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RESEARCH ARTICLE

Impact of Surface Roughness on Pantograph-Catenary Current Collection Quality

FENGYI GUO[1], (Senior Member, IEEE), XIAOKANG WANG[1], JIABAO KOU[1], (Member, IEEE), FUHUA LI[1], (Member, IEEE), AND CONGXIN HAN[2]

[1]College of Electrical and Electronic Engineering, Wenzhou University, Wenzhou 325035, China
[2]Faulty of Electrical and Control Engineering, Liaoning Technical University, Huludao 125105, China

Corresponding author: Jiabao Kou (20210373@wzu.edu.cn)

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ABSTRACT In the pantograph-catenary system, the change of the surface roughness of pantograph sliding plate directly affects the current collection quality of electric locomotive. In this paper, a large number of current-carrying friction experiments have been carried out on the self-developed high-performance sliding electric contact experimental machine, and the effects of the surface roughness of the sliding friction pair on important performance parameters have been studied, including pantograph-catenary contact resistance (R_j), current carrying efficiency (η), current collection stability (δ) and the friction coefficient (μ). Further, the current conduction mechanism is revealed by the microscopic approach. In order to quantitatively reveal the effect of roughness on each evaluation index of current collecting performance, the paper formulates the functional relationship between R_a (arithmetic mean height of contour) and R_j, η, δ, μ by nonlinear fitting. On this basis, a comprehensive evaluation equation is established by the entropy weight method, and then the optimal R_a value is derived for the best pantograph-catenary current collecting performance. The experimental results show that with the increase of the surface roughness R_a of the sliding plate, R_j decreases first and then increases, while η increases first and then decreases, δ increases monotonically, and μ gradually increases. The optimal pantograph-catenary current collection condition can be achieved by reconciliation of these indices. The research results of this paper provide a theoretical basis for improving the current collection quality of pantograph-catenary systems, and is useful for material selection or new type design of pantograph sliding plates.

INDEX TERMS Sliding electrical contact, roughness, current collection quality, optimal roughness.

I. INTRODUCTION

In electrified railway, the sliding electrical contact between pantograph slide plate and catenary conductor (abbreviated as "pantograph-catenary system") is the main way of electric energy transmission of electric locomotive. In the current collection process, changes of the surface roughness of the sliding plate will greatly change the contact state between the sliding friction pairs, which directly affects the power transmission quality of the high-speed railway, and also shortens the service life of sliding plates. Appropriate roughness will reduce friction loss and the contact resistance between friction pairs, and improve the current collection efficiency and stability of pantograph-catenary systems. Therefore, it is important to study the impact of surface roughness of sliding friction pairs on the current collection performance of pantograph-catenary systems and determine the optimal roughness value.

In recent decades, domestic and foreign scholars have conducted a lot of research work on how to improve the current collection quality of pantograph-catenary systems from the two aspects of experimental simulation and simulation

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calculation, and have achieved many positive results. In terms of macro experiments, many scholars have deeply discussed the evolution law of contact resistance, and have carried out a large number of experiments under conditions with different traction current, sliding speed and contact pressure. The relationship between dynamic contact resistance and these three conditions [1] has been clarified by establishing the corresponding mathematical model [2]. The experimental results show that increasing the contact pressure, reducing the sliding speed and contact current can appropriately reduce the contact resistance and improve the pantograph-catenary current collection quality [3]. In addition, some scholars have obtained the best normal load of pantograph during actual operations by comprehensively considering the current collecting efficiency, current collection stability and wear rate of sliding plate [4]. As for the influence of the properties of friction pair materials on the current collection condition of pantograph-catenary systems, Guo *et al.* [5] have verified that under the same contact pressure and contact current, the contact resistance of copper impregnated carbon sliding plate is greater than that of copper based powder metallurgy sliding plate, but the wear resistance of the former is better than that of the latter. Bohua *et al.* [6] have reviewed the characteristics and existing problems of several common electrical contact materials, providing a reference for the further development of graphene materials with better performance. Some scholars [7], [8], [9], [10], [11] have conducted in-depth research on the effects of the temperature, morphology and lubricant of the pantograph-catenary friction pair surface for current collection. However, most of these literatures have discussed under macro experimental conditions, and the conduction mechanism of pantograph-catenary current have not been thoroughly studied from the aspect of micro roughness characteristics of materials.

