Simulation Analysis of Friction Braking Performance of Electric Hydraulic Block Brake

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Abstract. This article is based on the definition of static friction force in Coulomb friction theory, through the finite element simulation of the friction process of the friction pair model between the electrohydraulic block brake lining and the brake disc, the friction stress of the friction pair under critical radial slip under different radial pressures is obtained. Saint-Venant’s principle and the definition of frictional stress are combined to calculate the corresponding maximum static friction and braking torque. Finally, the braking performance of the brake is affected by the coefficient of static friction, and the law that the coefficient of static friction is affected by environmental factors is further discussed. In this paper, the simulation evaluation of the braking performance of the electric hydraulic block brake through simulation experiments has a certain reference for the evaluation of the friction braking performance of the electric hydraulic block brake.

Keywords: Block brake; Friction mechanism; Coulomb friction theory; Static friction coefficient; Finite element simulation.

1. Preface
For electro-hydraulic block brakes for cranes, the main performance index for measuring their braking performance is the magnitude of their braking torque. The magnitude of the braking torque of the block brake is equal to the product of the friction force generated by the friction pair and the radius of the brake disc. When the radius of the brake disc is constant, the braking torque mainly changes with the magnitude of the friction force. Therefore, when the radial pressure applied to the brake lining will not change, the static friction coefficient of the friction pair formed by the brake lining and the brake disc is the key factor that determines the braking performance of the brake. In the actual selection of brakes, the static friction coefficients are all empirical values, and the difference between the empirical value of the static friction coefficient and the actual value of the static friction coefficient of the brake friction pair is not obvious. Due to the large lifting capacity of large lifting equipment and the fact that the braking equipment is mostly in an aerial working environment, it is difficult to directly observe or test the friction process of the braking equipment on site. If the brake friction brake testing machine is established in the laboratory, it is not only expensive and only applicable to individual models of brakes, so this paper chooses the software simulation method to simulate the friction process of the block brake for cranes [1]. Through simulation experiments, the static friction and dynamic friction stages of the brake friction process can be effectively distinguished. Through the numerical simulation, the static friction coefficient corresponding to the static friction process of the brake lining is obtained [2]. The influence of friction pair environmental temperature, torque of brake disc and contact area of friction pair on friction process was studied [3-5]. The simulated value of the static friction coefficient is used as
a reference basis for measuring the real-time braking performance of the brake. Therefore, when the radial pressure applied to the brake lining is a fixed value, the static friction coefficient of the friction pair formed by the brake lining and the brake disc is the key factor that determines the braking performance of the brake.

This article is based on the definition of static friction force in the Coulomb friction theory. The model of friction between the brake lining of the crane block brake and the brake disc is combined. First, the motion simulation software ADAMS is used to simulate the friction process of the model, and the time at which the maximum static friction force is generated by the brake lining and the brake disc is measured through simulation. Then, the friction model is brought into the finite element analysis software ANSYS Workbench. Through the finite element analysis, the friction stress value of the friction model at this time point is obtained, and the corresponding static friction coefficient and the corresponding braking torque value of brake are calculated. Finally, the finite element simulation operation is repeated to summarize the external factors that affect the braking performance of the brake. Braking torque value of brake.

2. The Principle of Saint Venan
The Saint Venant’s Principle was proposed by the French Scientist Saint Venan. Its content is: when a part of the area or volume of the elastic body is subjected to a load, the stress in the object caused by the load will only be distributed near the load acting area. The area farther away from the load acting area, the stress is basically only related to the resultant force and moment of the load.

For the friction pair model to be studied in this paper, since the contact surface is an arc-shaped surface, the contact surface will undergo a slight elastic deformation during the friction process, resulting in uneven distribution of friction stress. In order to calculate the friction force reasonably, it is necessary to use the Saint-Venant principle to analyze the friction pair model locally, and convert the contact area of the friction pair into the actual friction force effective area with different values but equivalent effects.

3. Determination of the Time Period during which Slippage Occurs

3.1. Steps of Simulation Operation
According to the Dahl effect [6], when two objects are in contact with each other and friction occurs, and the external force on the object is less than the maximum static friction force, this means that the object is in a static friction state, and the rough peak of the object contact surface will produce a small displacement. If the external force is cancelled at this time, the object will tend to return to its original position and the small displacement under static friction is called pre-sliding displacement.

