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SMART CRACK SENSOR AND ITS APPLICATION IN SUBWAY SHIELD TUNNEL

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ABSTRACT

China subway tunnel is now facing significant levels of structural deterioration during the service period. Owing to soft soil consolidation, dewatering of the whole ground, nearby construction, dynamic load of train operation, etc., a series of structural safety problems emerge such as water leakage, structural crack, convergence deformation and longitudinal settlement. Thus how to carry out a solution which can make structural health monitoring of subway tunnel cheap, smart and efficient has become a significant issue. This paper presents one part of long-term wireless monitoring of subway shield tunnel, that is crack and segment joint monitoring, which contains choice of displacement transducer, sensor node integration, performance test and on-site application. Firstly, two different types of displacement transducer, linear potentiometric displacement transducer (LPDT) and linear variable differential transformer (LVDT), which can provide with small range and high precision, are selected for site monitoring. Then, wireless crack sensor is integrated incorporating displacement transducer, temperature sensor, AD convertor, microcontroller and power module. In order to verify their environmental adaptability, performance tests under condition of temperature variation and vibration are done in laboratory. The tests prove that effect of vibration can be ignored, also get their temperature coefficient. An on-site test is then carried out in a newly constructed subway tunnel. Crack sensors are installed across circumferential joints and longitudinal joints to monitor their opening or compressing trend. Two months' data indicates that the sensor is suitable for long-term monitering. The existing work has constructed fundamental structure of smart crack sensor. Much further improvement still remain to be done.

KEYWORDS

Subway shield tunnel, wireless sensor network, smart crack sensor, segment joint.

INTRODUCTION

China has the potential to construct the world's largest subway system. Based on World Metro Database (2013), Beijing has been the city which possesses the longest subway mileage; Shanghai follows closely. For the next few decades, the high-speed construction will still go on.

As the subway network expanding, the structural health of subway tunnel has been of great concern. Engineers find that subway tunnels are facing significant levels of structural deterioration along with serving time. Owing to soft soil consolidation, dewatering of the whole ground, nearby construction, dynamic load of train operation, etc., a series of structural safety problems emerge such as water leakage, structural crack, convergence deformation and longitudinal settlement (Ye *et al.* 2007). According to 2012 structural inspection report of Shanghai subway shield tunnel, there exist 4202 spots of leakage and 815 spots of crack; in some areas, segment joints are widely opened because of large deformation; concrete carbonating and concrete aging are also found in old tunnels. Thus it is a significant issue to find out a solution which can make structural health monitoring of subway tunnel cheap, smart and efficient.

Now detection of subway tunnel mainly rely on visual inspection and cabled based sensing system. But both of these two methods have shortages. Visual inspection is time-consuming and can not realize real-time monitoring. The other, however, cost much money and time to deploy cables (Lynch *et al.* 2000).

The technology of Wireless Sensor Network (WSN) shows brilliant prospect in long-term monitoring of large civil engineering infrastructure items such as subway tunnels. According to World Metro Database (2013), the

average length of a subway tunnel is 1.21 kilometers. Wireless monitoring for such a long structure can not only provide real-time monitoring, but also avoid the difficulties in deploying cables. Bennett *et al.* (2010) and Stajano *et al.* (2010) present some case studies of WSN application in London, Barcelona and Prague subway tunnels, proving its flexibility.

This paper presents one part of long-term wireless monitoring of subway shield tunnel, that is crack and segment joint monitoring, which contains choice of displacement transducer, sensor node integration, performance test and on-site application. The aim is to provide a smart crack sensor suitable for subway shield tunnel application.

SMART CRACK SENSOR

Selection of Displacement Transducer

Cracks and segment joints are weak parts of shield tunnel. Engineers always express concern for crack width, for it has great impact on structural safety. Similarly, width change of segment joint is intimately related to tunnel deformation, and may lead to water leakage. So it is important to get the information of crack/joint width change.