In the research into the impact of the surface roughness characteristics of sliding friction pairs on the current collection quality of pantograph-catenary, domestic and foreign scholars have mainly carried out simulation calculations by establishing the contact model between sliding friction pairs of pantograph-catenary [12], [13], [14]. Liu *et al.* [15] studied the influence of contact position on contact resistance by establishing a finite element rough contact model, and concluded that positions at convex peaks of the contact surface will produce greater contact resistance. Bai *et al.* [16] discussed the influence of surface roughness on static contact resistance by taking the commercial electrical contact as the research object. Wang *et al.* [17] established a complex model of contact between two rough surfaces based on fractal theory, and obtained the quantitative relationship between contact resistance, current density and surface roughness under arbitrary load; Ueno *et al.* [18] studied the contact voltage drop between the graphite brush and the slip ring under different roughness conditions through experiments. The results showed that when the two roughness were the same, the contact voltage drop became larger. Gao *et al.* [19] revealed the reason why surface roughness affects contact resistance by proposing the concept of similarity index. However, these documents have not comprehensively considered the influence of roughness on the current collection indicators of pantograph-catenary systems.

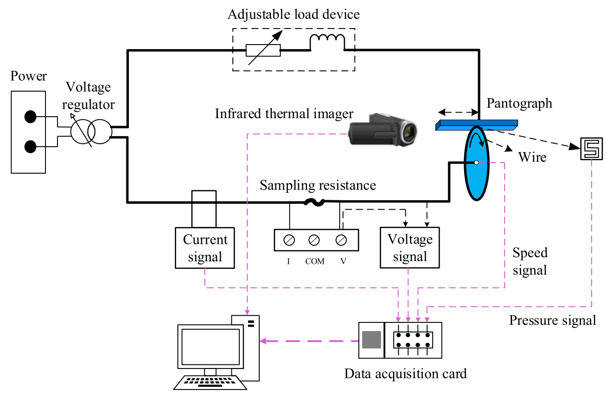

FIGURE 1. Structural diagram of sliding electrical contact testing scheme.

According to the existing literature, the research on the current collection characteristics of pantograph-catenary mainly focuses on the macro experimental conditions, while the research on the roughness characteristics of friction pair materials is relatively few, and the optimal roughness value is not given. In this paper, a large number of experiments have been carried out to clarify the variation rule between the surface roughness of the pantograph sliding plate and the current collection evaluation indexes, reveal the current transmission mechanism from the microscopic approach. And on this basis, a comprehensive evaluation equation is established, and the optimal roughness value is obtained, under which the current collection performance is the best.

The paper consists of four sections. The definition of experimental system, experimental scheme and evaluation indexes are introduced in Section II. In Section III, the variation rules of different roughness parameters and evaluation indexes are discussed, and nonlinear fitting of the experimental results is performed. In Section IV, the comprehensive evaluation equation of pantograph-catenary current collection quality is established by using entropy weight method, and the optimal roughness value for best current collection performance is calculated by using mathematical method. Finally, Section V concludes this paper.

II. EXPERIMENTAL SYSTEM AND SCHEME

A. SLIDING ELECTRIC CONTACT EXPERIMENTAL SYSTEM

A high-performance pantograph-catenary sliding electric contact experimental machine developed by the research group is used to carry out the current carrying friction experiment. The structural diagram of the experimental system is shown in FIGURE 1. In order to adjust the contact pressure F_N between sliding friction pairs and truly simulate the "zigzag" trajectory of pantograph -catenary in actual operation, the experimental machine is equipped with horizontal and vertical sliding platforms. In addition, the size of the

TABLE 1. Experimental materials and their performance.

Parameter	Pure carbon slide	Copper conductor
Brinell hardness [N/mm^2]	30	86
Density [10^3kg/m^3]	1.67	9.02
Resistivity [μΩ·m]	25	0.024
Thermal conductivity [W/(m·k)]	769	398
Specific heat [J/(kg·K)]	769	384

TABLE 2. Specifications of tools of experiment.

Tool	Model					
File	Coarse tooth		Middle tooth		Fine tooth	
Sandpaper	80	200	240	400	1000	1200

loop current I can be adjusted by the voltage regulator, and the sliding speed V and the running distance D can be set by the host computer. The experimental machine is equipped with JLBV13 Hall voltage sensor and HAL200-S Hall current transformer, which can measure the voltage and current signals online during operations. The experimental parameters can be read and stored in real time through USB310XA data acquisition card, and finally are fed back to the computer for further processing and analysis. Therefore, the experimental machine completely satisfies the experimental requirements under different roughness conditions.

B. EXPERIMENTAL SCHEME

Pure carbon sliding plates with overall dimension of 250mm*36mm*27mm and copper wire with a cross-sectional area of 120mm^2 are selected as sliding electrical contact materials in this experiment. At room temperature, the physical properties of pure carbon sliding plate and copper catenary conductor are shown in TABLE 1.

