Long-Period Dynamic Characteristics of Embedded Track Using Machine Learning

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Abstract: Different from traditional fastener systems, embedded track is a rail placed in the groove and wrapped by a variety of polymer materials, thus realizing the longitudinal continuous support and vibration noise reduction. Due to its superior dynamic characteristics, it has been initially used in trams, subways and high-speed railways. With the promulgation of the Noise Law, its demand is also increasing. However, its structure and mechanism are relatively complex, and its dynamic characteristics changes with the service life. In addition, its performance is difficult to measure directly and service life is as long as 30 years or more. In order to analyze the dynamic characteristic changes of the embedded track throughout its life cycle, fatigue tests are performed by subjecting the embedded track to sinusoidal excitation of different amplitudes and periods. This allows to simulate its service process during the whole life cycle. Meanwhile, the vibration response of embedded track at different stages is collected. Unfortunately, it is difficult to judge the performance and state of embedded track according to the vibration response directly. In order to solve this problem, this paper proposes an embedded track long-period dynamic response analysis method based on machine learning. This method can evaluate the performance change of the embedded track without any label only based on the dynamic response. Among them, self-supervised deep learning networks are used to autonomously extract deep features of the vibration response. These features are then classified by clustering algorithms into different phases of the service life. Finally, the change law of vibration and noise performance of embedded track in different stages is explored. The proposed method can determine the performance status of the pre-embedded track based on the field vibration response test results. It also estimates the decay process of track performance with service life and determines the maintenance cycle according to the performance requirements.

Keywords: machine learning; embedded track; life-cycle; vibration and noise reduction

1. Introduction

Different from traditional fastener systems, embedded track is a rail placed in the groove and wrapped by a variety of polymer materials, thus realizing the longitudinal continuous support and vibration noise reduction. As shown in Fig. 1, this type of track structure is primarily composed of multiple high-polymer materials that provide continuous longitudinal support. This design significantly reduces the vibration of the track structure caused by the unevenness associated with traditional discrete supports. Furthermore, the deformation of the elastic materials surrounding the trough-shaped rail contributes to energy dissipation, resulting in excellent vibration attenuation and noise reduction properties[1][2][3]. Additionally, this track structure offers enhanced stability [4] and safety [5].

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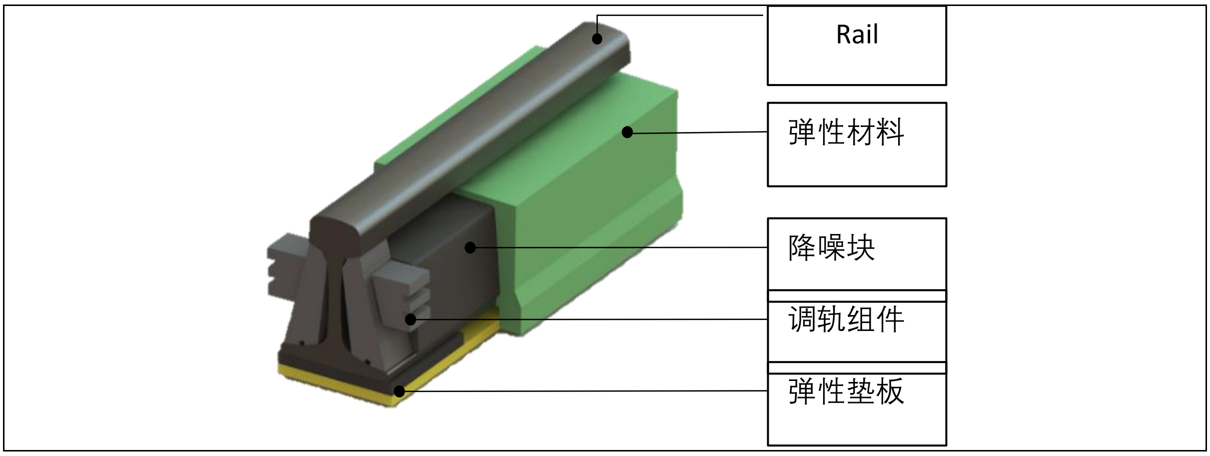


Fig. 1 Schematic diagram of the embedded track

Since the occurence of first continuous supported embedded track in Deurne of Netherlands in 1976[1], vast number of scholars have carried out their studies on its vibration and noise reduction performance. The advantage in vibration and noise reduction has caught wide attention[2][3], at the same time, many scholars start to conduct a lot of studies on the interaction between wheel-rail and vibration noise properties of embedded track.

