The Effect of Bionic Brake Drum Point Unit Body on Friction and Wear of Brake Pad

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Abstract. In this paper, the elasticity theoretical analysis has been used to analyze the interaction between the point unit body on the bionic brake drum and the brake pad. Through the analysis, the contact stress distribution law of their interaction has been obtained, and the change in friction and wear of brake pad based on the point unit body is calculated according to the stress distribution law. Only considering the change of the surface feature regardless of other factors, the friction and wear of the point unit body on the brake pad has increased by more than 50%. Based on the research, it is indicated that the small convex point unit bodies are added on the surface of the bionic brake drum, which make the contact surface between the brake drum and the brake pad no longer the original plane contact, and the pressure and direction between the contact surfaces are different. In addition, even if the external pressure remains unchanged, the contact pressure between two surfaces will be increased, thereby increasing the friction and wear of the brake pad.

1. Introduction
The braking of the truck is achieved by the frictional resistance between the brake drum and the brake pad. The surface of the brake drum can be considered as an inner cylindrical surface, and the surface of the brake pad is a part of the outer cylindrical surface. During the braking process, the brake drum fixed on the truck wheel is pressed by the brake pad fixed on the truck body which generates the friction force. Both of them rub each other to generate frictional resistance and form a frictional resistance moment, which prevents the auto from moving and achieves the purpose of braking. The bionic brake drum processed by laser technology has the high stiff convex unit on the friction surface. The unit formed by the laser, plays the important role which can significantly reduce the wear of the brake drum and increase its service life [1, 2]. However, based on the study [3], this bionic feature can increase the wear of the brake pad which reduces the service life of brake pad and increase the brake pad replacement frequency. Therefore, it is necessary to study the friction and wear of the unit body and the brake pad comprehensively. While reducing the wear of the brake drum, the wear condition of the brake pad should also be taken into account to ensure the service life of the brake pad, thereby reducing the cost of vehicle maintenance.
2. The contact stress between the point unit body and the brake pad

Considering the large radius of the cylindrical surface where the brake drum and the brake pad rub against to each other, the friction surface is similar to planar friction. For the convenience of analysis, the friction is considered as the planar friction. With the external force to the brake pad, the brake pad is pressed on brake drum which forms the elastic deformation and non-plane contact. The friction between the brake drum and the brake pad is no longer pure plane friction, and its friction mechanism is completely different from the traditional plane friction. There are many kind of bionic unit form. In this article, the point body shape unit is studied. Consider the small size of the unit, to facilitate the analysis, the point body unit is supposed as the spherical surface as shown in Fig. 1. Since the surface of the brake pad is still flat, the contact between the unit body and the brake pad is the contact between the spherical surface and the semi-infinite body, and the friction between them is the friction between the spherical surface and the flat surface. The contact pressure between their surfaces is no longer a simple uniform distribution of pressure between the planes. This stress distribution is relatively complex, so that the friction and wear of the unit body to the brake pad will also undergo new changes, which should be analyzed in detail.

![Figure 1: Diagram of the interaction between a point unit body and a brake pad](image1)

As shown in Fig. 1, the spherical radius of the unit body is \( \rho \). The pressure of the unit body perpendicular to the surface of the brake pad is \( P \), and \( O \) is the initial contact point between the point unit body and the brake pad. With the pressure \( P \) implemented, the point unit body and the brake pad will be elastically deformed. After the laser processing, the point unit body has a high stiffness and less deformation. For the convenience of analysis, the point unit body deformation is ignored and it is assumed that its surface is still spherical surface after being stressed. Besides, the brake pad will be elastically deformed under the pressure of the unit body to form a dent and the \( O \) point will move downward, as shown in Fig. 2.

![Figure 2: Diagram of the deformation of the brake pad under the action of the point unit body](image2)

The flat surface of the brake pad is deformed under the action of the unit body into a concave spherical surface like the unit body surface. Thus, the radius of concave spherical surface of the brake pad is also \( \rho \). The contact radius of the contact surface between the unit body and the brake pad is \( R_c \). The vertical axle through the center of the unit body downward is the \( Z \) axis. Moreover, the axle
through the lowest point \( O \) of the contact surface between the unit body and the brake pad. Since the deformation of each point on the contact surface of the brake pad and the unit body is different, the contact stress on the contact surface is also different. It is defined that \( F \) is the contact stress between the unit body and the contact surface of the brake pad. Considering symmetry, the contact stress \( F \) at any point \( M \) on the contact surface is only related to the distance \( R_1 \) from the point \( M \) to the \( Z \) axis. \( Q_0 \) is the contact stress at the lowest point \( O \) of the contact surface between the unit body and the brake pad. Considering that the \( O \) point on the brake pad has the biggest downward displacement and deformation during braking, the contact stress \( Q_0 \) of the \( O \) point is also the maximum contact stress on the contact surface. According to elastic mechanics [4], the contact stress of a certain point \( M \) on the spherical contact surface of the unit body and the brake pad is

\[
F = \frac{Q_0}{R_c} \sqrt{R_c^2 - R_1^2}
\]  