In order to avoid the influence of mechanical wear on the surface roughness of friction pairs in the experiment, the sliding distance is reduced as much as possible on the premise of obtaining effective data. The macro experimental conditions set in this study are $I = 50$A, $V = 30$km/h, $F_N = 50$N and $D = 0.2$km.

The different roughness values of the carbon sliding plate surface are formed by grinding in the same direction with different types of sandpaper and files (its specifications are shown in TABLE 2). At the same time, in order to minimize the experimental error, the roughness of the sliding plate surface is obtained by taking the average of repeatedly measurements on five different contact areas before and after the experiment.

C. ROUGHNESS PARAMETER AND PANTOGRAPH-CATENARY CURRENT COLLECTION EVALUATION INDEX

R_a, which represents the arithmetic mean height of the contour of the micro convex on the surface of the sliding

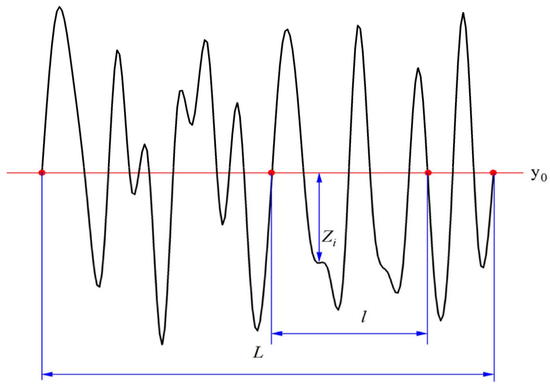

FIGURE 2. Physical meaning of roughness parameter R_a.

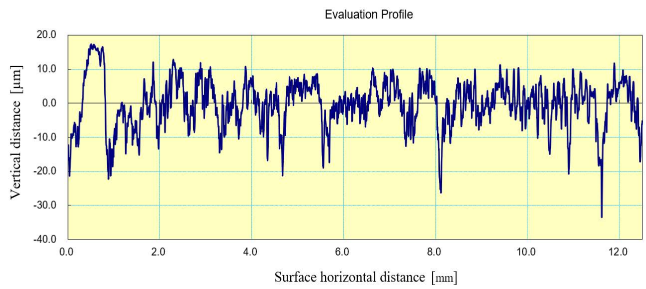

FIGURE 3. Profile curve of sliding plate ($R_a = 5.392$ μm).

plate, is selected in the Geometric Product Specification (GPS) ISO4287-1997 standard as a characteristic parameter to measure the surface roughness of sliding friction pairs. R_a value not only reflects the change of surface roughness of friction pairs, but also contains important information related to pantograph-catenary current collection characteristics. As shown in FIGURE 2: R_a is the average arithmetic deviation from the contour curve to the least square centerline within the sampling length l, which can be calculated by formula (1). Its unit is μm.

$$R_a = \frac{1}{l}\int_0^l |Z_i| di \tag{1}$$

where Z_i is the distance from a point on the evaluation curve to the center line. It can be seen that the larger the R_a value is, the rougher the surface of the sliding plate is.

In the experiment, the surface roughness R_a of the sliding plate is directly measured by SJ-210 roughness measuring instrument (the accuracy is 0.001um, and the actual measured contour measurement curve is shown in FIGURE 3). The temperature rise of the sliding plate surface is obtained by real-time measurement and average of the whole experiment with FLIRT530 infrared thermal imager.

In the process of electric energy transmission of high-speed railway, contact resistance, current carrying efficiency, current receiving stability and friction coefficient are the key indicators to measure the current receiving quality of pantograph-catenary system. They directly reflect the quality of electric contact performance between friction pairs and are the key factors affecting the current receiving status of pantograph-catenary system. Therefore, it is very necessary to study the influence of surface roughness of sliding friction pair on these four current receiving indexes.

The contact resistance value R_j is the averaged value computed from instantaneous voltage and current values measured by the data acquisition card, according to Ohm's law. Its value directly reflects the electrical contact performance between friction pairs [20], and it is the key factor affecting the current collection condition of pantograph-catenary systems.

Current carrying efficiency of pantograph-catenary η is the ratio of the averaged dynamic current carrying value $\overline{I}$ to the static given current I_S, calculated from formula (2) [21].

$$\eta = \overline{I}/I_S \tag{2}$$

The relative stability of contact current between sliding friction pairs is denoted by the relative stability coefficient δ of contact current, and its calculation formula is shown in (3).

$$\begin{cases} \delta = S_I/\overline{I} \times 100\% \\ S_I = \sqrt{\dfrac{1}{n-1}\displaystyle\sum_{i=1}^{n}(I_i - \overline{I})^2} \end{cases} \tag{3}$$

where S_I is the standard deviation of dynamic contact current. The higher the value of δ, the better the current collection stability of the pantograph-catenary system.

