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Evaluation Method of BTM Antenna Radiation Emission Environmental Effect Based on Similarity Theory

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ABSTRACT: In the pursuit of comprehensively assessing the radiation emission characteristics of the balise transmission module (BTM) antenna within diverse train environments, this paper puts forward a novel approach grounded in similarity theory. Herein, the ideal radiation emission field distribution of a single BTM antenna serves as the reference two-dimensional dataset. The radiation emission field distribution specific to a given train environment is adopted as the input data. By calculating the similarity coefficients, the extent of influence exerted by different train settings on the radiation emission traits of BTM antennas can be accurately gauged. In addition, 13 representative train environments have been meticulously measured and evaluated. The results reveal that the mean square error (MSE) of this evaluation method is less than 0.011. This compellingly demonstrates the effectiveness of the method's predictive capabilities. In light of the above-mentioned theoretical postulations and practical exigencies, the proposed method empowers us to effectively evaluate the impact of a particular environment on the radiation characteristics of the BTM antenna even prior to the installation of BTM equipment.

1. INTRODUCTION

Balise transmission module (BTM) is an on-board device used for train-to-ground data transmission, processing signals and messages on the uplink and downlink to the transponder, and communicating with the core equipment on the train [1–3]. BTM equipment consists of two parts: BTM host and on-board antenna (hereinafter referred to as BTM antenna). BTM antenna continuously sends 27.095 MHz of energy to the ground to activate the transponder, receives uplink signals sent by the ground transponder, and parses the transponder message, and the BTM host simultaneously sends the received transponder message information to the train control system on-board computer [4].

Scholars have done a lot of research on the influence of the installation environment of the transponder transmission system on et al. established a theoretical model of magnetic field distribution and angle deviation of rectangular antenna. Meanwhile, they also analyzed the influence of BTM antenna installation height and angle deviation on transponder operating distance [5]. Utilizing the optimization strategy of artificial intelligence, Song proposed suppression measures to reduce the electromagnetic coupling of the antenna port by optimizing the installation position of the roof antenna [6]. Based on the strategy of loading redundant antennas, Gong et al. studied the effect of redundant antennas on the effective range of BTM antennas at different installation distances [7]. Meng proposed a method to optimize the size of the BTM antenna and the installation height of the transponder based on the principle of electromagnetic coupling [8]. Sun et al. studied the influence of ballastless track plate on the electromagnetic interference of BTM and put forward guiding suggestions on the installation height of the antenna [9]. Aiming at the noise interference of the transponder signal, Lv and Zhao [10] and Liang et al. [11] proposed a signal processing method of the transponder uplink based on cognitive control. Zhao and Jiang studied and evaluated the adaptability and reliability of the signal system under high-speed operating conditions [12]. In summary, the key issues affecting the performance of the transponder transmission system (antenna size, installation height, Angle) have been studied in the early stage, but the field train environment is diverse and complex, and the adaptation performance of BTM to the overall environment of different vehicles is different, and especially the performance of BTM antenna radiation emission is affected. It will directly lead to the quality of the on-site downlink signal, so it is necessary to study a method of application evaluation of the transponder transmission system for the actual environment, set the corresponding indicators, and evaluate the adaptability of BTM to the installation environment of different models, so that problems can be found and solved as soon as possible in the early stage of installation.

At present, the installation environment of BTM antenna has little influence on the near-field distribution of antenna radiation emission. At the same time, considering the complexity of the train model structure and the uncertainty of the surrounding environment, simple one-dimensional analysis method such as angle and height is not enough to evaluate. Therefore, it is necessary to realize multi-dimensional evaluation with the help of surveying and mapping methods [13, 14]. Correlation methods have been applied in many fields, such as using three-dimensional spatio-temporal correlation method to assist Unmanned Aerial Vehicle (UAV) signal map reconstruction. Besides, the correlation method is also applied in the field of medical image processing, which provides strong support for the

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rapid analysis of complex brain deformation in brain magnetic resonance imaging [15, 16].