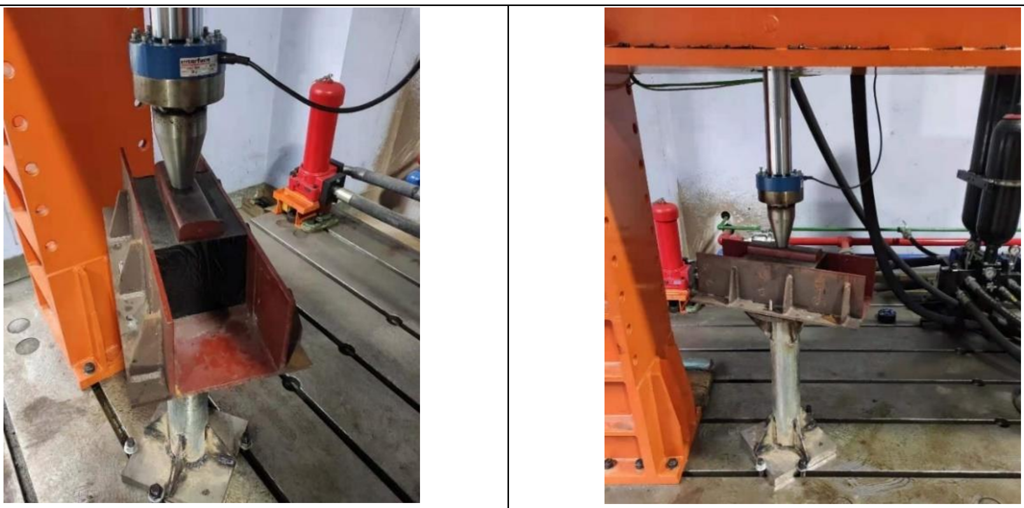
Shamalta et al[6] have built up 1D and 2D kinetic models of embedded track under the excitation of mobile loading. On this basis, Ling L, Han J et al [4] took advantage of multi-rigid body dynamics and chose springs and dampers as filling materials to do approximate simulation. They compared and analyzed the difference between embedded track and fastener track in terms of wheel-rail interaction and pointed out the advantages of embedded track from the perspectives of dynamic stability, smoothness, comfort, etc through a coded fastener. However, the method has to intercept the rail, which is not conducive to the high frequency research on embedded track[7][8]. In the literature article [9], X.Sheng has inferred the dynamic properties of periodically supported and continuously supported tracks from the theory of infinitely long periodic structures, pointing out that the dynamic properties of a continuously supported track and a discrete supported track are the same at the frequency of 200Hz(200Hz is related with track structure parameter, the literature employs the track from Europe, whose fastener's stiffness is considerably higer). The conclusion drawn is the same as the literature articles[10][11], but the difference increases in case of frequency above 200Hz. He pointed out in his further research that periodic discrete support would lead to parameter excitation[12]. However, what's regretful is it still employs stiffness damping to simulate the dynamic flexibility of a new system of a continuously supported track, not reflecting the dynamic property of polymer materials of embedded track in the model.

In order to consider the inception form of embedded track and frequency response property of polymer material in details, Van Lier[13] utilized TWINS model combined with the finite element method to study the ascoutic radiation properties of an existing embedded track and optimize it to some extent. The optimized steel rail turned out to be a shorter steel rail and increased the stiffness of rail pad and surrounding elastic body. He then compared the traditional embedded track and the optimized embedded track with the ballasted track. The result showed that the corresponding vehicle wheel-track system's noise is 46~dB(A) less than the ballasted track for the optimized embedded track. Zhao et al[8] used site testing, 3D finite element and boundary element methods to predict the vibration ascoutic radiation of the embedded track employed by a railed tram and perform relevant testing, verifying the model effectiveness through the comparison of simulation and test results. He carried out the vibration noise property analysis on the embedded track for a railed tram, and further optimized the structure within the slot of the embedded track. However the excitation condition employed for simulation is the actually measured steel rail roughness spectra of the route, the relevant optimizing result and rules showed a certain level of reliance on the steel rail roughness. What’s more, the finite element and boundary element in the model require inception handling. Although the article has verified the effectiveness of finite element inception, it yet verifies the effectiveness of boundary element inception. On top of this, Nilsson[14] calculated the ascoutic radiation of embedded track and traditional steel rail by using the wavenumber finite element and boundtry element methods. The result showed that at some frequencies, due to the existence of free surface of elastic body of the embedded track, it made the ascoutic radiation efficiencies of steel rail and elastic body surface higher than that of traditional steel rail. However, due to a good attenuation effect on vibration by the embedded track, it counteracted the effect of the increased ascoutic radiation efficiency of the embedded track. But, at the low frequencies, the embedded track may radiate more noise than a common steel rail, which is mainly due to that a common steel rail is a linear monopole sound source while an embedded track presents as a linear dipole sound source.