The friction coefficient μ is indirectly calculated by measuring the torque of the disc table of the experimental machine, and its calculation formula is derived as follows [5]:

$$\mu = \frac{F_t}{F_r} = \frac{N_B F_t r}{N_B F_r r} = \frac{T_t}{N_B F_r r} = \frac{T - T_0}{N_B F_r r} \tag{4}$$

where F_t is friction force, F_r is loading force, N_B is the number of friction pairs, r is radius of rotary table, T_t is friction torque, T is load torque and T_0 is no-load torque. Under the same pressure, the greater the value of μ, the greater the friction between the sliding friction pairs and the greater the wear of the sliding plate.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The current carrying sliding friction experiment is carried out under the preset experimental conditions, aiming to obtain the variation relationship between pantograph-catenary contact resistance, current carrying efficiency, current carrying stability and friction coefficient under different roughness conditions. At the same time, in order to intuitively reflect the variation relationship between each electrical contact index and R_a, the experimental data are fitted with cubic polynomials, sin functions, peak functions and exponential functions, as shown in FIGURE 5 to FIGURE 8.

A. INFLUENCE OF R_a ON PANTOGRAPH-CATENARY CONTACT RESISTANCE

It can be seen from the experimental results in FIGURE 4 that the dispersion of the data is large, and according to the

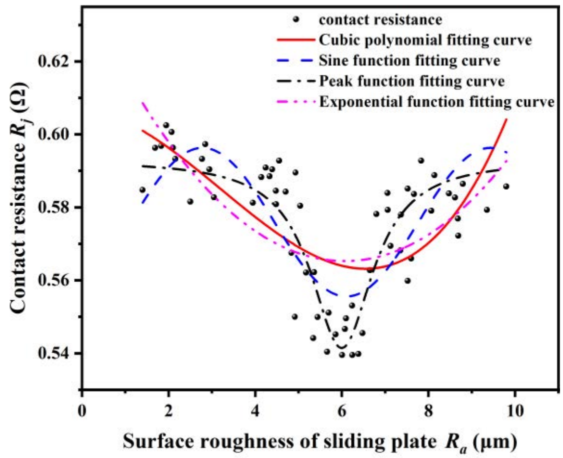

FIGURE 4. Relationship between R_a and contact resistance.

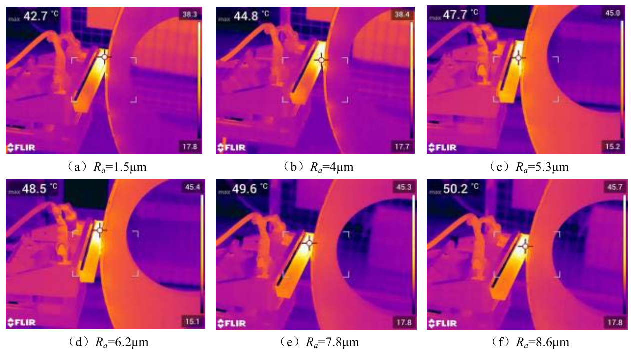

FIGURE 5. Temperature of sliding plate surface under different roughness R_a.

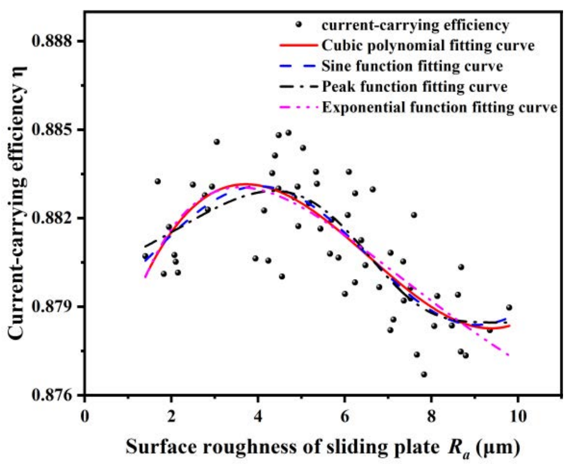

FIGURE 6. Relationship between R_a and current-carrying efficiency.

change trend of the four fitting curves, with the increase of the roughness value R_a, the contact resistance first decreases and then increases, which is approximate to the "V" shape change trend. When $R_a = 6$ μm, R_j reaches the minimum of about 0.54 Ω. Among the four fitting curves, the fitting

