Optimization of Braking Force for Electromagnetic Track Brake Using Uniform Design

CHUN XIANG\(^1\), SHI-AN CHEN\(^1,2\), MING YAO\(^2\), YU-FENG GU\(^2\), AND XIN YANG\(^2\)

\(^1\)College of Mechanical and Automotive Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou 310058, China
\(^2\)School of Automobile and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China

Corresponding author: Ming Yao (ymluck@ujs.edu.cn)

This work was supported by the financial support from the Postgraduate Practical Innovation Project of Jiangsu under Grant 5561120021.

ABSTRACT Electromagnetic track brake is increasingly applied to improve emergency braking force together with the main wheel-rail brake system, while larger electromagnetic braking force is demanded. The bottom of pole shoe is designed as the same curved surface like track top in order to achieve a good contact between pole shoe and track and the pole shoe chamfering is also designed to improve electromagnetic attractive force. Three main variables that decide the electromagnetic attractive force are selected in the paper: pole shoe contact width, protection block length and pole shoe length. The reliability of electromagnetic simulation is verified through prototype test and then the electromagnetic attractive force in this study is achieved by electromagnetic simulation. First, the effects of the three variables on electromagnetic attractive force are investigated singly. Then, a uniform design method is employed in this study to further optimize electromagnetic attractive force by researching the interactional effects of the three variables. A regression model is established with pole shoe contact width, protection block length and pole shoe length as the independent variables, and electromagnetic attractive force as the dependent variable. Depending on the regression model, the optimum conditions of the three variables are achieved. In addition, finite element simulation of electromagnetic track brake is developed to investigate electromagnetic attractive force and magnetic field distribution by Ansoft Maxwell. Compared to the existing electromagnetic track brake, the electromagnetic braking force and electromagnetic braking deceleration of the optimized electromagnetic track brake are improved by 6.3% under the optimum conditions, which can greatly improve train safety in emergency. The proposed reinforcement optimizations have two outstanding characteristics. The first is keeping the space usage of electromagnetic track brake unaltered, and the other is its simplicity to conduct.

INDEX TERMS Electromagnetic track brake, uniform design, multi-objective optimization, braking performance.

I. INTRODUCTION

Since the high-speed rail system Shinkansen was first launched in 1964, such rail systems have developed rapidly in Japan, Germany, France, and China [1], [2]. The current maximum speed of high-speed trains reportedly reaches 574.8 km/h [3]. Reducing the speed of trains as quickly as possible during emergencies is important. The magnet track brake is employed together with the main wheel-rail brake system in emergency circumstances because it is independent of wheel–rail adhesion [1], [4]. Moreover, the magnet track brake was reported to be used against slippery tracks caused by contaminants such as snow, sand, and leaves, among others [5].

During the operation of the magnet track brake, its pole shoes are driven by magnets to attract and contact the track. A sliding motion occurs between the pole shoes and the track to generate braking force (BF) [6]. Magnet track brakes can be categorized into permanent-magnet track brake and electromagnetic track brake (ETB), classified by excitation mode [7]. The magnet circuit of ETB has two layout forms, namely, lateral-axis form and longitudinal-axis form [8]. The ETB is increasingly used to improve security when emergency occurs. Shi-an Chen proposed a new ETB with...
longitudinal-axis magnetic circuits and the pole shoes extending outward displayed in Figure 1 [9]. The ETB has been designed, optimized and experiment, it performs better than the one for German inter-city express (ICE) in electromagnetic attractive force (EAF) [10]. However, the larger electromagnetic BF (EBF) is demanded in order to achieve better security.

FIGURE 1. (a) Electromagnet structure and (b) assembly drawing of ETB.

The main factor affecting EBF is magnetic field intensity. In recent years, some complex materials [11] such as metamaterials [12] metasurface [13], graphene [14] and nanostructures [15] have been exploited to enhance the electromagnetic properties of materials.

Magnetic field intensity and magnetic pole area between pole shoe and track are primary in enhancing EAF, which can be optimized by changing the iron core length (protection block length), pole shoe contact width and pole shoe length. The bottom of pole shoe is designed as the same curved surface like track top in order to achieve a good contact between pole shoe and track and the pole shoe chamfering is also designed to improve EAF. These optimizations are all subject to the preconditions that do not change the installation and work conditions of ETB. The reliability of electromagnetic simulation is verified through prototype test and then the electromagnetic attractive force in this study is achieved by electromagnetic simulation. Factors such as pole shoe contact width, protection block length and pole shoe length are respectively analyzed and their effects on EAF are described in figures. However, further study is demanded base on the previous research.