In response to the above-mentioned requirements and deficiencies, this paper puts forward a method for evaluating the environmental effects of BTM radiation emission based on the similarity theory. This method is applied to assess the impact of the installation environment of the BTM antenna on the communication transmission quality of the uplink and downlink. It can achieve quantitative prediction during the train design process, providing theoretical support for analyzing the performance of the balise transmission module.

The rest of this paper is structured as follows. In Section 2, the evaluation method of the environmental effects of BTM antenna radiation emission is introduced, and the corresponding logic diagram is presented. In Section 3, the radiation fields of BTM antennas of four typical models are simulated using numerical calculation techniques, and the influence of different models on the radiation fields is analyzed. In Section 4, experimental verification is carried out, along with discussion and analysis. Finally, a summary is provided in Section 5.

2. EVALUATION METHOD OF ENVIRONMENTAL EFFECTS OF BTM ANTENNA RADIATION EMISSION

The BTM antenna is installed on the bottom of the train, and the installation environment around the antenna varies greatly due to different models [18]. BTM antenna is an important signal transmitter in downlink, and the surrounding metal environment will affect its radiation emission characteristics in different degrees [19, 20]. Therefore, it is necessary to develop a method to evaluate the environmental effect of BTM antenna radiation emission, which is used to evaluate the influence of the environment under the train on the train radiation field. Fig. 1 shows a logical diagram of the evaluation method of environmental effects of BTM antenna radiation emission.

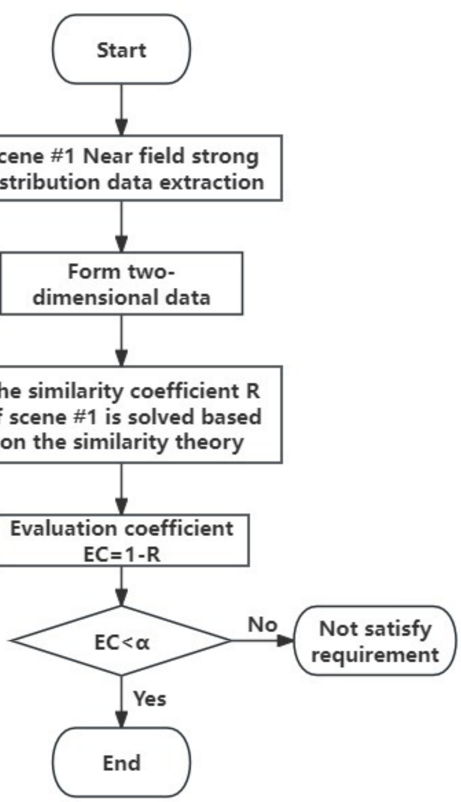

FIGURE 1. Logical diagram of the method of the BTM antenna radiation emission environmental effect evaluation method.

The method to evaluate the environmental effect of BTM antenna radiation emission is to analyze the similarity between the radiation field of single BTM antenna and the two-dimensional electromagnetic field after the installation of the train bottom by using the similarity principle. The similarity coefficient is used to quantify the effect of the environment on the radiation field of the BTM antenna, so that the signal transmission of the uplink and downlink can be predicted before the installation of the BTM.

The near-field intensity $[\mathbf{E}_{BTM}]$ of radiation emission of a single BTM antenna and the near-field intensity $[\mathbf{E}_{BTM-i}]$ of BTM in scenario i are obtained by simulation calculation, and then the correlation coefficients of the two are calculated as follows:

$$R = Corr\left([\mathbf{E}_{BTM}], [\mathbf{E}_{BTM-i}]\right) \tag{1}$$

Through practical testing and engineering experience, the impact threshold α of the scene is determined, and the relationship between $1 - R_i$ and α is judged to evaluate the impact of the scene on the BTM antenna radiation transmitting site.