In this paper, displacement transducers are used to measure changes in widths of cracks and joints. Based on the characteristic of crack/joint width change in tunnel, several principles are presented for selection of displacement transducer.

(1) For changes of crack/joint width is a slow and long-time process, the sensor must have a high resolution and precision; additionally, the sensor output must be stable for a long time (e.g. 3~5 years).
(2) For the tunnel environment is usually humid and full of dust, the sensor must reach a high protection level.
(3) Movement of crack/joint may be out of plane, installation of the sensor should capable for out-of-plane movement; namely, the sensor could not be broken in that situation.

Four types of displacement transducer, strain-gauge displacement transducer, vibrating-wire displacement transducer, linear potentiometric displacement transducer (LPDT) and linear variable differential transformer (LVDT), are commonly used in engineering practice. The former two are not suitable for long time application, since there could be considerable shifts with time. Thus LPDT and LVDT are selected for site monitoring.

Based on market investigation, two types of specific displacement transducer are chosen (Figure 1). Their technical parameters are showed in table 1. It can be seen that the LPDT has smaller size, lighter weight but lower precision, and the LVDT has higher precision, but larger size.

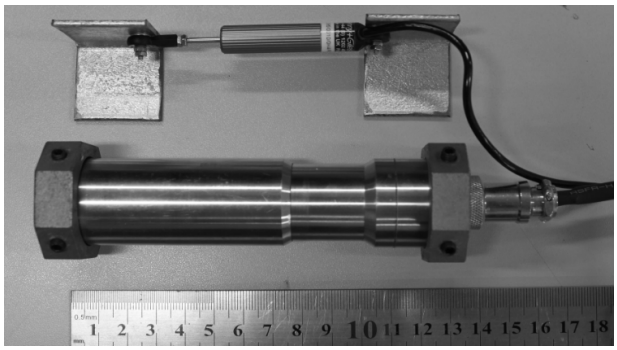


Figure 1. Two displacement transducers: the upper is LPDT, the lower is LVDT

Table 1. Transducer technical parameters

Type	LPDT	LVDT
Size	85×ϕ9.5 mm	180×ϕ15 mm
Measuring range	10 mm	5 mm
Input voltage	5 V D.C.	±12 V D.C.
Output	0~5 V D.C.	0~5 V D.C.
Resolution	Virtually infinite	Virtually infinite
Sensitivity	0.5 V/mm	1 V/mm
Precision	0.01 mm	0.0025 mm
Sealing	IP 66 standard	IP 66 standard

Wireless Sensor Integration

The structure of wireless crack sensor mainly consists of displacement transducer, temperature sensor, AD convertor, microcontroller and power module (Figure 2). The displacement transducer, LPDT or LVDT, has small range and high precision. The temperature sensor is used for temperature compensation. Its precision is ±0.5 °C in the range of -10 °C to +85 °C. The 16 bit analog-to-digital convertor has a resolution of 0.0625 mV, which can meet requirement of the system. The microcontroller combines the excellent performance of a wireless transceiver (based on Zigbee protocol) with an industry-standard enhanced micro control unit. It has various operating modes, including ultralow power-consumption operating mode, making it have advantages in terms of power consumption and data rate. The power is supplied by a high-storage battery. To provide a stable input voltage for the displacement transducer, voltage regulator circuit is designed in the PCB board. The integrated wireless crack sensor is shown in Figure 3. The voltage regulator, AD convertor and microcontroller are all integrated in a PCB board, making it small sized, also low power-consumption.