The uniform design method basing on the orthogonal design method is firstly designed by Chinese mathematicians Yuan Wang and Kaitai Fang [16], [17] through combining the number theory with multivariate statistics, and frequently applied for multi-factor and multilevel experimental design approaches. Uniform design can achieve the effect of factors on characteristic properties and the optimal conditions of factors. When more factors and levels are studied, the uniform design method requires fewer tests than other test design methods. Therefore, the optimization process of multiple factors is more efficient. On the other hand, the results of treatment usually needs to be done by regression analysis method, few tests will result in the failure to establish an effective model, so a very good basis and rich experience of previous work is needed. This paper has done a lot of optimizations and experiments for the relevant factors of ETB, so the uniform design method is applicable.

In general, uniform design is preferred because it lessens the experiment number significantly in researching multiple factors and their interactions. Therefore, the purpose of this study is to further optimize the EAF with the uniform design method, by investigating the effects of pole shoe contact width, protection block length and pole shoe length on EAF. A regression model is established and the optimum condition is obtained and validated. In addition, finite element simulations of ETB are developed by Ansoft Maxwell to investigate EAF and magnetic field distribution. Finally, the EBF and braking deceleration are estimated using friction coefficient. Compared to the pre-optimization ETB, the EBF and electromagnetic braking deceleration are very improved by 6.3%, when the pole shoe contact width, protection block length and pole shoe length are 47 mm, 40 mm and 164 mm respectively, which can greatly improve train safety in emergency. The proposed reinforcement optimizations have two outstanding characteristics. The first is the unaltered space usage of ETB, which do not affect its installation. The second is its simplicity to conduct.

This paper is organized as follows: First, we develop multiple-factor optimization of EAF, including theoretical basis, factor selection and simulation experiment design. Second, the single and interactional effects of pole shoe contact width, protection block length and pole shoe length are researched by uniform design. The optimum condition of the three factors are achieved by the regression model and validated. Third, electromagnetic simulation analyses of the optimized ETB are presented using Ansoft Maxwell. Finally, the BF and braking deceleration are calculated and the comparisons between the optimized ETB and the existing ETB are carried out.

II. MULTIPLE-FACTOR OPTIMIZATION OF EAF

A. THEORETICAL BASIS OF OPTIMIZATION

The fundamental formula of electromagnetic force is Maxwell formula, expressed as:

\[ F = \frac{\varphi^2}{2\mu_0} - \frac{B^2}{2\mu_0} \]

where F is electromagnetic force, N; B is magnetic induction, T; S is the total area of magnetic pole surface, m²; \( \mu_0 \) is air magnetic permeability, H/m; \( \varphi \) is the magnetic flux of magnetic pole surface, Wb.

The EAF between the ETB and the track is mainly composed of two parts. The first one is between the electromagnet and the track and the other one is between the protection block and the track. According to Equation (1), the EAF can be defined as:

\[ F_a = \sum_{i=1}^{n} \frac{\varphi_{mg}^2}{2\mu_0 \cdot S_c} + \sum_{i=1}^{n} \frac{\varphi_{pg}^2}{2\mu_0 \cdot S_p} \]

\[ = \sum_{i=1}^{n} \frac{B_{mg}^2}{2\mu_0} \cdot S_c + \sum_{i=1}^{n} \frac{B_{pg}^2}{2\mu_0} \cdot S_p \]

(2)
where $F_a$ is the electromagnetic attractive force, N; $\varphi_{pgi}$ is the magnetic flux through pole shoe, Wb; $\varphi_{mgi}$ is the magnetic flux through protection block, Wb; $S_c$ is the magnetic pole area between pole shoe and track, $m^2$; $S_p$ is the magnetic pole area between protection block and track, $m^2$; $B_{mgi}$ is the magnetic induction through pole shoe, T; $B_{pgi}$ is the magnetic induction through protection block. In Equation (2), the EAF is inversely proportional to the magnetic pole area between pole shoe and track when the magnetic flux through pole shoe is fixed. On the other hand, the EAF is in direct proportion to the magnetic pole area between pole shoe and track when the magnetic induction through pole shoe is fixed. Thus, an optimum value of magnetic pole area between pole shoe and track exists when the ETB works.

**B. OPTIMAL FACTOR SELECTION AND ANALYSIS**

According to Equations (1) and (2), it has two parameters in enhancing EAF, that is, magnetic field intensity and magnetic pole area. The magnetic field intensity can be strengthened by changing the iron core length and pole shoe shape. The magnetic pole area can be altered by changing the pole shoe shape and measure. As exhibited in Figure 2, the contact area between pole shoe and track top is restricted when the existing ETB works due to the bottom of pole shoe is plane and the track top is curved surface. Then, the bottom of pole shoe is designed as the same curved surface like track top in order to achieve a good contact between pole shoe and track.