Embedded tracks, known for their excellent vibration and noise reduction performance, are currently being widely used in tramways, subways, and high-speed railways. The demand for embedded tracks is further increasing with the implementation of noise regulations. Unfortunately, over time, the characteristics of the polymer materials used in embedded tracks gradually change [15][16]. According to relevant studies, the vibration and noise reduction performance of embedded tracks are closely related to the properties of the polymer materials. Consequently, it becomes challenging for embedded tracks to maintain consistently high performance throughout their service life. In order to analyze the dynamic characteristic changes of the embedded track throughout its life cycle, fatigue tests are performed by subjecting the embedded track to sinusoidal excitation of different amplitudes and periods. This allows to simulate its service process during the whole life cycle. Meanwhile, the vibration response of embedded track at different stages is collected. Unfortunately, it is difficult to judge the performance and state of embedded track according to the vibration response directly. In order to solve this problem, this paper proposes an embedded track long-period dynamic response analysis method based on machine learning. This method can evaluate the performance change of the embedded track without any label only based on the dynamic response. Among them, self-supervised deep learning networks are used to autonomously extract deep features of the vibration response. These features are then classified by clustering algorithms into different phases of the service life. Finally, the change law of vibration and noise performance of embedded track in different stages is explored. The proposed method can determine the performance status of the pre-embedded track based on the field vibration response test results. It also estimates the decay process of track performance with service life and determines the maintenance cycle according to the performance requirements.

2. Fatigue experiment description

The mostly used equipment and accessories in the experiment in the paper include stiffness experimental system, embedded track short trial piece, data collection system etc. Fig. 2 gives out the installation and the loading means of MTS and the trial pieces of the embedded track. The trial pieces for the embedded track mainly contain 60kg/m short rail, polymer material, pad underneath the rail, wrapping body steel plate etc.



(a) The trial piece for the embedded track

(b) the experiment photo of the embedded track

Fig. 2 The installation and loading means of the stiffness experiment for the embedded track

3. Model establishment

The modeling process is depicted in the following flowchart, as shown in Fig. 3. It can be divided into the following steps:

Step 1: The dynamic response variations of embedded track during its service life cycle were investigated through fatigue experiments. As it is difficult to monitor the dynamic properties of the track structure in real time during the experiment, instead Dynamic response tests of the track structure were conducted at fatigue cycles of 0, 1 million, 2 million, and 3 million cycles. The structural dynamic stiffness and damping ratio were obtained from these tests.

Step 2: The finite element model is compared with experimental test results for verification and the numerical model is used to complement the complete experimental working conditions.

Step 3: Classification of embedded track noise reduction effects using long-period machine learning models.

Fig. 4 presents the on-site test photographs of the dynamic response of the embedded track in its initial state, along with a comparison of the test results with the predicted values. From the figure, it can be observed that the numerical prediction results are consistent with the experimental results. The numerical model demonstrates good agreement with the experiments, indicating its capability to replace experimental testing and provide data inputs for long-term machine learning models.