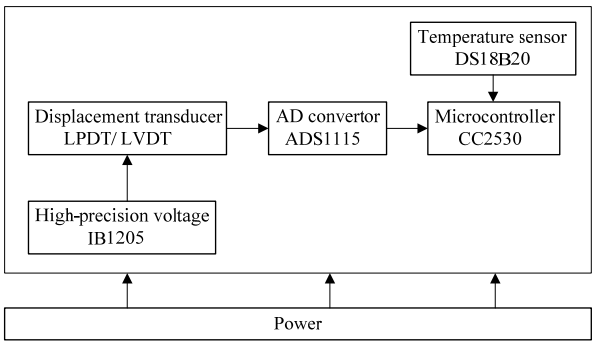


Figure 2. Structure of wireless crack sensor

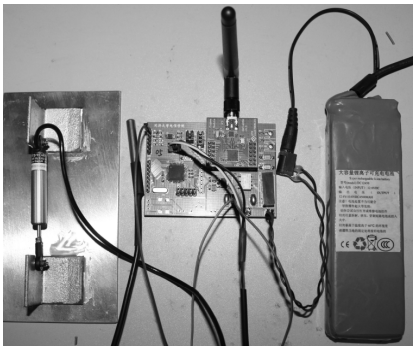


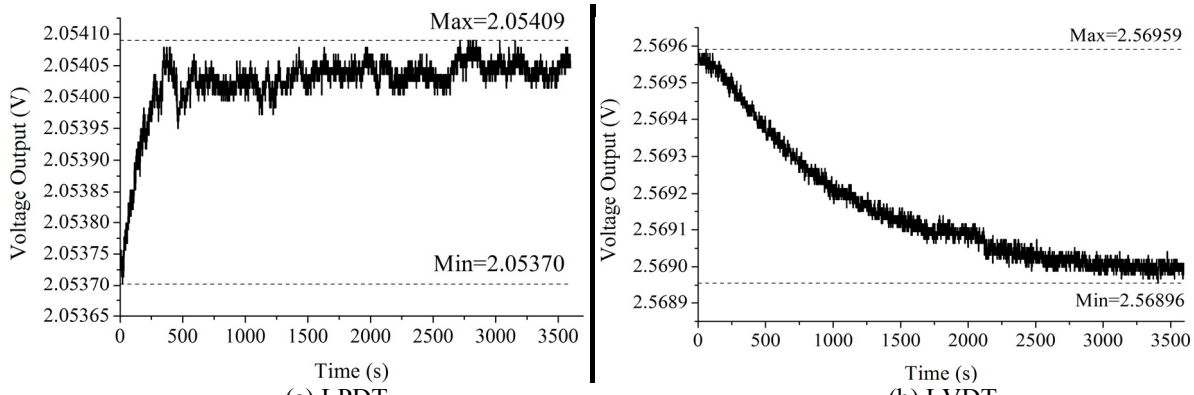
Figure 3. Wireless crack sensor (unsealed)

PERFORMANCE TEST

The environment of subway tunnel is complicated, for example, high humidity, temperature variation and mechanical vibration induced by running train. This part contains three tests in laboratory, including output stability test, vibration effect test and temperature drift test. The aim is to check the performance of displacement transducer in harsh conditions.

Output Stability Test

Sensors may have some warm-up time, meaning that their output need a while to reach stable. This test is to get voltage output change curve of the sensor after power-on. The two sensors, LPDT and LVDT, are fixed at position of about 1/2 full scale. Sensors are powered by stabilized voltage supply, then their outputs are acquired for one hour. All workers left the laboratory in the test process to guarantee the results without any external disturbance. Figure 4 shows the acquired data.



(a) LPDT (b) LVDT

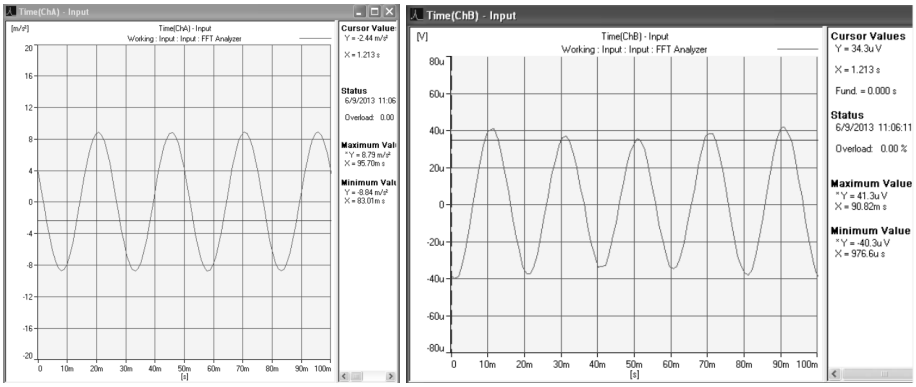
Figure 4. Voltage output with time

In an hour's time after power-on, outputs of the two displacement transducer trend to be steady. Maximum output differences of LPDT and LVDT are 0.00039 V (equal to 0.78 μm) and 0.00063 V (equal to 0.63 μm).