**C. THE REALIZATION OF THE CURVED POLE SHOE**

The curved pole shoe may generate motion interference when the train is on unsmooth track or crossroad. Thus, the following pole shoe design is put forward to avoid motion interference effectively.

As presented in Figure 4(a), the main braking block is in the middle of the pole shoe, whose width is 20 mm. Two braking

---

**FIGURE 2.** Section view of pole shoe and track.

**FIGURE 3.** Section view of bonding surface between chamfered pole shoe and track.

**FIGURE 4.** (a) Section view of the designed pole shoe and (b) top view of the designed pole shoe.
sliding blocks are arranged at the two flanks of the main braking block together with a locating shaft across the three blocks. The locating shaft stretches out the braking sliding blocks with two fixed baffles on the head, and a pressure spring is located between the braking sliding block and fixed baffle of the same side. Then, the braking sliding blocks can slide on the locating shaft and they are adhered closely to the main braking block by the pressure of pressure spring.

The bottom of the three blocks are all designed as the same curve surface as the track top to achieve a good contact between pole shoe and track. As showed in Figure 4(b), two horizontal locating shafts are installed for a steady structure.

The braking sliding blocks are adhered closely to the main braking block by the pressure of pressure springs when the train is on the lank track and their braking force is transmitted to the ETB through the locating shafts. However, the braking sliding blocks are pushed to the outsides when the train is on unsmooth track or crossroad to avoid motion interference.

**D. RELIABILITY TEST OF ELECTROMAGNETIC SIMULATION**

A previously design and analysis of ETB has been done [10]. The prototype of the existing ETB is manufactured and the EAF is tested to verify the reliability of electromagnetic simulation. In this paper, electromagnetic simulation is conducted by Ansoft Maxwell which is a finite element software that specializes in electromagnetic simulation, and it uses electromagnetic field information to predict product performance accurately from physical design information.

Figure 5(a) shows a picture of the final prototype assembly. The threaded holes on the top of the longitudinal beam are used to install rings when performing the experiment. The holes on the side face of the longitudinal beam are used to install a suspension system of ETB. Figure 5(b) shows the assembly, where the ETB is connected to an electronic scale through rings and a pendant chain, and is lifted up gradually by a traveling crane. The track is fixed on the floor by U-profile steels. The numerical value of EAF and the track brake weight can be directly read from an electronic scale when the track brake is separated from the track. The numerical value of track brake weight is a constant value. Therefore, the EAF is easy to obtain.

The average value of EAF is achieved as the final result through many experiments. The contrastive analyses of tests and simulations are exhibited in Table 1.

**TABLE 1. Comparison between the results of test and simulation.**

| Magnetomotive force (Ampere-turn) | Test force (kN) | Simulation force (kN) | Error (%) |
|----------------------------------|-----------------|-----------------------|-----------|
| 5000                            | 56.9            | 61.4                  | 7.8       |
| 3300                            | 48.0            | 50.2                  | 4.5       |
| 1630                            | 36.1            | 39.7                  | 10.0      |

The EAF of tests agrees with that of the simulations. The error is within the acceptable range and then the following EAF will be achieved by electromagnetic simulation. The following explanations for discrepancies between the test and the simulation are given after careful observations of the test process.

1. Negative factors, such as pits and dust on the track surface, have some effect on the experiment result. In addition, the contact between pole shoes and track may be incomplete due to assembly error.
2. The material property of ETB is constant during the simulation, while temperature influences copper wire resistance during the test.
3. The magnetizing curve used in the simulation is referred to as the electrical engineering handbook, whose value is slightly larger than the actual value.

**E. SIMULATION EXPERIMENT DESIGN AND STATISTICAL ANALYSIS**

Uniform design is applied to determine the optimum EAF of ETB when it works. For uniform design and subsequent analysis, the uniform design software is applied to achieve the simulation experiment designs, statistical analysis and regression model. The simulation experiment results are achieved using Ansoft Maxwell software. More levels of each factor are chosen to reach the optimum regression model. The U21*(217) uniform design table is used in this study according to the uniform design method. The combination effects of independent variables \(X_1\) (pole shoe contact width, mm), \(X_2\) (protection block length, mm), and \(X_3\) (pole shoe length, mm) at 21 variation levels in the electromagnetic simulation are presented. The responses functions \(Y\) are EAF which related to the coded variables by a third-order polynomial equation as follow:

\[
Y = k_0 + \sum_{i=1}^{m} k_iX_i + \sum_{i=1}^{m} k_{ii}X_i^2 + \sum_{i=1}^{m} k_{iii}X_i^3 \\
+ \sum_{i<j}^{m} k_{ij}X_iX_j + \sum_{i<j}^{m} k_{ij}X_iX_j + k_{ij}X_iX_j + E
\]

(3)
where $Y$ is the predicted response; $k_0$, $k_i$, $k_{ij}$, $k_{iij}$ and $k_{iju}$ are the regression coefficients; $X_i$, $X_j$ and $X_u$ are the independent variables.