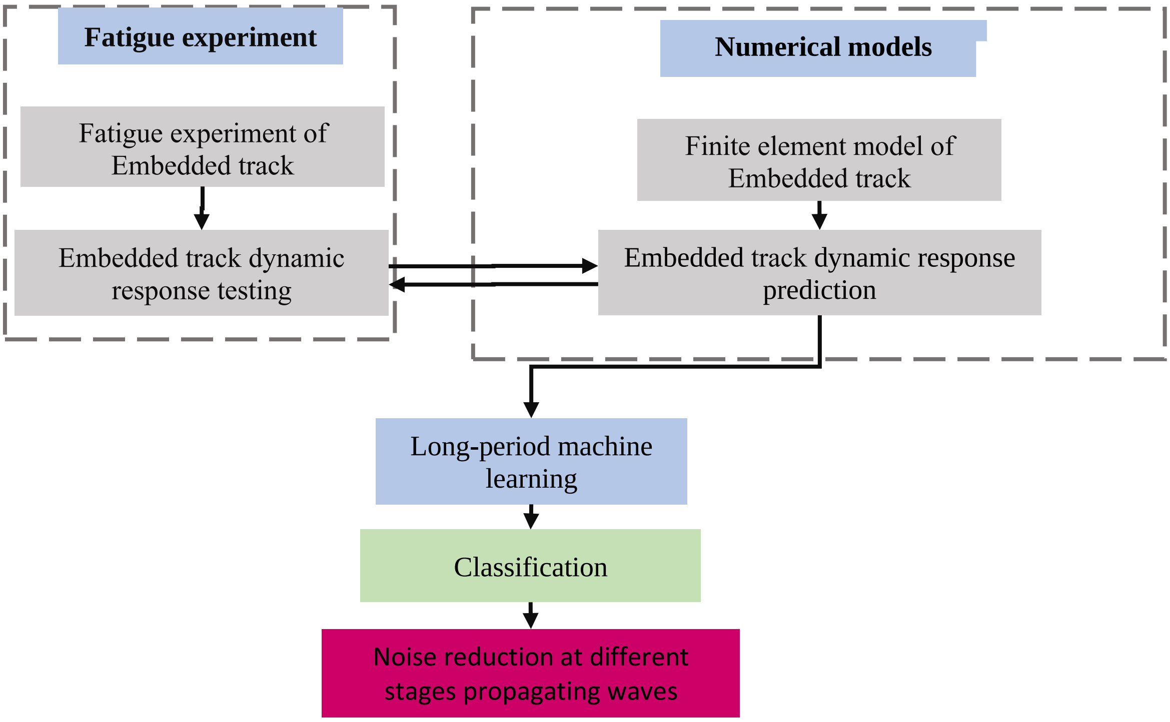
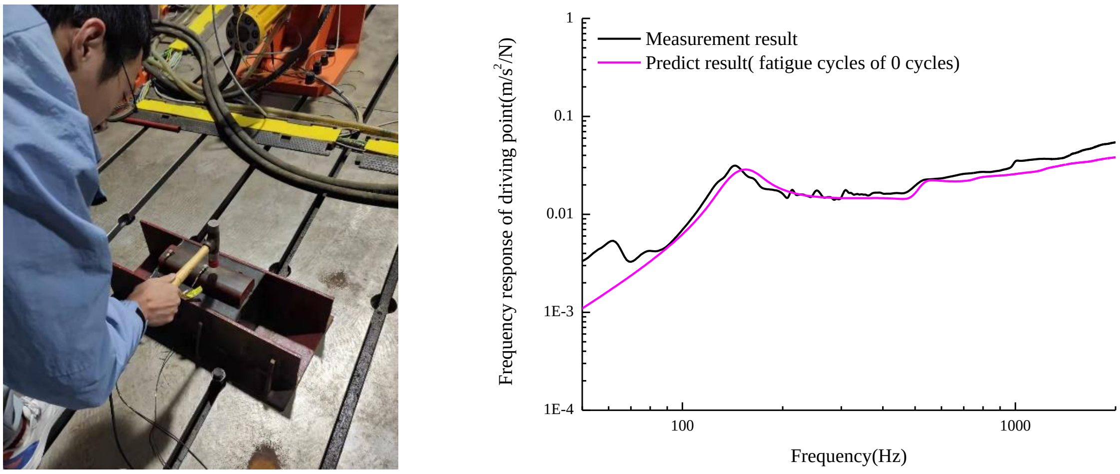


Fig. 3 A flowchart of prediction model.