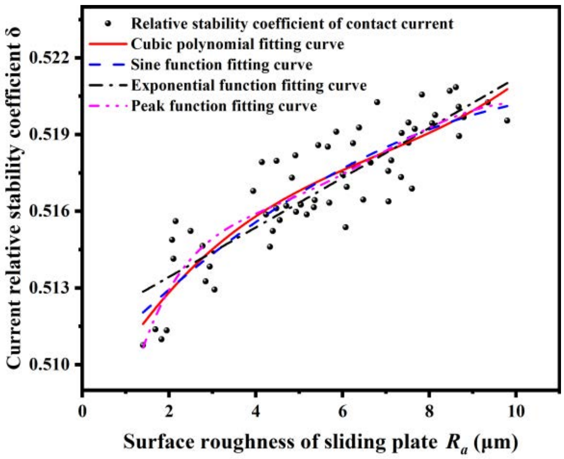

FIGURE 7. Relationship between R_a and current collection stability coefficient.

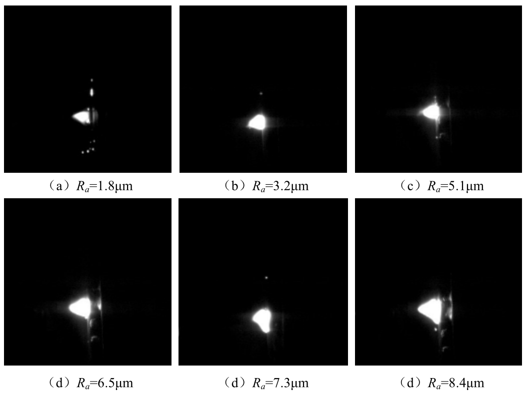

FIGURE 8. Arc image between friction pairs under different roughness conditions.

degree of the peak function is the highest, which can better reflect the variation relationship of R_j and R_a.

The main reason for the variation of contact resistance with roughness is that when the external conditions remain unchanged, the average height of conductive spots on the plate surface gradually increases with the increase of roughness R_a.

On the one hand, when the value of R_a increases within a small range, the pressure on a single micro convex body becomes larger and the contact state between friction pairs is improved. The actual conductive area increases, and the current line shrinkage decreases, so the contact resistance gradually decreases. At $R_a = 6\mu$m, the contact resistance reaches the minimum. Then, with the increase of R_a, the surface of the sliding plate becomes rougher and rougher, and the contraction degree of the current line increases. At the same time, due to the joint action of mechanical heat, joule heat and arc heat, the temperature of contact area rises rapidly, and the temperature effect gradually increases the contact resistance [20]. Under different roughness conditions, the temperature of the sliding plate surface is shown in FIGURE 5.

On the other hand, according to the G-W statistical contact model, the total conductivity G of the expected contact of the friction pair is [22]:

$$G = 2N\rho^{-1}\beta^{\frac{1}{2}} \int_{\mathrm{d}}^{\infty} (z-d)^{\frac{1}{2}} \phi(z)\, dz \tag{5}$$

where N is the total number of micro convex bodies of the friction pair, ρ is the resistivity, β is the radius of curvature of the micro convex body, d is the distance between the two reference planes, $\phi(z)$ is the probability density of the distribution of the surface micro convex body, and z is the height expected to contact any rough body; When other conditions remain unchanged, the increase of R_a and the effect of plate temperature rise will affect ρ and z in the model, so that the contact resistance first decreases and then increases with the increase of roughness R_a.

B. EFFECT OF R_a ON CURRENT CARRYING EFFICIENCY OF PANTOGRAPH-CATENARY

FIGURE 6 shows the relationship between the current carrying efficiency of pantograph-catenary systems and the surface roughness R_a of sliding plate. According to the distribution of experimental data and the change trend of fitting curve, it can be seen that with the increase of roughness R_a, η first increase and then decrease. And in the whole experimental range, when R_a is about 4.55 μm, the maximum value of η obtained is 0.884. Then with the increase of R_a, η gradually decreases. According to the nonlinear curve fitting results, the cubic polynomial has the highest goodness of fit, which can better reflect the relationship between R_a and η.

This is because the contact resistance is one of the key factors affecting the current carrying efficiency of pantograph-catenary systems. When the roughness R_a is small, the contact resistance gradually decreases, and the deviation of dynamic current from the static given current also decreases, and hence the current carrying efficiency increases. When $R_a > 5$ μm, the contact state of the friction pair surface becomes worse, the number of micro convex body actually participating in the current conduction on the plate surface decreases, thus the current receiving area decreases. At the same time, $R_a > 6$ μm, the gradual increase of contact resistance also makes the pantograph-catenary current collection efficiency gradually reduce.