The regression analysis of the simulation data is achieved by the simplex and step-back methods using the uniform design software. The importance of each coefficient was determined using the t-value and partial correlation coefficient $\rho$. The surface characteristic is investigated for the response function ($Y$) using the regression equation. Responses are simulated and results are compared with model predictions. The optimum condition is verified by conducting simulations under these conditions. In order to visualize the relationship between the response and experimental levels of each factor and to deduce the optimum conditions, the fitted polynomial equation is expressed as surface.

III. RESULTS AND DISCUSSION

A. SINGLE FACTOR RESULTS

1) THE EFFECT OF THE POLE SHOE CONTACT WIDTH ON THE EAF

This simulation experiment adopted the pole shoe contact width from 20 mm to 60 mm as the step length is 5 mm to study the effect of different pole shoe contact width on the EAF. In this simulation experiment, other experimental conditions are as follows: protection block length, 50 mm; pole shoe length, 160 mm. The results are presented in Figure 6, which imply the EAF is always enhanced before the pole shoe contact width is 45 mm and then reduced when the pole shoe contact width was added over 55 mm.

2) THE EFFECT OF THE PROTECTION BLOCK LENGTH ON THE EAF

The effect of the protection block length on the EAF is researched in this work when different protection block length from 34 mm to 106 mm as the step length is 9 mm. The work is set under the other experimental conditions as follows: pole shoe contact width, 45 mm; pole shoe length, 160 mm. It can be seen in Figure 7 that the EAF gradually reduced when the protection block length is over 43 mm.

3) THE EFFECT OF THE POLE SHOE LENGTH ON THE EAF

The EAF is simulated when the pole shoe contact width is 45 mm and the protection block length is 50 mm, and different pole shoe length from 148 mm to 168 mm as the step length is 2.5 mm. Figure 8 shows that the EAF is always increased before the pole shoe length is 163 mm and then decreased when the pole shoe length was added in 168 mm.

The protection block length must be over 30 mm for its protection function and the interaction effects between the three parameters are unknown. Thus, in the uniform design experiment, we adopt pole shoe contact width of 35-55 mm, protection block length of 34-54 mm, and pole shoe length of 158-168 mm for further study objects in reinforcement optimization of ETB.

B. DATA ANALYSIS OF UNIFORM DESIGN

The 21 variation levels and the combination effect of independent variables $X_1$, $X_2$ and $X_3$ at 21 variation levels in the electromagnetic simulation is presented in Table 2. The relationship between the EAF and the three variable parameters
is achieved using uniform design software, as follow:

\[
Y = 10319 - 5938X_1 + 1172.8X_2 + 79.329X_1^2 \\
-12.407X_1X_2 + 72.757X_1X_3 - 7.458X_2X_3 \\
-0.34938X_3^2 + 0.11142X_1^2X_2 - 0.4263X_2^2X_3 \\
+ 0.029449X_2^3 - 0.052755X_2^2X_3 - 0.16625X_3^2X_1 \\
+ 0.035352X_3X_2
\]

\[(4)\]

Obviously, the Y value can be predicted for non-test point combinations of the independent variables \((X_1, X_2 \text{ and } X_3)\) within their definition ranges by Equation (4). Several combinations of independent variables \((X_1, X_2 \text{ and } X_3)\) within the ranges are picked for validation tests, and the calculated values \((Y)\) were compared with the simulated values \((Y_e)\).

It can be seen in Table 3 that the difference values between the calculated values and the simulated values are very small, which demonstrate the reliability of the regression equation.

The results of simulation experiment and model prediction are also displayed in Table 2 and a regression analysis is carried out in Table 4. The multiple correlation coefficient \(R\) is 0.9987 and the determination coefficient \(R^2\) is 0.9974, indicating the high accuracy of the regression model as well. The significance of coefficients is evaluated using t-value and partial correlation coefficient \(\rho\). A corresponding variable is more crucial when the absolute t-value and \(\rho\)-value are larger.