The differences are negligible compared to their precision, which is 10 μm and 2.5 μm respectively. So voltage outputs acquired just after power-on can be regarded as real and valid ones.

Vibration Effect Test

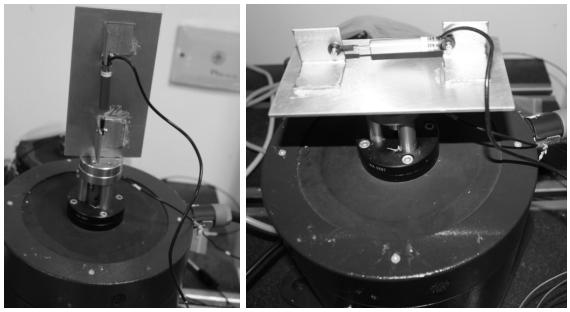
One important feature of subway tunnel environment is its vibration induced by train running, which may influence output of displacement transducer. In this test, the sensors' vibration frequency response are tested using a vibration excitation system. The system gives out vibration signals to control shaking table which can fix sensors (Figure 5(a)). Then, the system analyzes sensor's alternating voltage output and get the voltage amplitude (Figure 5(b)).



(a) Vibration excitation signal (b) Output of alternating voltage

Figure 5 Working steps of vibration excitation system

The vibration of subway tunnel is mainly low frequency below 200 Hz; the acceleration is no more than 0.1 g (Zhou *et al.* 2012). In this test, output response of two vibration directions (Figure 6) at acceleration of 0.1 g, frequency of 5 Hz, 10 Hz, 20 Hz and 80 Hz are measured. Table 2 shows their voltage amplitudes.



(a) (b)

Figure 6. Two vibration directions: (a) parallel to sensor's axis; (b) vertical to sensor's axis

Table 2. Voltage amplitudes at acceleration of 0.1g

Excitation frequency (Hz)			5	10	20	40	80
LPDT	Parallel to sensor's axis	Voltage amplitude (mV)	0.0513	0.0113	0.0078	0.0132	0.0038
		Equal displacement (μm)	0.1026	0.0226	0.0155	0.0264	0.0077
	Vertical to sensor's axis	Voltage amplitude (mV)	0.0274	0.0246	0.0246	0.0207	0.0187
		Equal displacement (μm)	0.0548	0.0492	0.0492	0.0413	0.0375
LVDT	Parallel to sensor's axis	Voltage amplitude (mV)	0.148	0.0071	0.0043	0.0038	0.0025
		Equal displacement (μm)	0.148	0.0071	0.0043	0.0038	0.0025
	Vertical to sensor's axis	Voltage amplitude (mV)	0.473	0.401	0.344	0.226	0.116
		Equal displacement (μm)	0.473	0.401	0.344	0.226	0.116

From the table above, it can be seen that sensors are more sensitive to low frequency vibration when vibration is vertical to sensor's axis, especially for LVDT. Maximal influence of vibration on LPDT and LVDT are 0.0548 μm and 0.473 μm respectively. Compared to their precision, which is 10 μm and 2.5 μm respectively, vibration effect is so small. Namely, vibration of tunnel can be ignored in practical application.

Temperature Drift Test

Temperature variation can change voltage output of displacement transducer, especially for LPDT. Because its output is related to its electric resistance, while temperature is an influence factor for resistance. The aim of this test is to get temperature coefficient of the two sensors, which will be used for temperature compensation.