3. SIMULATION OF TYPICAL BTM ANTENNA RADIATION FIELD

3.1. BTM Antenna Radiation Field Simulation

The surrounding metal objects and BTM antenna are placed on xoy plane, and the radiation of BTM antenna is simulated and analyzed by FEM (finite element method) algorithm, which is implemented by python programming. As shown in Fig. 2 to Fig. 5, the installation environment of BTM antenna varies greatly among different models. The main difference is the shape and position of the metal plates around the antenna. In Fig. 2, only one side has a metal plate, which is 30 cm away

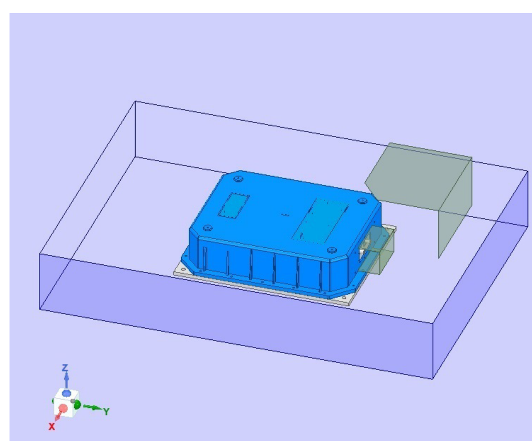

FIGURE 2. BTM installation environment I.

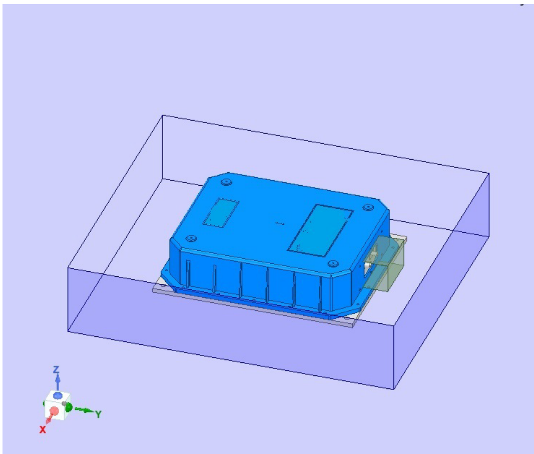

FIGURE 3. BTM installation environment II.

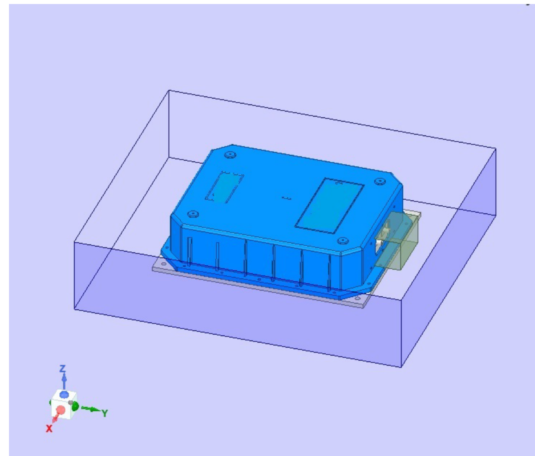

FIGURE 4. BTM installation environment III.

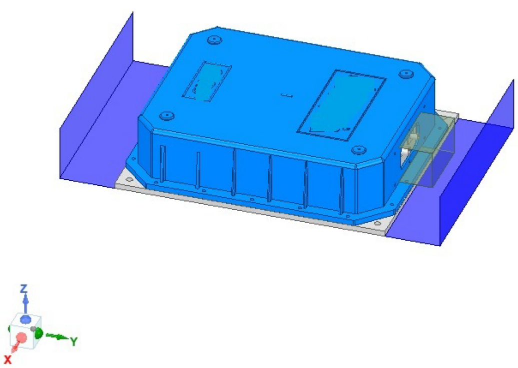

FIGURE 5. BTM installation environment IV.