As showed in Table 4, the variable with the greatest effect is the interaction effect of the pole shoe contact width and pole shoe length \((X_1X_3)\), the square term of the pole shoe contact width \((X_1^2)\), followed by the cubical term of the pole shoe contact width \((X_1^3)\). Thus, the pole shoe contact width is the most important parameter in this study.

The relationships between dependent and independent variables are showed in Three-dimensional representation of the response surfaces generated by the model. Two independent variables within analysis range are described in one Three-dimensional surface plots while the other variable is constant.

---

**TABLE 2.** Uniform design with the simulated responses and predicted values.

| Series No | \(X_1\) (mm) | \(X_2\) (mm) | \(X_3\) (mm) | Simulation experiment | Predicted \(Y_e\) (kN) | \(Y_e/Y_p\) (%) |
|-----------|--------------|--------------|--------------|-----------------------|-----------------------|-----------------|
| 1         | 1(35)        | 7(40)        | 9(162)       | 71.8                  | 71.9                  | 0.14            |
| 2         | 2(36)        | 14(47)       | 18(166.5)    | 73.3                  | 73.5                  | 0.27            |
| 3         | 3(37)        | 21(54)       | 5(160)       | 72.9                  | 72.7                  | -0.27           |
| 4         | 4(38)        | 6(39)        | 14(164.5)    | 74.1                  | 74.3                  | 0.27            |
| 5         | 5(39)        | 13(46)       | 1(158)       | 73.5                  | 73.8                  | 0.41            |
| 6         | 6(40)        | 20(53)       | 10(162.5)    | 74.8                  | 74.7                  | -0.13           |
| 7         | 7(41)        | 5(38)        | 19(167)      | 75.9                  | 75.9                  | 0.00            |
| 8         | 8(42)        | 12(45)       | 6(160.5)     | 75.9                  | 75.7                  | -0.26           |
| 9         | 9(43)        | 19(52)       | 15(165)      | 76.2                  | 76.0                  | -0.26           |
| 10        | 10(44)       | 4(37)        | 2(158.5)     | 76.1                  | 76.0                  | -0.13           |
| 11        | 11(45)       | 11(44)       | 11(163)      | 76.6                  | 76.8                  | 0.26            |
| 12        | 12(46)       | 18(51)       | 20(167.5)    | 76.8                  | 76.5                  | -0.39           |
| 13        | 13(47)       | 3(36)        | 7(161)       | 77.0                  | 76.8                  | -0.26           |
| 14        | 14(48)       | 10(43)       | 16(165.5)    | 76.7                  | 76.9                  | 0.26            |
| 15        | 15(49)       | 17(50)       | 3(159)       | 76.8                  | 76.6                  | -0.26           |
| 16        | 16(50)       | 2(35)        | 12(163.5)    | 76.5                  | 76.6                  | 0.13            |
| 17        | 17(51)       | 9(42)        | 21(168)      | 75.8                  | 75.9                  | 0.13            |
| 18        | 18(52)       | 16(49)       | 8(161.5)     | 76.2                  | 76.1                  | -0.13           |
| 19        | 19(53)       | 1(34)        | 17(166)      | 75.3                  | 75.2                  | -0.13           |
| 20        | 20(54)       | 8(41)        | 4(159.5)     | 75.7                  | 75.9                  | 0.26            |
| 21        | 21(55)       | 15(48)       | 13(164)      | 74.3                  | 74.4                  | 0.13            |

---

**TABLE 3.** Validation tests of EAF between the simulated responses and predicted values.

| Series No | \(X_1\) (mm) | \(X_2\) (mm) | \(X_3\) (mm) | Simulation experimental | Predicted \(Y_e/Y_p\) (%) |
|-----------|--------------|--------------|--------------|-----------------------|-----------------------|
| 1         | 136         | 47           | 159          | 72.2                  | 72.1                  | -0.14           |
| 2         | 44          | 42           | 156          | 75.6                  | 75.8                  | 0.26            |
| 3         | 39          | 53           | 166          | 74.9                  | 74.7                  | -0.27           |
| 4         | 52          | 35           | 161          | 76.5                  | 76.3                  | -0.26           |
| 5         | 48          | 38           | 163          | 76.8                  | 76.9                  | 0.13            |

