brillouin fibre sensing technology, which realizes the long-distance and high spatial resolution monitoring of tunnel structure strain and temperature field. The spatial resolution of the structural strain measurement points along the tunnel is no more than 1 m. Distributed Brillouin fibre sensing technology uses ordinary single-mode fibre in fibre-optic communication as the sensing medium. Since the fibre itself is a sensor, it can realize continuous measurement in space, and its monitoring points are reach up to million level. The measuring distance is long, up to the order of 100 kilometers. So it is especially suitable for large-scale, long-distance, long-term overall monitoring of large-scale infrastructure, large-scale structural equipment and geological disasters.

4.2. Structural analysis of this tunnel

The finite element model of the G4~G14 section of Liuchangshan Tunnel was carried out by the ANSYS software. The length of this section is about 360m. The model extends 40m (Total 120m wide) on the basis of the left and right side walls of the tunnel, and the height of model is 25.6m. According to the actual average value of the thickness of the covering soil, the soil in the upper part of the model is taken as 4m. The construction method is open cut, the tunnel cross-section structure is flat-top straight wall type (double-hole rectangular closed frame). The main structure of the tunnel
(primary support, secondary lining) and surrounding soil are solid45 elements and mesh200 units are used for meshing. For the 25cm brick layer outside the left and right side walls of the tunnel, the bottom 25cmC20 cushion layer, the top 10cmC20 concrete layer, the shell elements will be used to simulated. Figures 4-5 show the deformation and stress nephogram under the extracted operational loads. The theoretical calculation of the key stress areas of the tunnel structure provides a theoretical basis for the rational deployment of fibre optic sensors.

![Figure 3](image3.png)

**Figure 3.** Schematic diagram of tunnel structure safety operation monitoring and early warning system based on BOTDA technology

![Figure 4 and 5](image4.png)

**Figure 4.** Deformation nephogram  
**Figure 5.** Stress nephogram

4.3. Placement of optical sensing fibre

The structural strain monitoring of Liuchangshan tunnel adopts high-performance distributed Brillouin fibre sensing technology. The fibre-optic sensor is arranged along the length of the tunnel structure, and the fibre-optic sensor will be laid along tunnel face at the railway section. The long-term online intelligent monitoring method is adopted to realize intelligent monitoring and rapid warning of tunnel bridge structure operation safety. The typical section layout is shown in Figures 6-7:
In addition, in order to ensure that the fibre can resist environmental interference for a long time, the project implements some necessary protection measures for the fibre under the condition of ensuring the performance of fibre monitoring, as shown in Figure 8 and Figure 9 shows the field deployment of fibre optic.

| Model                       | RP-S-2-05                                      |
|-----------------------------|------------------------------------------------|
| Outer diameter of optical fibre | 5.0mm                                        |
| optical attenuation         | ≤0.3dB/km(1550nm)                             |
| Mechanical tensile strength | long-term: 750N, short-term: 1500N           |
| Mechanical compressive strength | long-term:1000N/10cm, short-term:3000N/10cm |
| operating temperature       | -40°C~75°C                                    |

4.4. Installation of data acquisition base station
The monitoring signal is converted to standard Ethernet and wireless network digital signals, and the data is transmitted remotely. The monitoring signal is pre-processed and reprocessed to provide an effective source of information or mechanical indicators to other subsystems, and program monitoring is set as needed.
4.5. Software introduction

The software system completes the archiving, querying, storing, managing and invoking of all static and dynamic data during the whole life cycle. The static and dynamic monitoring data of the tunnel structure during the whole life cycle are classified and displayed to different users according to user requirements, and the control and input of different users are accepted according to the authorization. The software system realizes the functions of visualization of monitoring data and structural finite element model, data pretreatment, modal analysis, structural finite element model updating, structural damage diagnosis, structure warning, and result output. The working process of monitoring software is shown in Figure 11. The software interface is shown in Figure 12.

**Figure 10.** Schematic diagram of acquisition base station installation

**Figure 11.** Flow chart of the software for structural health monitoring system
5. Technical function
The system takes methods of structural health monitoring as the kernel technique, and obtains the deformation information and temperature field distribution of Liuchangshan structure in the operating environment in real time. Meanwhile, this technique can comprehensively diagnose and evaluate the operational safety status of tunnel, and timely and accurately predict the potential risks of structural operation. The specific technical functions are as follows: (1) Strain Monitoring of all tunnel sections with high spatial resolution; (2) Monitoring of the temperature field of tunnel structure; (3) Monitoring whether the main components of the tunnel are damaged or cumulatively damaged; (4) Inference of potential damage risk of the main tunnel components; (5) Projection of the remaining service life of the tunnel structure; (6) providing structural big data information support required for tunnel operation, maintenance, and maintenance.

6. Conclusions
Aiming at the necessity of health monitoring of Liuchangshan tunnel, this study introduces an advanced distributed optical fibre sensing technology, and the detailed information of an architecture of BOTDA-based tunnel operation security monitoring and early warning system are described. The system achieves the high spatial resolution of measured points of strain of an actual tunnel and effectively warns the potential structural risks of this tunnel through the BOTDA technology. This system has broad application prospects.

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References
[1] Yoshihura H, Yuki T, Yamada Y, et al. Analysis and Monitoring of the Miyana Railway Tunnel Constructed Using the New Austrian Tunnelling method[J]. International Journal of Rock Mechanics & Mining Science & Geomechanics Abstracts, 1986, 23(1): 67-75.
[2] Sulem J, Panet M, Guenot A, et al. An Analytical Aolution for Time-dependent Displacements
in a Circular tunnel[J]. International Journal of Rock Mechanics & Mining Science & Geomechanics Abstracts, 1987, 24(3): 155-164.

[3] Horiguchi T, Kmurashima T, Tateda M. Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers[J]. Photonics Technology Letters, 1989, 1.5:107-108.

[4] Enckell M, Glisic B, Myrvoll F, et al. Evaluation of a Large-scale Bridge Strain, Temperature and Crack Monitoring with Distributed Fibre Optic Sensors[J]. Journal of Civil Structural Health Monitoring, 2011, 1(1-2): 37-46.