Because it is difficult to directly observe the pre-sliding displacement through experiments, the ADAMS motion simulation software is used to indirectly observe the pre-sliding displacement generated during the friction between the brake lining and the brake disc. ADAMS software is used to monitor the period of static friction of the object, and according to this, the time point when the object generates the maximum static friction force is obtained.

The steps of monitoring the pre-sliding displacement process through the simulation software ADAMS include: the establishment of the brake model; the simplification of the model; the definition of the material parameters; the setting of the motion pair; the definition of the load and the setting of the simulation time, and viewing the simulation results [7].

3.2. Determination of the Maximum Static Friction Time
(1) First of all, a three-dimensional model of the brake is created. The brakes selected in this article are YWZB series brakes. Three-dimensional modeling software is used to model the actual brakes. The schematic diagram of the resulting brake model is shown in Figure 1.
Figure 1. Schematic diagram of the brake model.

(2) After the model is established, the model file is opened in the motion simulation software ADAMS. Due to the excessive number of model parts, in order to reduce the amount of calculation in the simulation process, it also avoids the influence of other unrelated factors. After the model is imported into the ADAMS software, the model is simplified. Only the key parts of the friction part are retained, and a brake disc with a radius of 200mm and a thickness of 240mm is added to the center of the left and right linings of the brake.

(3) The material properties of model components are defined. The connecting pin, brake shoe and brake disc are made of steel, the density is 7.801E-006kg/mm³, the Young's modulus is 2.07E+005 N/mm², and the Poisson's ratio is 0.29. The brake lining materials are mostly mixed materials, and the density can be defined as 4.0E-006 kg/mm³, the Young's modulus is 1.1E+004 N/mm², and the Poisson's ratio is 0.33.

(4) The model was added with a sports pair. The connecting pin and the brake shoe are the contact pair, the brake shoe and the brake lining are the fixed pair, and the brake lining and the brake disc are the friction pair.

(5) The load is defined. The 2kN radial pressure F in the opposite direction is added to the left and right brake linings. At the same time, in order to cause friction in the friction pair model, it is necessary to add torque to the brake disc to cause the brake disc to rotate or critically slip under the radial pressure of the brake lining. Since the specific value of the torque that causes the critical slip of the brake disc cannot be determined, the value of the brake disc torque is indirectly measured in the software. The time at which the critical slip of the brake disc occurs is measured first, and then the brake disc torque at this moment is measured based on this time. The value of the brake disc torque is added to the STEP function in the functional relationship, and the functional relationship between the torque and the simulation time is set to STEP (time, 0, 0, 30, 600), which means that at the 0th second, the brake disc torque is 0 N · m. At the 30th second, the brake disc torque is 600 N · m [8]. The purpose of setting the brake disc torque and time function is to determine the specific value of the brake disc torque at this moment according to the functional relationship when the next step is to determine when the brake disc is critically slipping. This value is used as the brake disc torque that causes the brake disc to slip critically.

The friction model is connected to other parts of the brake through the connecting pin and does not contact the ground, so the gravity of the model is not counted. The simplification of the model in step (2) is combined to obtain a schematic diagram of the stress of the model parts. Figure 2 shows a schematic diagram of the force on the model.
(6) A marked point is selected on the brake disc, which forms a certain initial angle value with the brake disc centroid and the origin of the coordinate system. An angle measurement was created in ADAMS, and the initial angle value was measured to be 56.1882°, and the simulation time was preliminarily set to 30s to perform braking process motion simulation.

(7) The simulation results are viewed. The angular displacement time diagram of the friction between the brake disc and the brake lining is viewed in the post-processing of the solution results. The friction angular displacement time diagram is shown in Figure 3.

The obvious angular displacement of the brake disc at the 10th second can be seen in Figure 6. So the angular displacement that occurred before 10 seconds can be regarded as the pre-slip angular displacement of the friction model. According to the pre-sliding displacement theory, the friction phase of an object before 10 seconds can be regarded as a static friction phase. The static friction force generated at the 10th second is the maximum static friction force reached by the friction model during the occurrence of friction. At the same time, according to the brake disc torque function diagram of FIG. 4, it can be measured that the brake disc torque is 151.2 N·m at the 10th second.

3.3. The Time Point of Maximum Static Friction is Estimated

The above operation steps are repeated, and the radial pressure is increased in turn, and the brake disc torque is increased accordingly (As the radial pressure increases, the brake disc torque that causes the critical slip of the brake disc will also increase accordingly. In order to measure the brake disc torque that causes the brake disc to slip critically, it is necessary to change the brake disc torque and time function relationship in turn to measure.) The time point when the friction pair reaches the maximum static friction force is shown in Table 1. In the table, F is radial pressure; M is the brake disc torque at this...
moment; \( t \) is the time point when the contact surface of the brake lining and the brake disc reaches the critical slip of the friction pair.