---

**TABLE 4.** Significance of regression coefficient for the EAF.

| Variables | Standard regression coefficient \(B\) | t-value | Computed correlation coefficient \(\rho\) | Partial correlation coefficient \(\rho\) |
|-----------|----------------------------------------|---------|------------------------------------------|-----------------------------------------|
| \(X_1\)   | -10.554                               | -2.525  | -0.6439                                  |                                          |
| \(X_2\)   | 2.8678                                | 1.371   | 0.4156                                   |                                          |
| \(X_1^2\) | 11.334                                | 4.604   | 0.8378                                   |                                          |
| \(X_1X_3\)| -2.0530                               | -1.155  | -0.3594                                  |                                          |
| \(X_2X_3\)| 20.628                               | 2.996   | 0.7066                                   |                                          |
| \(X_2^2\) | -2.7520                               | -0.6497 | -0.2117                                  |                                          |
| \(X_1^3\)| -3.2215                               | -3.094  | -0.7929                                  |                                          |
| \(X_1^2X_3\)| 1.3641                               | 0.8583  | 0.2751                                   |                                          |
| \(X_1X_2^2\)| -9.3057                               | -5.070  | -0.8606                                  |                                          |
| \(X_2^3\)| 1.1252                               | 1.662   | 0.4847                                   |                                          |
| \(X_1X_2X_3\)| -2.6628                               | -2.329  | -0.6133                                  |                                          |
| \(X_2^2X_3\)| -7.9652                               | -2.111  | -0.5754                                  |                                          |
| \(X_1^2X_2\)| 2.2740                               | 0.9105  | 0.2904                                   |                                          |

\[R = 0.9987; R^2 = 0.9974.\]
The interaction effects of the pole shoe contact width and the protection block length ($X_1$ and $X_2$) are presented in Figure 9, which indicate the influence between the two factors is existed. The pole shoe length is a constant equals 160 mm in this figure. Besides, the pole shoe contact width also demonstrates an increase on the EAF in Figure 9 when it is below 45 mm, but a reducing when it is above 50 mm, which accord with the results of Figure 6.

As depicted in Figure 10, the interaction effects of protection block length and pole shoe length ($X_2$ and $X_3$) on the EAF are presented when the pole shoe contact width is 45 mm. It can be found that the EAF always increases before the pole shoe length is 162mm and then decreases when the pole shoe length is added over 166mm, which is in agreement with the results of Figure 8. The protection block length show an increase on the EAF in Figure 10 when it is less than 38 mm, but a decrease when it is above 42 mm, which correspond to the results of Figure 7.

Figure 11 shows 3D graphic surfaces of the influences of the two variables, namely, the interaction effects of the pole shoe contact width and the pole shoe length ($X_1$ and $X_3$) on the EAF, whose change rules are similar to Figures 9 and Figures 10.

Overall, these analyses depending on 3D graphic surfaces are well accorded with the results of single factor simulation experiments illustrated in Figures 6 to 8.

Finally, an optimum condition is achieved base on the results in Figures 9 to 11 and Equation (4) as follows: pole shoe contact width of 47 mm, protection block length of 40 mm and pole shoe length of 164 mm. The EAF of the optimum condition is calculated to be 76.9 kN by Equation (4). The simulation experiments of the optimum condition are carried out three times and its mean value of EAF is 76.8 kN which is very close to the calculation value. In this study, the well results are achieved and less simulation experiment time is demanded using uniform design.

**IV. SIMULATION ANALYSES OF THE OPTIMIZED ETB**

**A. FINITE ELEMENT MODEL**

For the analysis of the present model, the following assumptions are made:

1. The process is steady and isothermal.
2. The model is three-dimensional, and it depends on x, y, and z directions.
(3) Adjacent electromagnet current has reverse directions.
(4) Waterproof layer, shell, and other structures are ignored because they have little influence on the electromagnetic field.
(5) The Natural boundary condition and Neumann boundary condition are applied for the model.
(6) The air gap between the pole shoes and the track is 1 mm.
(7) The air gap between the main braking block and the braking sliding block is 0.5 mm.

The software can automatically develop a grid partition. However, some meshes are added manually to increase magnetic field accuracy. According to partition methodology, a refined mesh is carried out in the contact zone to achieve EAF and magnetic distribution precisely. As depicted in Figure 12, a very fine mesh is employed to achieve desired results, which can meet the accuracy of finite element analysis.

![FIGURE 12. Grid partition model.](image1)

**B. SIMULATION RESULTS ANALYSES**

The simulation results are shown in Figure 13 to Figure 16. As showed in Figures 13 and 14, the various colors represent different magnetic field intensities. The color of the pole shoes is red, which indicates a large magnetic flux density. The magnetic field gradually strengthens as one moves closer to the pole shoe gap because of looping-in that develops between adjacent magnets. However, the desired BF can be provided only when the magnetic flux density is sufficiently large.