The test is done in a temperature/humidity chamber. To simulate conditions of practical application, each sensor is anchored in a 300*100*100 mm concrete block (Figure 7). The humidity is controlled at 60%. Temperature change process is showed in Figure 8. Sensors' outputs at five temperature point, -10 °C, 10 °C, 25 °C, 40 °C and 60 °C, are acquired via wireless module. Each temperature point is kept for about one hour, guaranteeing that the chamber reach heat balance and sensors have stable outputs.

Figure 7. Temperature/humidity chamber and fixed sensor

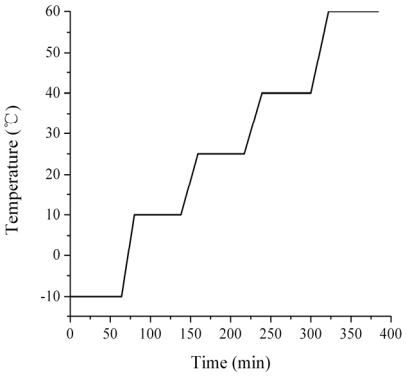
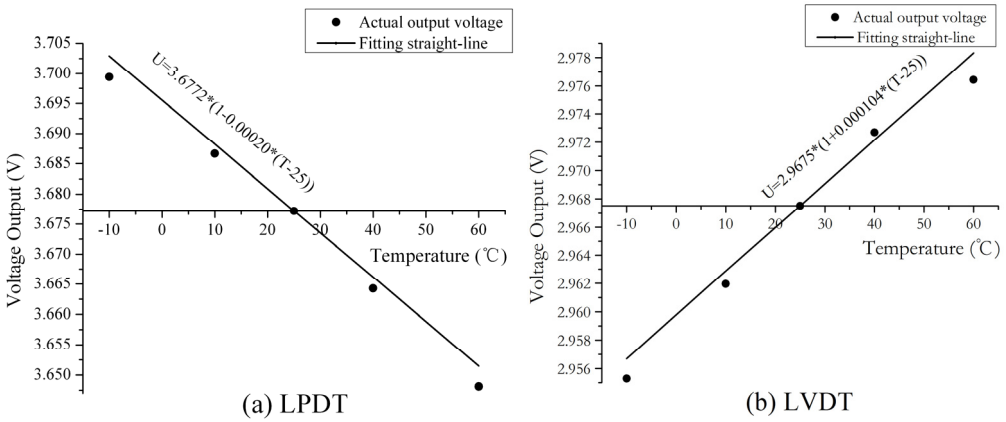


Figure 8. Temperature change process



(a) LPDT (b) LVDT

Figure 9. Voltage output at each temperature point

Results are shown in Figure 9. The readings of LPDT and LVDT at 25 °C are 3.6772 V and 2.9675 V respectively. From -10 °C to 60 °C, output of LPDT decrease 0.0513 V (equal to 0.1026 mm), and LVDT increase 0.0211 V (equal to 0.0211 mm). The relation between temperature and voltage is approximately linear. The results indicate that temperature effect can not be ignored.

According to the test data, temperature coefficient can be calculated as

$$\alpha = \frac{\sum_{i=1}^{m-1}[(U_{T_{i+1}} - U_{T_i}) / (T_{i+1} - T_i)]}{(m-1)U_{T_0}} \tag{1}$$

where m is the total number of temperature test points; U_{T_i} is the voltage output at the temperature of T_i; specially, U_{T_0} is the voltage output at the reference point T_0; here, T_0 is set as 25°C. So temperature coefficients of LPDT and LVDT are -0.000200 /°C and 0.000104 /°C respectively.