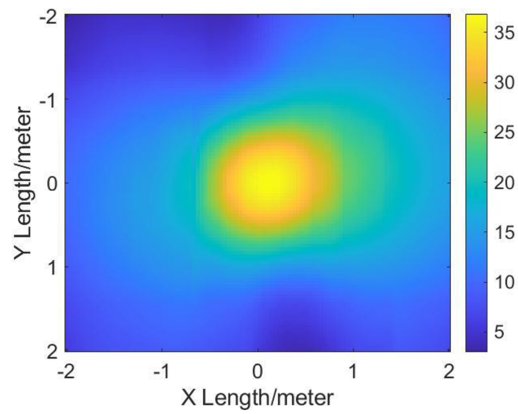

FIGURE 6. Electric field intensity distribution 220 mm from BTM surface.

from the side of the antenna. In Fig. 3, the metal plates around the antenna are 30 cm away from the side of the antenna. In Fig. 4, the metal plates around the antenna are 15 cm away from the side of the antenna. In Fig. 5, the metal plates on both sides of the antenna are 10 cm away from the side of the antenna. In addition, the installation environment includes metal and non-metal environments, which have a certain impact on the near-field distribution, so the signal strength of the upstream and downstream links will have a certain impact.

Based on the above installation environment, this section uses simulation software to carry out simulation calculation for four models. The electric field strength at a distance of 220 mm from the BTM surface has been obtained through the calculations. Fig. 6 shows the radiation field distribution of the BTM antenna. The area is $4\,\text{m} \times 4\,\text{m}$ plane area, and 100×100 points are collected.

As can be seen from the electric field distribution results shown in Fig. 6, the area with strong intensity is not located in the center of BTM but near the feed end.

Fig. 7 shows the measured site:

Test procedure:

a) Place the BTM antenna above the radio anechoic room turntable, 91 cm away from the ground.

b) Collect the data of the field intensity probe once every 10 deg rotation.

c) The probe distance from the top of the BTM antenna includes 220 mm, 350 mm, 460 mm, and 600 mm.

d) The probe distance from the BTM center includes 20 cm, 40 cm, 60 cm, 100 cm, and 200 cm.

As shown in Fig. 8, the simulated results are close to the measured ones. The above and below figures show the comparison between the measured and simulated results when the electric field probe is 20 cm and 40 cm away from the BTM center, respectively. The average error is 2.3 dB, which indicates the validity of the simulation results.

Based on the distribution of electromagnetic field intensity presented in Fig. 9 and Fig. 10, it is evident that the structural environment at the bottom of different train models exerts a non-negligible influence on the radiation emission field of the Balise Transmission Module (BTM) antenna. Notably, the impact on the electric field is more significant than that on the magnetic field. This can be primarily ascribed to the metal conductivity of the installation environment at the bottom of the train. To be specific, the permeability in the area beneath the train is relatively low, whereas the conductivity is remark-

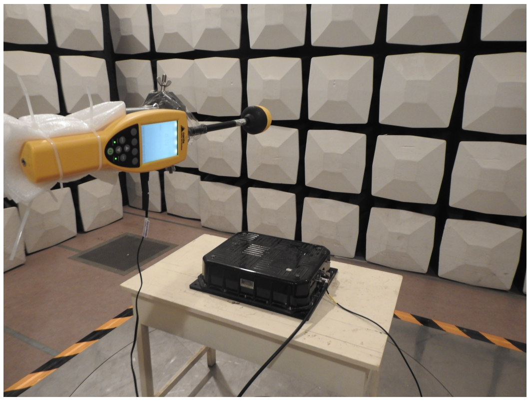

FIGURE 7. Electric field intensity distribution from BTM surface radiation emission measurement photos.

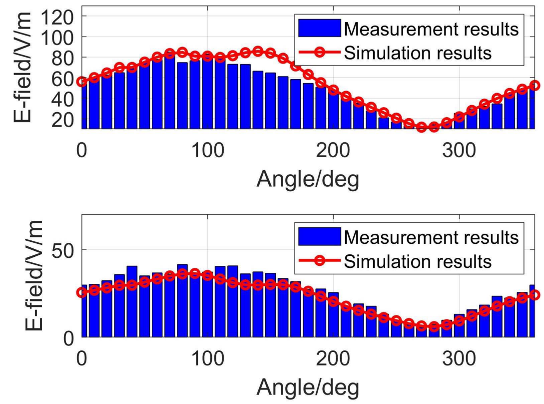

FIGURE 8. Comparison between simulated and measured results.

