Intruder detection trial in subway tunnel based on distributed vibration response

Jie Wang¹, Yang Qiu¹ and Sheng Li²*
¹School of Information Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China
²National Engineering Laboratory for Fiber Optic Sensing Technology, Wuhan University of Technology, Wuhan, Hubei, 430070, China
*Corresponding author’s e-mail: lisheng@whut.edu.cn

Abstract. Identifying illegal intruders is a crucial issue in subway safety management. This paper performs an intrusion detection trial through distributed vibration measurements on a real underground engineering and the ultra-weak fiber optic Bragg grating (FBG) sensing technology was adopted to glean the structural vibration signal of the intruder loading. The results showed that the signal model in the distributed structural vibration can be utilized to illustrate the location and speed of the intruders. Besides, the information in both time and frequency domains in the selected experimental area demonstrated that the ultra-weak FBG-based approach is able to distinguish designed intrusion cases in terms of pattern and strength.

1. Introduction
Locating illegal intruders and avoiding the risks due to intrusions that often occur in subway outages is an issue of interests to engineers and administrators. At present, there have been similar research reports on railway perimeter safety based on FBG sensors [1] and DAS technology [2]. However, the FBG-based application is affected by the restricted sensor multiplexing capacity, which can only cover a finite monitoring range. The main disadvantage of DAS-based engineering applications is the relatively low SNR of this vibration response, which makes it difficult to capture or distinguish different intrusion modes in time with high spatial resolution over long distances. The previous comparison in [3] illustrated that the ultra-weak FBG array [4] can not only be performed for static and dynamic tests, but also has a better SNR than that of DAS technique. Therefore, the ultra-weak FBG array was considered to be more suitable for measuring distributed vibrations and was expected to achieve the illegal incursion detection that frequently occurred in the scenario of a subway tunnel.
This paper discussed the feasibility of distributed vibration measurement based on the ultra-weak FBG sensor array to deal with the human intrusion in a subway tunnel. The observed phenomena of detecting intruders in a real underground engineering are given. The basic detection principle forms the second part of the article, which is followed by the detailed information to verify the on-site design and implementation of the proposed methodology. Finally, the detecting effectiveness for different incursion modes is analysed based on the designed test plan.

2. Detection sensing principle
Figure 1 gives the basic principle for detecting the structural distributed vibration. The phenomenon of light interference caused by the reflection signals of adjacent two ultra-weak FBGs is used to detect the
vibration of the object of interest. The parameter \( L \) determines the spatial resolution of the vibration probe distributed along the sensing fibre. The frequency response and sensitivity of the vibration signal represented by the phase variation of strain-induced of two ultra-weak FBGs are enhanced by the interferometer. The Faraday rotator is adopted in the demodulation process to suppress the polarization effect in the ultra-weak FBG array. Furthermore, the reconstruction of time domain signal adopted the 3-by-3 coupler phase demodulation algorithm to get satisfied phase information of the vibration signal. In the above process, the interrogation for both the vibration frequency and amplitude can be acquired.

Figure 1. Basic principle for detecting the distributed vibration responses.

The high sensitivity of large-capacity ultra-weak FBGs and the demodulation system of high speed [5] secure the ability of the sensing cable extremely appropriate in positioning structural vibration of the moving intruders in a long-distance region.

As shown in Figure 2, the intruder can be equivalent to a moving load. Owing to this excitation, the surface waves propagate in all directions on the ground. Since the surface wave are coupled to the track bed structures, distributed sensing probes amounted asi de the rail track of the subway can obtain the footstep responses. Through interrogating the addresses of light interference region represented by each monitoring zone of ultra-weak FBG, a determine correspondence between each known light interference region and the tunnel mileage can be established.

Figure 2. Principle of detecting the moving intruders based on distributed vibration response.

In addition, the moving speed of the people can be calculated through the \( \tau \) lag time by cross-correlation analysis (1), and the distance of any two monitoring regions \( i \) and \( j \) illustrated in Figure 2.

\[
R_{D_iD_j}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T D_i(t)D_j(t + \tau) dt
\]

where \( D_i(t) \) and \( D_j(t) \) are the structural vibrations of interests at light interference zones \( i \) and \( j \). The lag time \( \tau \) corresponds to the duration between the ranges \( i \) and \( j \). Moreover, 5-meter equidistance between each FBGs along with the sensing optic fibre can be obtained by the preparation of the draw-tower grating preparation.