![FIGURE 13. Vector magnetic flux density.](image2)

![FIGURE 14. Magnetic flux density.](image3)

**FIGURE 15. Magnetic flux density on the track surface.**

**FIGURE 16. Magnetic flux density on the pole shoes surface.**

**V. ESTIMATION OF BF AND BRAKING DECELERATION**

A facility for a dynamic EBF test is unavailable. Therefore, EBF and braking deceleration are estimated using friction coefficient [8], [9].

As the weight of CRH2M is 441,180 kg [8], its air braking force \( F_{ab} \) is expressed as:

\[
F_{ab} = 510170 \times \frac{v + 150}{2v + 150}
\]  

where \( v \) is train speed, km/h. CRH2 has eight carriages, and it can be equipped with 16 ETBs in total [10]. According to the empirical equation from a Soviet Union laboratory [8, 11], the friction coefficient of track \( \mu_k \) and the EBF \( F_{eb} \) are expressed as:

\[
\mu_k = 0.19 \times \frac{10.8v + 100}{21.6v + 100}
\]  

\[
F_{eb} = 76900 \times 16 \times \mu_k
\]

\[
= 233776 \times \frac{10.8v + 100}{21.6v + 100}
\]  

As the running resistance of CRH2 is too small compared with the air BF and the EBF [8], the braking deceleration of CRH2 is calculated according to equations (5) to (7) as:

\[
a_b = \frac{F_{ab}}{M} + \frac{F_{eb}}{M}
\]

\[
= 1.16 \times \frac{v + 150}{2v + 150} + 0.53 \times \frac{10.8v + 100}{21.6v + 100}
\]
The single ETB before optimized and the one after optimized can provide 61.4 kN and 76.9 kN EAF respectively. When they are used for CRH2, the braking deceleration of CRH2 are $a_{sb}$ and $a_{sb}$ respectively, expressed as:

$$a_{sb} = 1.16 \times \frac{v + 150}{2v + 150} + 0.42 \times \frac{10.8v + 100}{21.6v + 100}$$

$$a_{sb} = 1.16 \times \frac{v + 150}{2v + 150} + 0.53 \times \frac{10.8v + 100}{21.6v + 100}$$

The optimized ETB can provide 0.27 m/s² braking deceleration while the pre-optimized ETB can provide 0.21 m/s² braking deceleration, when the train speed is 200 km/h. As showed in Figure 17, the optimized ETB can enhance CRH2 braking deceleration by 6.3% than the pre-optimized ETB.

![Emergency brake deceleration curves.](image)

**FIGURE 17.** Emergency brake deceleration curves.

**VI. CONCLUSION**

Optimizations of BF for ETB had conducted that have the following two outstanding characteristics: The first is keeping the space usage of electromagnetic track brake unaltered, and the other is its simplicity to conduct. Three main variables that decide the EAF are selected in the paper: pole shoe contact width, protection block length and pole shoe length. The reliability of electromagnetic simulation was verified through prototype test. Uniform design method is applied to optimum EAF, by investigating the interactional effects of pole shoe contact width, protection block length and pole shoe length on EAF. Besides, we applied electromagnetic simulations to investigate EAF and magnetic field distribution. The calculation of EBF and braking deceleration are conducted as well as the comparisons between the optimized and existing ETB are carried out.

This study makes the following contributions:

1. The bottom of pole shoe is designed as the same curved surface like track top in order to achieve a good contact between pole shoe and track.
2. The pole shoe chamfering is designed to improve EAF.
3. A regression model is established with pole shoe contact width, protection block length and pole shoe length as the independent variables, and EAF as the dependent variable.
4. Depending on the regression model, the optimum conditions of the three variables are: pole shoe contact width of 47 mm, protection block length of 40 mm and pole shoe length of 164 mm.
5. The magnetic field distribution of the optimized ETB is developed through finite element simulation using Ansoft Maxwell.
6. The braking deceleration of CRH2 with the optimized ETB are improved by 6.3% under the optimum conditions.

Reducing the speed of trains as quickly as possible during emergencies is very important. Thus, it is very significant that the optimized ETB can enhance the braking deceleration of CRH2 by 6.3% than the pre-optimized ETB, which can greatly improve train safety in emergency.

**FUTURE WORK**

This article mainly optimized the braking force of ETB with uniform design. However, to verify the rationality of the optimization, we need to study from many aspects. As an example, we could discuss the influence of the materials and temperature of parts of the ETB. Furthermore, the analysis of the influence of the ETB with other kinds of brake devices installed on trains can be researched in the future.