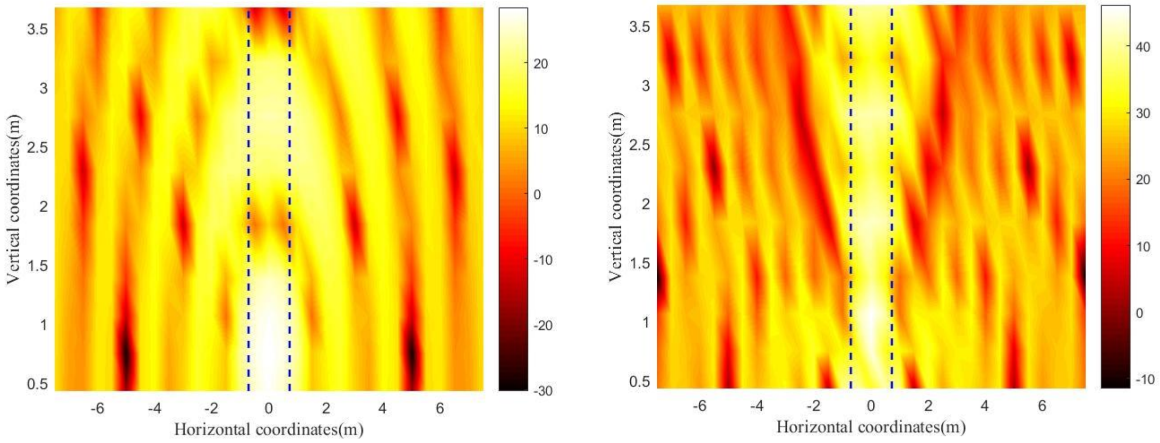


(a) Field test photos (b)Model validation

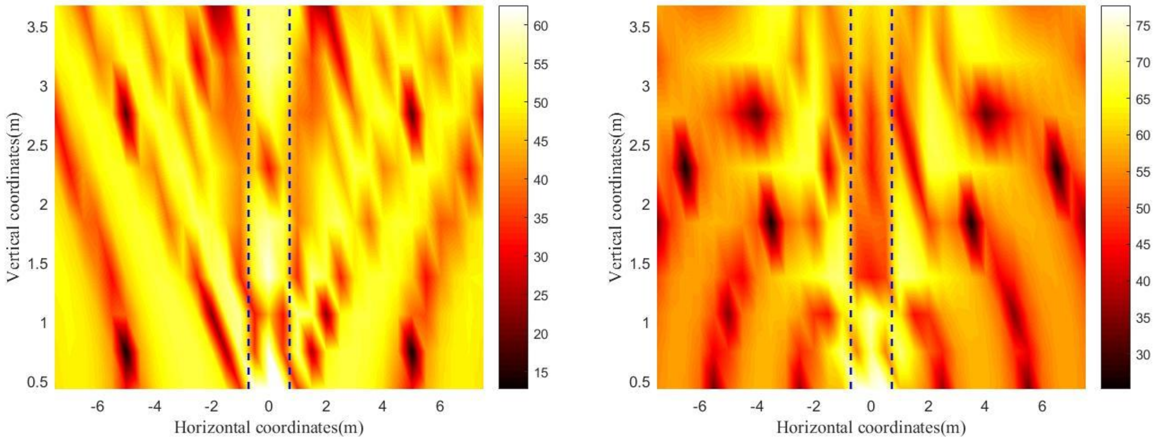
Fig. 4 Comparison of tested results with predicted results

4. Predicted results

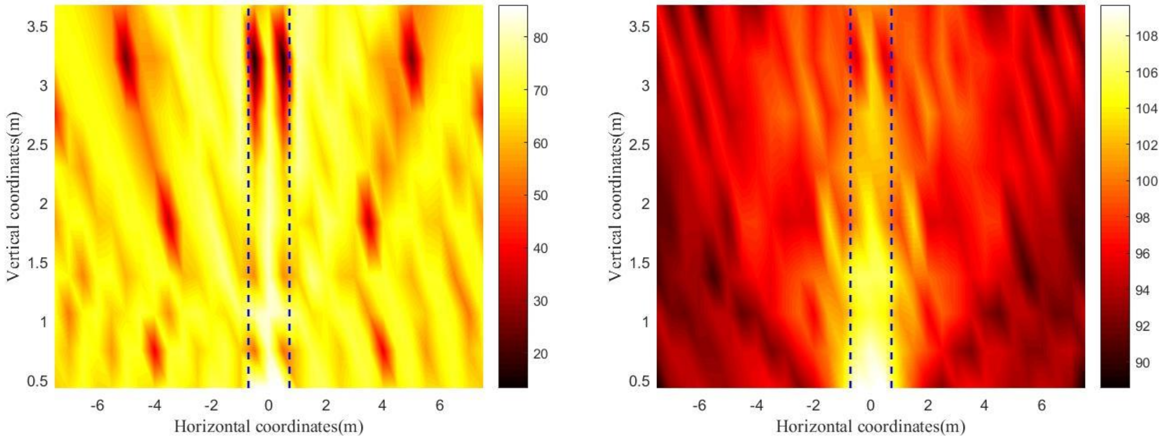
Fig. 5 presents the contour maps of noise distribution in the embedded track structure at different frequencies. From the figure, it can be observed that the embedded track structure exhibits non-directional noise below 100 Hz, and as the frequency increases, the directional characteristics become more prominent with increasing sound pressure. Furthermore, the overall sound pressure is mainly concentrated within the track area, specifically between the two side rails, while the external field noise exhibits stronger directional characteristics.