C. EFFECT OF R_a ON CURRENT CARRYING STABILITY OF PANTOGRAPH-CATENARY

As can be seen in FIGURE 7, the experimental data are relatively concentrated, and the overall change trend is obvious. With the increase of roughness R_a, the value of δ also gradually increases, and the pantograph-catenary current collection stability becomes worse. According to the fitting results of the four curves, the goodness of fit of the exponential function is the highest and the sum of squares of the residuals is the smallest, δ varies approximately as an exponential function of R_a. That is, the increase of the surface roughness of the sliding friction pair makes the current collection stability coefficient

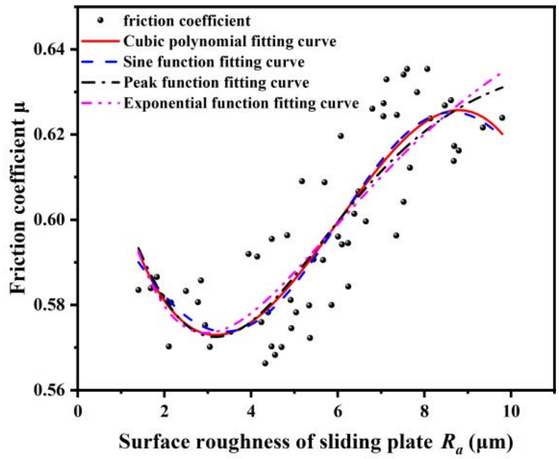

FIGURE 9. Relationship between Ra and friction coefficient.

larger and the pantograph-catenary current collection stability worse.

The main reasons why the surface roughness of the sliding plate affects the current carrying stability of the pantograph-catenary are: on the one hand, with the increase of R_a, that is, the average height of the micro convex peak on the surface of the sliding plate gradually increases, and the micro convex body participating in current conduction is more likely to be sheared and broken under the action of the plate temperature rise, and the contact point is damaged [5], so that a new micro convex body will replace the previous conductive spots. The larger R_a, the more intense this change, the dynamic change of the number of conductive spots makes the fluctuation of contact current larger and the stability of current collection worse; On the other hand, under the set experimental conditions, the increase of the surface roughness R_a of the sliding plate makes the conductive spots flow more charges at the micro crest, and the arc energy generated by the friction pair at the offline moment is larger, which makes the pantograph-catenary current collection stability worse. Under different roughness conditions, the arc image between friction pairs taken by Phantom VEO-710 high-speed camera is shown in FIGURE 8. It can be seen from the figure that the arc brightness and arc area between friction pairs tend to increase with the increase of roughness.

D. EFFECT OF R_a ON FRICTION COEFFICIENT

It can be seen in FIGURE 9 that the friction coefficient μ gradually increases with the increase of roughness R_a, but in the early stage when $R_a < 3\mu$m, the friction coefficient decreases slightly. When $R_a = 3\mu$m, the friction coefficient reaches the minimum value of about $\mu = 0.57$. According to the fitting results of four nonlinear curves, the fitting degree of sin function is higher and the fitting difference is smaller. Therefore, it can be considered that the variation relationship between friction coefficient μ and roughness R_a is approximately a sin function.

With the increase of R_a, the rougher the surface is, the smaller the curvature radius of the micro convex body is, and

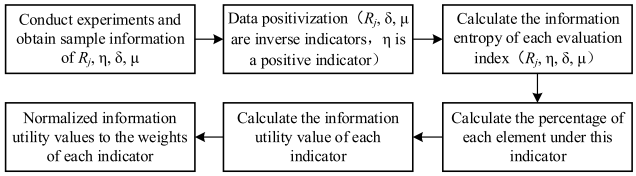

FIGURE 10. Calculation process of entropy weight method.

the worse the contact state of the friction pair is. The friction factor is composed of three parts: the deformation component μ_d of the surface asperities, the plowing component μ_p by wear particles and hard asperities, and the adhesion component μ_a of the flat portions of the sliding surface [23]. When R_a is small, the deformation component μ_d of the micro convex body is also small. According to the experimental results, with the increase of roughness R_a, due to the reduction of shear resistance of micro convex body, the abrasive wear and adhesion wear on the sliding plate surface are serious, and the plowing component μ_p increases, which makes the friction coefficient gradually increase with the increase of roughness R_a on the sliding plate surface.

IV. ESTABLISHMENT OF COMPREHENSIVE EVALUATION EQUATION AND OPTIMAL RA VALUE

After obtaining 59 sets of experimental data, this paper utilizes the entropy weight method to obtain the weight coefficients of the relative changes of each current collection evaluation index under different roughness conditions, and then η, δ, μ and R_a, so as to establish a comprehensive evaluation equation of pantograph-catenary current collection.