**REFERENCES**

[1] L. X. Qian, “Recent technical development of high-speed trains in the world,” *China Railway Sci.*, vol. 24, no. 4, p. 1, 2003.
[2] T. Numano, “Development of high-speed trains for shinkansen in Japan,” *Rail Int.*, no. 4, pp. 19–27, Apr. 1994.
[3] K. Herman, “All aboard for high-speed rail,” *Mech. Eng.*, vol. 118, pp. 94–97, Sep. 1996.
[4] M. J. Leigh, “Brake blending,” *Proc. Inst. Mech. Eng., F*, vol. 208, no. 1, pp. 33–49, 1994.
[5] O. Arias-Cuevas and Z. Li, “Field investigations into the performance of magnetic track brakes of an electrical multiple unit against slippery tracks. Part 2: Braking force and side effects,” *Proc. Inst. Mech. Eng., F*, vol. 226, no. 1, pp. 72–94, Jan. 2012.
[6] L. Zhang and X. Zhu, “Optimal operation of heavy-haul trains equipped with electronically controlled pneumatic brake systems using model predictive control methodology,” *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 1, pp. 13–22, Jan. 2014.
[7] M. Yao, J. Miao, S. Cao, S. Chen, and H. Chai, “The structure design and optimization of electromagnetic-mechanical wedge brake system,” *IEEE Access*, vol. 8, pp. 3996–4004, 2020.
[8] A. R. Albrecht, P. G. Howlett, P. J. Pudney, and X. Wu, “Energy-efficient train control: From local convexity to global optimization and uniqueness,” *Automatica*, vol. 49, no. 10, pp. 3072–3078, Oct. 2013.
[9] S. L. Lu, Y. F. Gu, S. A. Chen, and S. Wang, “A numerical method of the electromagnetic force for the electromagnetic track brake,” *Appl. Mech. Mater.*, vols. 253–255, no. part 1, pp. 2160–2162, 2013.
[10] C. Xiang, J.-C. Wang, Y.-F. Gu, S.-J. Zhang, and S.-A. Chen, “Experiment, optimization, and design of electromagnetic track brake for high-speed railways system,” *Math. Problems Eng.*, vol. 2020, pp. 1–11, Mar. 2020.
[11] N. J. Greymbush, V. Pacheco-Peña, N. Engheta, C. B. Murray, and C. R. Kagan, “Plasmonic optical and chiroptical response of self-assembled Au nanorod equilateral trimers,” *ACS Nano*, vol. 13, no. 2, pp. 1617–1624, Jan. 2019.
[12] L. La Spada and L. Vegni, “Near-zero-index wires,” *Opt. Express*, vol. 25, no. 20, pp. 23699–23708, Oct. 2017.
[13] L. La Spada, C. Spooner, S. Haq, and Y. Hao, “Curvilinear MetaSurfaces for surface wave manipulation,” *Sci. Rep.*, vol. 9, no. 1, Dec. 2019, Art. no. 3107.
[14] I.-H. Lee, D. Yoo, P. Avouris, T. Low, and S.-H. Oh, “Graphene acoustic plasmon resonator for ultrasensitive infrared spectroscopy,” *Nature Nanotechnol.*, vol. 14, no. 4, p. 313, 2019.

[15] L. La Spada and L. Vegni, “Electromagnetic nanoparticles for sensing and medical diagnostic applications,” *Materials*, vol. 11, no. 4, p. 603, Apr. 2018.

[16] K.-T. Fang, “Miscellanea. A connection between uniformity and aberration in regular fractions of two-level factorials,” *Biometrika*, vol. 87, no. 1, pp. 193–198, Mar. 2000.

[17] Y. Wang and K. T. Fang, “Number-theoretic methods in applied statistics,” *Chin. Ann. Math.*, vol. 11, no. 1, pp. 51–65, 1990.

CHUN XIANG is currently a Professor with the College of Mechanical and Automotive Engineering, Zhejiang University of Water Resources and Electric Power. Her main research interests include mechanical design and mechatronic engineering.

SHI-AN CHEN is currently a Professor with the School of Automotive and Traffic Engineering, Jiangsu University. His main research interests include automobile conservation technology and vibration analysis in vehicles.

MING YAO is currently an Associate Professor with the School of Automotive and Traffic Engineering, Jiangsu University. His main research interests include vehicles’ safety technology and energy saving.

YU-FENG GU is currently a Graduate Student with the School of Automotive and Traffic Engineering, Jiangsu University. His main research interest includes emergency braking systems.

XIN YANG is currently a Graduate Student with the School of Automotive and Traffic Engineering, Jiangsu University. His main research interest includes mechanism analysis of braking systems.