Table 1. Time points of radial pressure and maximum static friction.

| F/kN | 2   | 4   | 6   | 8   | 10  |
|------|-----|-----|-----|-----|-----|
| M/N·m| 151.2 | 290.21 | 437.16 | 583.8 | 729.86 |
| T/s  | 10.0 | 9.7  | 9.8  | 10.5 | 9.8 |

As can be seen from the above simulation results, for the same brake friction pair, although different radial pressures are applied to the brake lining, as long as the brake disc torque is increased accordingly. The brake disc will reach the critical rotation state from the static state under the torque. That means the time for generating the maximum static friction force is about 10s. In subsequent simulations, it is only necessary to check the braking condition of the friction pair when it is around 10s.

4. Simulation estimation of braking torque of block brake

4.1. Finite Element Simulation

After the time point when the friction pair reaches the maximum static friction force is determined, the next step is to calculate the static friction force reached by the friction pair at that time point. The static friction force at this time is the maximum static friction force of the friction pair during the friction process [9].

3D model is imported into ANSYS Workbench. Transient Structural module is opened in ANSYS Workbench. First, the brake lining material is defined. The new material is defined in Engineer data, the new material density is set to 4.0E-006 kg / mm³, the Young's modulus is 1.1E + 004 N / mm², and the Poisson's ratio 0.33.

The model produced by the three-dimensional drawing is imported into Geometry, the brake disc material is set to structural steel in the Model, and the brake lining material is new material; Set up is opened after the above settings are saved, and the model is meshed; After the analysis step total time is set to 10s in Analysis Settings (time to reach maximum static friction), 2KN of radial pressure is added to the left and right brake linings respectively, and at the same time, the brake disc is added with torque of 151.2N · m (the torque measured in the previous section to rotate the brake disc).

After the above settings are completed, solve is clicked in solution and the model is solved. After the solution is completed, the solution result of the Frictional Stress in the contact tool unit of the solution is viewed. The frictional stress diagram of the friction pair during simulation when the critical slip occurs can be viewed, as shown in Figure 4.

Figure 4. Friction stress diagram.
4.2. Calculation of Static Friction Coefficient

After the simulation results are obtained, it is necessary to convert the calculated friction stress calculation into the static friction coefficient of the friction pair. According to the definition of friction stress: Friction stress is the friction force per unit area on the friction surface. It can be seen from Fig. 9 that the frictional stress on the friction surface is not uniform, and the frictional stress on some of the contact surfaces is small. The contact area of the friction pair can be converted into the actual acting area of the friction force by using the Saint-Venant principle. The contact area $S_c$ of the friction pair measured in the 3D software is 79200mm², and the actual acting area $S_a$ of the friction force can be equivalent to $\frac{2}{5}S_c$, and its value is 15840mm². After the actual acting area of friction force is obtained, the average friction force is calculated according to formula (1). In the formula, $f_a$ is the calculated average friction force, which can be regarded as the maximum static friction force of the friction pair obtained through simulation, $S_a$ is the actual acting area of friction force; $\sigma$ is the friction stress obtained by simulation.

$$f_a = S_a \cdot \sigma.$$  \hspace{1cm} (1)

The maximum static friction force calculated by equation (1) is 712.6N. According to the definition of static friction coefficient, the static friction coefficient of this friction model is the ratio of maximum static friction force to radial pressure. Therefore, the static friction coefficient $\mu$ of the friction model can be calculated by formula (2). In the formula, $\mu$ is the static friction coefficient; $f_a$ is the maximum static friction force calculated by formula (1); $F$ is the radial pressure applied to the brake lining, and the value is 2KN. The calculation result is $\mu = 0.3563$.

$$\mu = \frac{f_a}{F}.$$  \hspace{1cm} (2)

According to the above model, different radial forces $F$ are sequentially applied to the two brake linings, and the corresponding brake disc torque $M$ is obtained. Repeat the above operation steps to obtain the corresponding friction stress $\sigma$ when the friction pair occurs during the critical slip during braking, simulate the results and calculate the coefficient of static friction as shown in Table 2. In the table, $F$ is the radial pressure applied to the brake lining; $M$ is the torque that causes the brake disc to rotate; $\sigma$ is the friction pair friction measured by the simulation Stress; $f_a$ is the calculated maximum static friction; $\mu$ is the calculated static friction coefficient.