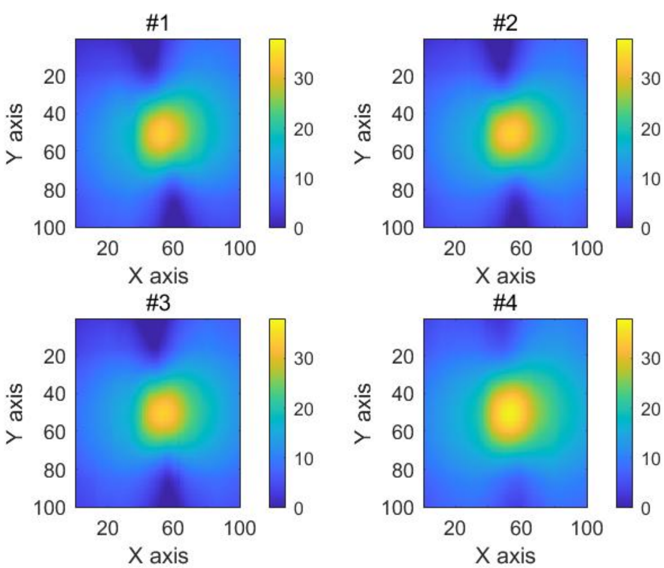

FIGURE 9. Electric field intensity distribution at 220 mm from BTM surface under different environments.

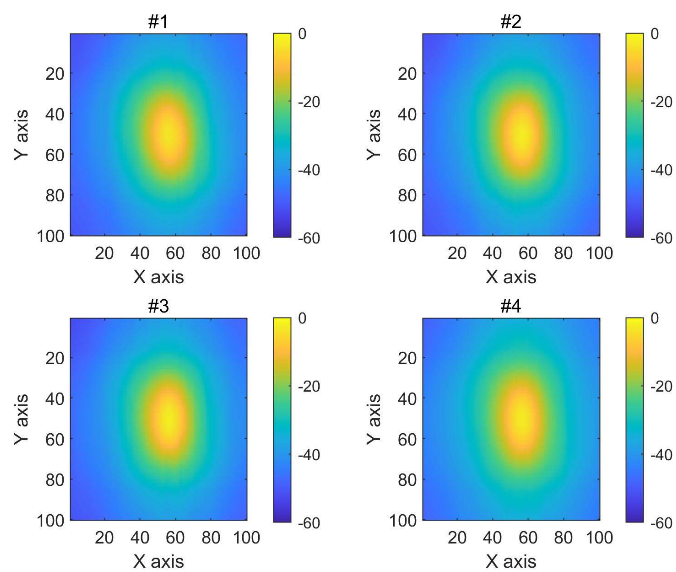

FIGURE 10. Magnetic field intensity distribution at 220 mm from BTM surface under different environments.

ably high. Consequently, it is imperative to conduct a comprehensive evaluation of the environmental impact effect. In both Fig. 9 and Fig. 10, the abscissas and ordinates denote the sampling points within the defined test area and are devoid of any explicit units of measurement.

3.2. Analysis of Influence of Train Environment on Radiation Field Distribution

Since the ground receiving antenna is a loop antenna, the intensity distribution of the BTM radiation field is a two-dimensional plane parallel to the ground. Therefore, two-dimensional correlation coefficient is used to characterize the impact of the train bottom environment on the BTM radiation field. Let $A = [E_{BTM}]$, $B = [E_{BTM-i}]$, and the two-dimensional correlation coefficient is expressed as follows [17]:

$$r = \frac{\sum_m \sum_n \left(A_{mn} - \overline{A}\right)\left(B_{mn} - \overline{B}\right)}{\sqrt{\left(\sum_m \sum_n \left(A_{mn} - \overline{A}\right)^2\right)\left(\sum_m \sum_n \left(B_{mn} - \overline{B}\right)^2\right)}} \tag{2}$$

where $\overline{A} = \text{mean2}(A)$ and $\overline{B} = \text{mean2}(B)$. A represents the two-dimensional field distribution when only BTM is present (E or H), and B represents the two-dimensional field distribution of BTM antenna in different installation environments (E or H).