Thus, the revised voltage output at T considering temperature compensation can be expressed as

$$U_{TC} = U_T(1 - \alpha(T - T_0)) \tag{2}$$

ON-SITE APPLICATION

Site Conditions

Shanghai Lijin Road Tunnel is a newly constructed subway shield tunnel. The circular lining system is assembled by jointed segmental precast concrete linings connected by steel bolts. One segment ring consists of 1 key segment (KP), 2 adjacent segments (AP), 2 standard segments (TP) and 1 bottom segment (BP) (Figure 10). Owing to a series of factors such as complex strata condition, surcharge on surface ground, small radius of curvature and poor construction technology, the tunnel faced large convergence deformation and serious concrete damage. Constructor immediately made a large-scale repair, thus steel sheets are fixed on the inner lining to reinforce the tunnel.

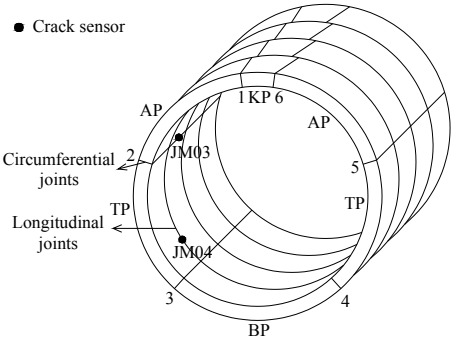


Figure 10. Illustration of crack sensors installed in jointed shield tunnel

To monitor the opening of joints, also to test long-term performance of the sensor, several crack sensors are deployed in the tunnel.

Installation of Crack Sensors

A perfect installation position is the joint which shall have apparent movement. Jointed shield-driven tunnel has two types of joints—circumferential joints and longitudinal joints. For circumferential joints, engineering practice (Ye *et al.* 2007) and numerical calculation (Zhang *et al.* 2013) show that internal edge of joint 1 and 6 (illustrated in Figure 10) have opening trend; while joint 2 and 5 have compressing trend. It seems that the ideal monitoring position is joint 1 or 6. But the proprietor forbid any installation on the crown of tunnel, afraid that they may endanger the running train safety. Thus crack sensors are deployed across joint 2 for circumferential joint monitoring. For longitudinal joints, it is known that longitudinal differential settlement can cause the opening of longitudinal joint (Zheng *et al.* 2005). An applicable position for longitudinal joint monitoring is its lower part, which may have large movement, also is convenient for installation.