(a) 100Hz （b） 200Hz



(c) 300Hz （d） 400Hz



(e) 800Hz （f） Total A-weighted sound pressure level

Fig. 5 Field point sound pressure

Fig. 6 illustrates the total wheel-rail noise levels of the embedded track at different stages, as classified by the long-term machine learning model, along with the corresponding noise reduction amounts. From the figure, it is evident that as the service life increases, the noise reduction effectiveness of the embedded track gradually diminishes and can be roughly divided into six stages. After the embedded track has undergone 3 million fatigue cycles, the noise reduction effectiveness decreases from an initial 8.1 dBA to 3.5 dBA.

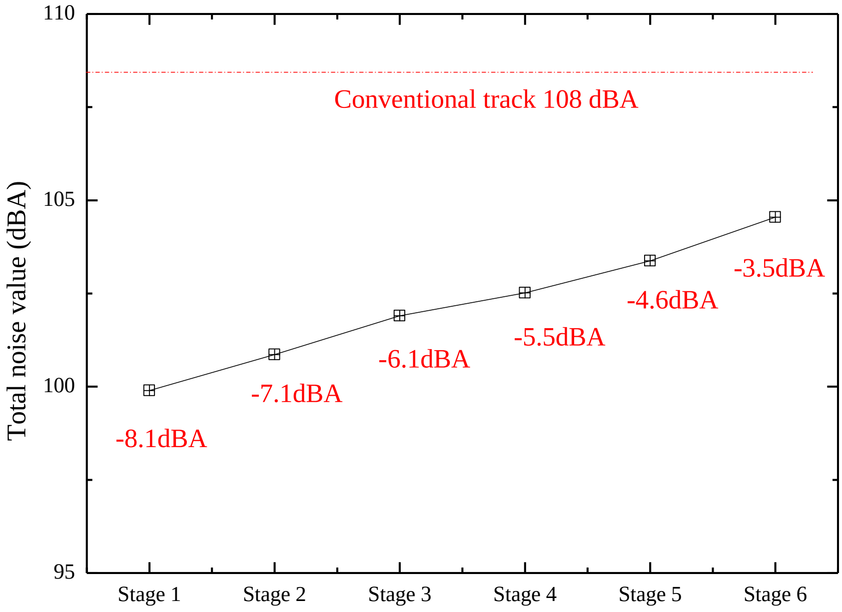


Fig. 6 Noise levels of the embedded track at different stages

5. Conclusion

this paper proposes an embedded track long-period dynamic response analysis method based on machine learning. This method can evaluate the performance change of the embedded track without any label only based on the dynamic response. Among them, self-supervised deep learning networks are used to autonomously extract deep features of the vibration response. These features are then classified by clustering algorithms into different phases of the service life. Finally, the change law of vibration and noise performance of embedded track in different stages is explored. The following conclusions were reached:

1、the embedded track structure exhibits non-directional noise below 100 Hz, and as the frequency increases, the directional characteristics become more prominent with increasing sound pressure. Furthermore, the overall sound pressure is mainly concentrated within the track area, specifically between the two side rails, while the external field noise exhibits stronger directional characteristics.

2、as the service life increases, the noise reduction effectiveness of the embedded track gradually diminishes and can be roughly divided into six stages. After the embedded track has undergone 3 million fatigue cycles, the noise reduction effectiveness decreases from an initial 8.1 dBA to 3.5 dBA.

Acknowledgements

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