| F/kN | 2    | 4    | 6    | 8    | 10   |
|------|------|------|------|------|------|
| M/N·m| 151.2| 290.21| 437.16| 583.8| 729.86|
| $\sigma$/MPa| 0.0452| 0.089| 0.134| 0.179| 0.226|
| $f_a$/N | 712.6| 1431| 2160| 2888| 3619|
| $\mu$ | 0.356| 0.358| 0.360| 0.361| 0.362|

The static friction coefficient values of the numerical simulation in the above table are added and the average value is taken, and the average value thereof is 0.359 as the estimated value of the static friction coefficient of the friction pair of this brake.

4.3. Calculation of Braking Torque

According to the calculation method of torque: torque is the product of force and brake arm. In the brake friction pair model, the braking torque of the brake is the product of the friction force of the friction pair formed by the brake lining and the brake disc and the radius of the brake disc. The calculation formula is:

$$M_a = f_a \cdot R.$$  \hspace{1cm} (3)
Among them, $M_a$ is the maximum braking torque of the brake, which is the braking torque at the maximum friction; $f_a$ is the maximum static friction of the brake friction pair; $R$ is the radius of the brake disc, and the value is 200mm.

According to formula (3), the maximum static friction force can be brought into the formula, and the braking torque of the brake under different radial pressures can be calculated separately.

**Table 3. Calculation table of braking torque.**

| F/kN | 2   | 4   | 6   | 8   | 10  |
|------|-----|-----|-----|-----|-----|
| $f_a$/N | 712.6 | 1431 | 2160 | 2888 | 3619 |
| $M_a$/N·m | 143.2 | 286.2 | 432.0 | 577.6 | 723.8 |

The comparison between the measured brake disc torque in Table 2 and the calculated brake torque in Table 3 shows that when the brake disc is critically slipped, the brake disc torque is slightly greater than the brake torque. The reason why the brake disc rotates at a critical value is that the braking torque is overcome by the brake disc torque. At this time, the brake disc torque should be greater than the braking resistance of the brake. This also proves the correctness of the above calculation from the side.

### 5. Simulation analysis of factors affecting braking performance

#### 5.1. Influencing Factors of Braking Torque

The previous formula (2) and formula (3) are combined and found that when the radial pressure on the brake lining and the radius of the brake disc are unchanged, the only factor that affects the braking torque of the brake is the static friction coefficient of the friction pair.

In actual conditions, factors such as the radial pressure on the brake lining, the ambient temperature of the friction pair, and the contact area of the friction pair may affect the friction coefficient of the friction pair. (The contact area of the friction pair is the actual contact area of the brake lining and the brake disc, which is related to the arc length and width of the brake lining.) In order to evaluate the braking performance of the brake more accurately, it is necessary to list the above-mentioned influencing factors, the above simulation operation is repeated in the simulation environment. When the other factors of the friction model are guaranteed to be the same, an influencing factor is changed, the friction coefficient of the friction pair is calculated and compared with the results obtained in other situations, and the influence of this factor on the friction coefficient is judged.

#### 5.2. Influencing Factors of Static Friction Coefficient

As shown in Table 4, the radial pressure on the brake lining is 2KN, 6KN and 10KN, and the actual area of friction is 15840mm². Through the simulation of the braking process, the brake disc torque $M$ corresponding to the critical slip of the brake friction pair is measured, and the friction coefficient and corresponding braking torque of the friction pair at different temperatures are calculated and obtained.
Table 4. Variation of static friction coefficient at different temperatures.

| Serial number | Radial pressure F/kN | Environment temperature T/°C | Brake disc torque M/Nm | Friction stress σ/MPa | Static friction force f/N | Coefficient of static friction μ | Braking torque M₀/N·m |
|---------------|---------------------|-------------------------------|------------------------|-----------------------|--------------------------|-----------------------------|------------------|
| 1             | 2                   | 22                            | 151.2                  | 0.0450                | 712.6                    | 0.3563                      | 142.52           |
| 2             | 24                  | 148.09                        | 711.6                  | 0.3558                | 142.32                   |                            |                  |
| 3             | 26                  | 147.4                         | 709.0                  | 0.3545                | 141.8                    |                            |                  |
| 4             | 28                  | 146.53                        | 704.6                  | 0.3523                | 140.92                   |                            |                  |
| 5             | 6                   | 22                            | 437.16                 | 0.1364                | 2160.0                   | 0.3600                      | 432              |
| 6             | 24                  | 436.86                        | 2159.4                 | 0.3599                | 431.88                   |                            |                  |
| 7             | 26                  | 433.54                        | 2145.6                 | 0.3576                | 429.12                   |                            |                  |
| 8             | 28                  | 429.45                        | 2127.0                 | 0.3545                | 425.4                    |                            |                  |
| 9             | 10                  | 22                            | 729.86                 | 0.2285                | 3619.0                   | 0.3619                      | 723.8            |
| 10            | 24                  | 726.07                        | 3610.0                 | 0.3610                | 722                       |                            |                  |
| 11            | 26                  | 723.34                        | 3588.0                 | 0.3588                | 717.6                     |                            |                  |
| 12            | 28                  | 720.02                        | 3587.0                 | 0.3587                | 717.4                     |                            |                  |