A. DETERMINATION OF WEIGHT COEFFICIENT BASED ON ENTROPY WEIGHT METHOD

Entropy weight method is an objective weighting method based on the dispersion degree of data itself. It calculates the corresponding information entropy according to the variation degree of each characteristic index, and then obtains the entropy weight of R_j, η, δ, μ, which is used to make corrections to get more objective index weights. That is, the more scattered the data, the smaller the entropy, the more information contained in the index, and the greater the weight. The specific calculation process of entropy weight method is shown in FIGURE 10.

In order to eliminate the unit differences among the indicators, the data need to be processed forward. Because R_j, δ and μ are reverse indicators, reverse processing is required. Here η is a positive indicator and needs to be processed in a positive way. The calculation formula of positive standardization of data is shown in formula (6).

$$\begin{cases} \text{Positive index} : Zij = \dfrac{xij - Min(xij)}{Max(xij) - Min(xij)} \\ \text{Nagetive index} : Zij = \dfrac{Max(xij) - xij}{Max(xij) - Min(xij)} \end{cases} \tag{6}$$

TABLE 3. Parameter values for curve fitting results.

Parameter	Fitting value	Parameter	Fitting value	Parameter	Fitting value
a_1	0.14926	b_2	0.687	c_3	0.7728
b_1	2.26118	c_2	-0.12906	d_3	5.24297
c_1	1.75587	d_2	0.00657	a_4	-0.22476
d_1	5.99641	a_3	0.51938	b_4	1.3942
a_2	-0.32043	b_3	0.37266	c_4	-0.15837

where Zij is the data after the normalization of the i-th sample in the j-th index. There are four evaluation indexes in this experiment, so $j = 4$ is taken. The calculation formula of information entropy e_j of each index is shown (7).

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln(p_{ij}) \tag{7}$$

where p_{ij} is the proportion of the i-th sample under the j-th index. The weight of each index can be calculated by formula (8).

$$W_j = d_j/\sum_{j=1}^{4} d_j = (1-e_j)/\sum_{j=1}^{4}(1-e_j) \tag{8}$$

where d_j is the information utility value of each index.

Through the computer-aided software to calculate the information utility value of each index, the weights of the four evaluation indexes respectively are: $W_{R_j} = 0.28903$, $W_\eta = 0.16817$, $W_\delta = 0.28083$, $W_\mu = 0.26197$. According to the obtained weight coefficient, it can be seen that $W_{R_j} > W_\delta > W_\mu > W_\eta$, and with the change of roughness value R_a, the variation degree of each evaluation index is $\eta > \mu > \delta > R_j$, which provides a theoretical basis for the comprehensive evaluation of the current collection condition of pantograph-catenary systems.

B. MATHEMATICAL MODEL OF EACH CHARACTERISTIC INDEX AND R_a

Standardize the experimental data according to formula (6), and comprehensively consider the goodness of fit and the sum of squares of residuals of the four fitting curves. In this paper, peak function, cubic polynomial, sin function and exponential function are selected to fit the standardized experimental data respectively, so the functional relationship between each evaluation index and roughness parameter R_a can be expressed as (9).

$$\begin{cases} f_{R_j} = a_1 + (2*b_1/\pi)*(c_1/(4*(R_a-d_1)^2+c_1^2)) \\ f_\eta = a_2 + b_2*R_a^1 + c_2*R_a^2 + d_2*R_a^3 \\ f_\delta = a_4 + b_4*\exp(c_4*R_a) \\ f_\mu = a_3 + b_3*\sin(\pi*(R_a-c_3)/d_3) \end{cases} \tag{9}$$

where the fitting results of each parameter in the formula are shown in TABLE 3.

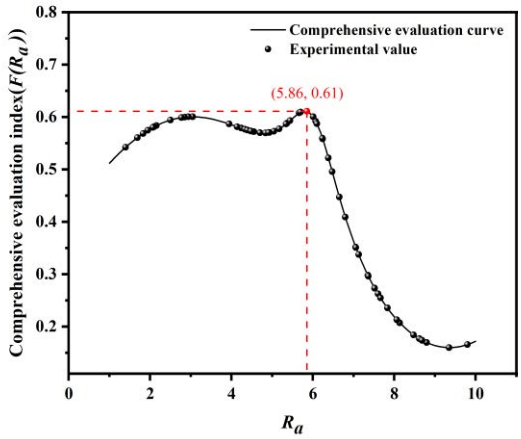

FIGURE 11. Comprehensive evaluation values under different roughness conditions.