3. Design and implementation

3.1. Engineering description

This study used a real tunnel in Wuhan as the engineering support for the test and verification. In the construction period of the subway, the ultra-weak FBG sensing cables with armoured structure were burred in the track bed surfaces of the selected experimental segments. In order to assess the structural vibration of the monitored structures, three methods for fixing the sensing cable were compared to determine the suppression capacity of the disturbance vibration. Three fixing methods were considered and after long-term testing and analysis. Finally, comparing to fixture fixing and epoxy adhesive, the
shallow groove embedding was regarded as the optimal means, which safeguard a better quality of vibration signals.

The adopted monitoring system covers 5 kilometres length with multiplexing capacity of one thousand FBG sensors. Figure 3 reveals that the test region primarily focuses on 3 subway stations range of approximately 3 kilometres. More than 500 vibration zones can be identified along the track bed.

![Figure 3. Schematic plan of the test range with two track bed structures.](image)

![Figure 4. Simulated incursion patterns in the selected tunnel area.](image)

From the right side of Figure 3, we know that both the common track bed and damping track bed are covered in the test range. During the test, the data sampling frequency was 1 kHz. The real-time vibration signal is transmitted to the remote platform monitoring centre, and the signal processing is completed by the demodulator and server.

### 3.2. Intruder detection test

In order to secure the next-day safe operation of the subway, various manual inspections are regularly performed in the outage period in early morning. Use this inspection window for intrusion testing. This is also the main period of illegal invasion. According to specific process coordination, multiple sets of designed intrusion tests are performed in the area of the damping track bed. In order to minimize the interferences for routine inspections, the designed tests were focused on a 130 m length region. From Figure 4, four types of incursion modes are considered, including walking and jogging in terms of different people and distance from the track bed. In each group of intrusion modes, the intruder moved back and forth in the test area.

### 4. Results and discussion

The on-site test information of the simulated human incursion is illustrated in Figures 5 and 6 in terms of time domain and frequency domain. Figure 5 shows that the distributed vibration response from walking can be distinguished from jogging. In addition, the opposite moving direction represented by two diagonal signals in the test process were clear, which reflects the capacity of detecting the round-trip process. Further, based on the different speed delegated by the magnitude of slope caused by different speeds of the intruder, the jogging mode shown in Figure 5 (c) can be easily distinguish from the walking modes shown in other monitored diagrams. The finding was consistent with results in Figure 6, which was more obvious in frequency domain due to higher fluctuation of the signal intensity of the jogging load.

![Figure 5. Time domain results of 4 incursion modes: (a) one person walking; (b) 4 persons walking; (c) one person jogging; (d) one person walking in the other side.](image)
Figure 6. Frequency results of 4 incursion modes: (a) one person walking; (b) 4 persons walking; (c) one person jogging; (d) one person walking in the other side.

The effective value described by the signal root-mean-square was calculated to quantify the differences among the 4 types of incursion modes, which is illustrated in Figure 7 (a). In the analysis, the round-trip process outside the test area were omitted. From the RMS distribution, the difference between jogging and walking was obvious as well in view of the signal magnitude. Also, it is possible to clearly distinguish the nuances of intrusions at different distances. Moreover, the overall distributions of the dominant frequency of different intrusion modes are quantified in Figure 7 (b). Here, the maximum energy in each column in Figure 6 is defined as the dominant frequency of the corresponding monitoring area.

Figure 7. Fitting distribution of (a) RMS and (b) dominant frequencies under different cases.

Due to environmental and structural difference in the test zones, the response distributions in Figure 7 (b) illustrated by dominant frequencies were different. However, the distribution similarity still exists under different invasion situations. In other words, the distribution features of modes 1 and 4 are relatively closer, while modes 2 and 3 show broader frequency information due to much stronger and more complex load excitations. Furthermore, the different fluctuation range in Figure 7 (b) is beneficial to distinguishing different simulated incursions based on the frequency domain magnitudes of dynamic distributed responses of ultra-weak FBG.

5. Conclusions
This study reports the feasibility of detecting intruders in subway tunnels through dynamic distribution measurements by ultra-weak FBG array. The experimental test in a real underground engineering illustrated that the distributed vibration along the track bed was able to identify different incursion strength and pattern in view of designed simulated cases. Future research will focus on common track
beds with higher structural stiffness to analyse the correspondence between signal features and intrusion modes when the excited distributed vibration response is weak.

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