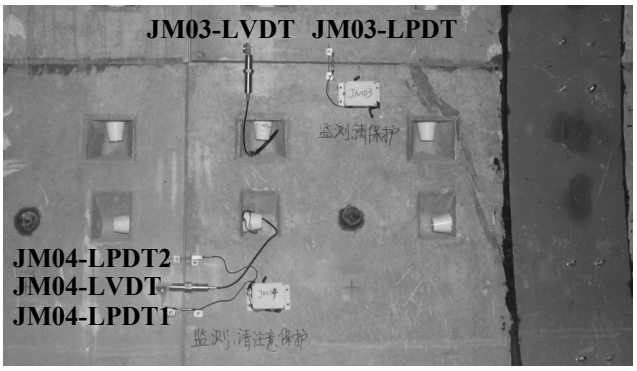


Figure 11. Deployment of crack sensors

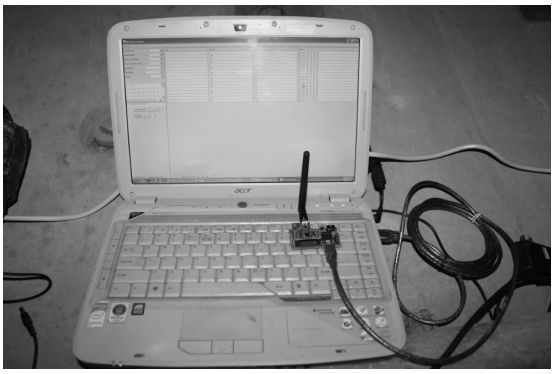
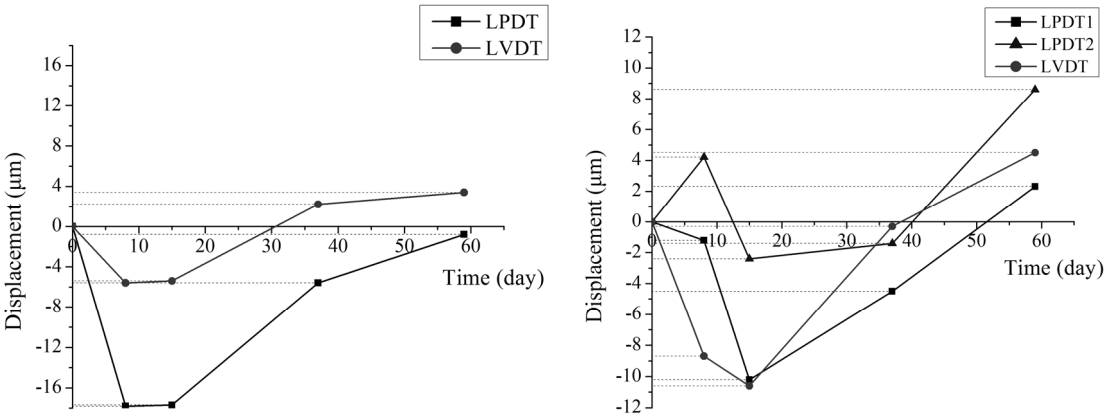


Figure 12. The receiving node connecting PC

Two sets of crack sensors, JM03 and JM04, are deployed in the tunnel. JM03 cross longitudinal joint, and JM04 cross circumferential joint (Figure 10 and 11). JM03 consists of 1 LPDT and 1 LVDT, and JM04 consists of 2 LPDT and 1 LVDT. Results of different displacement transducer of the same set can compare to each other. All sensors are fixed on the segment using expansion bolt. To acquire data, a simple wireless sensor network based on Zigbee protocol is created. In the network, the data gathered from each sensor node are sent directly to the receiving node. The receiving node, connecting to a PC, is about 10m far away from each sensor node (Figure 12).

Results and Discussion



(a) JM03 (b) JM04

Figure 13. Comparison of readings from different displacement transducers

In two months time, five times of readings are acquired. Each time the outputs of all displacement transducers are collected for at least 10 minutes; the sample interval is 3 seconds. The average value of these hundreds of data is set as the final reading. Results are shown in Figure 13. It can be seen that readings of different displacements in one set have the same growth/descent trend. But their magnitudes exist differences. Readings of LPDT have bigger ups and downs compared to LVDT. The reason is that LPDT has a lower precision.

It seems that JM03 (circumferential joint) and JM04 (longitudinal joint) all have compressing trend in the first 15 days, and then have opening trend. But joint displacement is so small that the maximum is only 0.017 mm. So we can not judge how is the deformation of the tunnel in these days. In reality, the tunnel is in a stage of newly constructed and without train running, it is at a relatively stable state. That can explain why the displacement is so little. On the other hand, little displacement can prove that the crack sensor is suitable for long-term monitoring, as there exists no apparent drift in two months.

Unfortunately, the last time we went into the tunnel we found that the PCB boards, which are for collecting and sending data, couldn't work because of extremely high humidity. It warns that moisture-proof handling must be done for the whole sensor.

CONCLUSIONS

As part of long-term wireless monitoring of subway shield tunnel, this paper presents the design and performance of crack sensor, which is used for crack and segment joint width monitoring. The wireless crack sensor, using LPDT or LVDT as the sensor unit, can sense tiny displacement

Laboratory tests and on-site application are done to learn the sensor performance in tunnel. The tests prove that effect of vibration can be ignored, also get temperature coefficient of the sensor. Two months' on-site application indicates that the sensor is suitable for long-term monitering.

There still exist some shortages for the crack sensor. Moisture-proof handling is not considered in the previous design. And Power management is also required so as to extend battery-life.

Our goal is to creat a "smart sensing system" for subway shield tunnel application. For a sensor node, "smart" means it should have some functions such as real-time and rubust communication, self-control, self-diagnosis, etc. The existing work has constructed fundamental structure of smart crack sensor. Much further work remain to be done not only in hardware but also in software.

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