C. ESTABLISH A COMPREHENSIVE EVALUATION EQUATION AND OBTAIN THE OPTIMAL R_a VALUE

After obtaining the corresponding weight coefficients of each evaluation index, the comprehensive evaluation equation of pantograph-catenary current collection characteristics is established by comprehensively considering the influence of roughness on Pantograph-catenary contact resistance, current carrying efficiency, current collection stability and friction coefficient, as shown in formula (10).

$$F(R_a) = W_{R_j}f_{R_j} + W_\eta f_\eta + W_\mu f_\mu + W_\delta f_\delta \tag{10}$$

where $F(R_a)$ is the comprehensive evaluation index. Since all evaluation indexes are standardized as positive, the larger the value of $F(R_a)$, it means that under this roughness condition, the contact resistance and friction coefficient are smaller, and the current carrying efficiency and current collection stability are better, that is, the overall current collection condition of pantograph-catenary system is better. Therefore, within the experimental range, the R_a value that maximizes $F(R_a)$ is the optimal roughness value.

The weight coefficient and functional relationship of each evaluation index are substituted into formula (10), and the comprehensive evaluation curve drawn under different roughness conditions and the corresponding comprehensive evaluation values calculated through experiments are shown in FIGURE 11.

According to the calculation method of derivative in mathematics (the calculation formula is shown in formula (11)), the roughness parameter $R_a = 5.86\ \mu$m, $F(R_a)$ reaches the maximum value, that is, the pantograph-catenary current collection condition is the best at this time.

$$\begin{cases} F'(R_a) = W_{R_j}f'_{R_j} + W_\eta f'_\eta + W_\mu f'_\mu + W_\delta f'_\delta \\ F'(R_a) = 0 \end{cases} \tag{11}$$

V. CONCLUSION

(1) The change of surface roughness of friction pairs in sliding electrical contact will affect the current collection

characteristics of pantograph-catenary systems. The experimental results have shown that, with the increase of roughness R_a, the pantograph-catenary contact resistance first decreases and then increases, showing an approximate ''V'' shape change trend. When R_a is 6 μm, the contact resistance reaches the minimum.

(2) With the change of the surface roughness R_a of the friction pairs, the current carrying efficiency of the pantograph-catenary system first increases and then decreases, while the current collection stability gradually becomes worse. With the increase of R_a, the friction coefficient between the pantograph sliding plate and the catenary gradually increases, which is approximate to the variation in exponential form.

(3) The surface roughness R_a of pantograph sliding plates is not the smaller the better. According to the established comprehensive evaluation equation, when the experimental conditions are $V = 30$km/h, $I = 50$A, $F_N = 50$N, $R_a = 5.86\mu$m, the comprehensive evaluation index $F(R_a)$ achieves the maximum value, and the pantograph-catenary current collection performs the best at this time.

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FENGYI GUO (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Fuxin Mining Institute, Xi'an Jiaotong University, in 1987, 1990, and 1997, respectively.

He was a Visiting Professor at the University of Pretoria, South Africa, from 2002 to 2003, and the University of Oxford, from 2008 to 2009, respectively. He is currently a Professor with the College of Electrical and Electronic Engineering, Wenzhou University, Wenzhou, China. His interests include electrical contact, arc, and intelligence appliance.

XIAOKANG WANG was born in Shanxi, China, in 1996. He received the B.S. degree from the College of Electrical Engineering and Automation, Shanxi Datong University, Datong, China, in 2020. He is currently pursuing the M.S. degree with the College of Electrical and Electronic Engineering, Wenzhou University, Wenzhou, China.

His current research interests include electrical contact theory and arc.

JIABAO KOU (Member, IEEE) was born in Heilongjiang, China, in 1990. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2013, 2015, and 2021, respectively.

Since 2021, he has been a Lecturer with the Department of Electrical and Electronic Engineering, Wenzhou University. His research interests include synchronous motor drives, sensorless control, electrical contact theory, and LCI optimization control.

FUHUA LI (Member, IEEE) received the B.Eng. and M.Eng. degrees in electrical engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2006 and 2009, respectively, and the Ph.D. degree in electrical and electronic engineering from the University of Hong Kong, Hong Kong, in 2014.

Since 2021, he has been a Lecturer with the College of Electrical and Electronic Engineering, Wenzhou University, China. His research interests include electrical machine design and control, arc-fault detection, sliding electrical contact, electromagnetic transient analysis, power transformer modeling, and grid frequency measurement.

CONGXIN HAN received the B.S. and M.S. degrees in electrical engineering from Liaoning Technical University, in 2017 and 2021, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering.

His research interests include electrical contact theory and electric arc.