4. EXPERIMENTAL VERIFICATION OF BTM ANTENNA RADIATION FIELD

The radiation power value of BTM antenna in the environment of various train models tested on site is shown in Fig. 11, which is converted to calculate the radiation voltage value and recorded. This paper uses the voltage data obtained from the field test as the measured results and normalizes the measured results to verify the effectiveness of the evaluation method.

Similarly, the two-dimensional similarity coefficients of BTM surface heights in different environments and at different distances were normalized, as shown in Fig. 12. The evaluation results were compared with the measured ones.

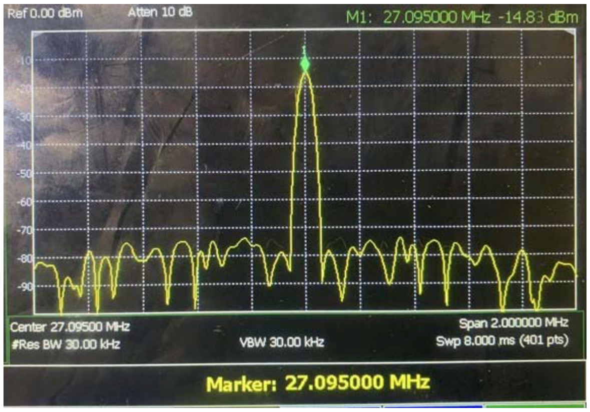

FIGURE 11. Field BTM antenna radiated power test results.

Mean square error (MSE) is used to evaluate the effectiveness of the proposed method. MSE's formula is as follows:

$$MSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \widehat{Y}_i\right)^2} \tag{3}$$

where Y refers to the deviation between the magnetic flux of the BTM antenna and the magnetic flux radiated by the antenna itself in different scenes under the determined height of the BTM antenna.

As shown in Table 1, the MSE of the evaluation method based on the similarity theory is below 0.011, and the farther away from the BTM antenna, the smaller the mean square error. It shows that this method can accurately evaluate the influence of BTM installation environment on the radiation field of BTM antenna.

TABLE 1. The mean square error of the evaluation method.

Distance	MSE
220 mm	0.0108
350 mm	0.0077
460 mm	0.0108
600 mm	0.0032

5. CONCLUSIONS

In this paper, the influence of train type on the radiation field of the BTM antenna installed under the train bottom is studied, and the field distribution of BTM antenna in the adjacent area under different train types is obtained by simulation. In order to evaluate the influence of the environment on the radiation field, the similarity theory in the field of image processing is introduced to analyze the radiation field in different environments. The similarity coefficient is used as an index to evaluate the radiation field affected by the environment, verified by the measured results, proving the validity of the above theory. The evaluation method based on similarity theory is of great significance for quantitatively analyzing whether the installation environment of BTM antenna meets the requirements and optimizing the design of BTM antenna. Based on the above research, we plan to analyze the relationship between antenna coupling characteristics and running speed under dynamic train running conditions in the future.

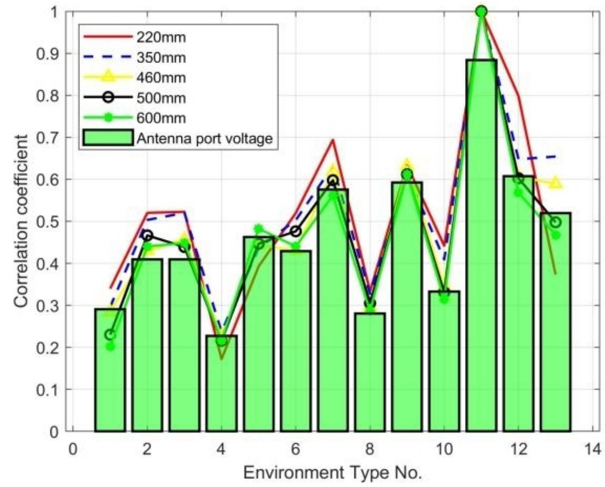

FIGURE 12. Comparison of the test results under different environments.

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