The data obtained from Table 4 is based on the static friction coefficient as the ordinate, the ambient temperature of the friction pair as the abscissa, and the radial pressures as 2kN, 6kN and 10kN. It can be obtained that the static friction coefficient changes with temperature under different radial pressures, as shown in Figure 5.

**Figure 5.** Variation of static friction coefficient with temperature under different pressures.

It can be clearly seen from the above figure that for the brake friction model studied in this paper, the static friction coefficient has a tendency to decrease as the temperature of the friction pair increases. Similarly, from Table 4, it can be seen that under different radial pressures, the law of static friction coefficient with temperature changes when the brake disc reaches the maximum static friction force is the same. Therefore, the real-time temperature of the brake friction surface needs to be measured online. The concept of correction coefficient ζ is introduced [10]. This coefficient substitutes the real-time temperature of the brake friction pair and the radial pressure applied to the brake lining into equation (4). The static friction coefficient calculated by the simulation can be modified to make the static friction coefficient calculated by the simulation more suitable for the theoretical friction coefficient calculated by the Coulomb friction theory.

\[
\mu = \zeta \cdot \frac{S}{\sigma} \cdot \frac{1}{F}.
\]
In the formula: $\zeta$ is the correction coefficient; $S$ is the actual acting area of friction force; $\sigma$ is the friction stress obtained by simulation; $F$ is the radial force on the brake lining.

In order to reasonably express the correction coefficient $\zeta$, a binary linear regression equation of the correction coefficient with respect to radial pressure and temperature can be constructed, Equation (5) is a relational expression.

$$\zeta = \beta_0 + \beta_1 F + \beta_2 T + e.$$  \hspace{1cm} (5)

In the formula, $\zeta$ is the correction coefficient, $\beta_0$, $\beta_1$, and $\beta_2$ are the regression coefficients, $e$ is the random error term, $F$ is the radial pressure, and the unit is kN; $T$ is the ambient temperature and the unit is $^\circ$C. The data in Table 3 is fitted in the linear regression equation in MATLAB to obtain the expression of the binary linear regression equation for the correction coefficient, it can be seen in formula (6).

$$\zeta = 0.3710 + 0.008F - 0.0007T + 0.$$  \hspace{1cm} (6)

### 5.3. Braking Torque Expression

After the above expressions are combined, the mathematical expressions of the brake braking torque with respect to the radial pressure, the ambient temperature, the actual acting area of the friction force, the friction stress, and the radius of the brake disc can be obtained.

$$M_a = \zeta \cdot S \cdot \sigma \cdot R$$  \hspace{1cm} (7)

Through formula (7), the braking torque of the brake, or the braking performance of the brake can be reasonably evaluated.

### 6. Conclusion

(1) Through multiple simulations, in the motion simulation software ADAMS, the measured friction pair has a more obvious displacement in the 10s, which shows that the static friction force reached by the friction pair in the 10s is the maximum static friction force.

(2) The friction model is finite element simulated in ANSYS Workbench, and the friction stress generated by the model in the 10s is measured. According to Saint-Venant's principle, the actual acting area of the friction force is equivalent to 2/5 of the contact area of the friction pair, and the value of the average friction force is calculated using the definition of the friction stress.

(3) This article sets different temperatures and radial pressures in the simulation environment, repeats the simulation operation on the model, respectively measures the static friction coefficient of the friction pair under different conditions, and compares the experimental value with the theoretical value calculated by the Coulomb friction theory. The concept of correction coefficient is proposed to modify the experimental value of static friction coefficient. Finally, the law that the braking torque changes with factors such as radial pressure, ambient temperature, actual area of friction, friction stress, and brake disc radius is summarized from the simulation results.

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