(1)

3. Friction and wear of the point unit body to the brake pad

When analyzing the friction and wear of the point unit body on the brake pad, the Preston equation [5] can be referred to calculate the amount of abrasive removal wear. This equation is defined that the material removal rate per unit time of friction pair is proportional to the pressure and instantaneous relative velocity, as shown below:

\[
\Delta Z = \int_0^t k v p_n dt
\]

(2)

where:
- \( \Delta Z \) —— The amount of abrasive removal wear;
- \( t \) —— Action time of the two in friction pair;
- \( k \) —— Proportional coefficient;
- \( v \) —— Relative speed of the friction pair;
- \( p_n \) —— The pressure of the interaction between the friction pair.

Referring to the Fig. 2, take the \( Z \) axis as the center axis, there is an \( M \) point on the contact surface. The distance between \( M \) and \( Z \) axis is the radius which is \( R_1 \). With the \( M \) point, a small micro circle has been considered with the width \( dR_1 \). The value of \( dR_1 \) is extremely small. Since the point on this micro circle radius is \( R_1 \), the pressure value on the contact surface is constant. Then the pressure \( dp_z \) of the two surfaces on the small micro circle along the \( Z \)-axis direction should be the product of the contact pressure stress \( F \) and its area, which is:

\[
dp_z = 2F\pi R_1 dR_1
\]

(3)

Where the pressure \( dp_z \) in the equation is along the \( Z \) axis in the vertical direction; the pressure of the interaction between the friction pair \( p_n \) in equation (3) is along the normal direction of the contact surface. Since the contact surface between the two pairs is spherical and not horizontal, the tangent plane of point \( M \) is at an angle \( \alpha \) to the horizontal plane, as shown in Fig. 2.

Therefore, the direction of \( p_n \) is not same with the direction of \( dp_z \). The equation (3) cannot be simply substituted into equation (2) to calculate the amount of friction and wear caused by the unit body on the brake pad on the micro circle. However, the vertical pressure \( dp_z \) in the equation (3) can be used to figure out the pressure \( p_n \) caused by the normal direction on the contact surface. Then \( p_n \) can be substituted into equation (2) to calculate the friction and wear of the micro circle on the unit body and the brake pad. Therefore, the point \( M \) in Fig. 2 can be partially enlarged which is shown in Fig. 3.
Figure 3. Magnified diagram of force on any contact point $M$

From the Fig. 3, it is shown that

$$p_n \cos \alpha_1 = dp_z$$

And,

$$p_n = dp_z / \cos \alpha_1$$

By substituting equation (3) into equation (4), the result is

$$p_n = 2\pi R_1 dR_1 / \cos \alpha_1$$

By substituting equation (5) into equation (2), the result is

$$\Delta Z_1 = \int_0^t \frac{2k\pi \rho \pi Q_o R_1 dR_1}{\cos \alpha_1} dt$$

where, $\Delta Z_1$ in equation (6) is the amount of friction and wear caused by the micro circle on the unit body and the brake pad. In order to calculate the wear amount $\Delta Z$ at the unit body on the brake pad at the certain time $t$, the integration is performed in equation (6) for $dR_1$. From the Fig. 2, it is shown that the range of $R_1$ is from 0 to $R_c$. Therefore,

$$\Delta Z = \int_0^t \int_0^{R_c} \frac{2k\pi \rho \pi Q_o R_1 dR_1}{\cos \alpha_1} dt$$

According to Fig. 2, it is indicated that

$$\cos \alpha_1 = \frac{\sqrt{\rho^2 - R_1^2}}{\rho}$$

By substituting equation (8) and equation (1) into equation (7), the result is

$$\Delta Z = \int_0^t \int_0^{R_c} \frac{2k\pi \rho \pi Q_o R_1 \sqrt{R_1^2 - R_1^2}}{R_c \sqrt{\rho^2 - R_1^2}} dR_1 dt$$

Since $k$, $v$, $\rho$, $\pi$, $Q_o$, $R_c$ and other parameters do not change with the change of $R_1$, they can be considered as the constant for $R_1$, so suppose: $C = k\pi \rho Q_o / R_c$, $x = R_1^2$, based on the equation (9), it is conducted that,

$$\Delta Z = \int_0^t C \int_0^{R_c} \frac{\sqrt{R_1^2 - x}}{\sqrt{\rho^2 - x}} dx dt$$

Integrate equation (10) on $x$, the result is

$$\Delta Z = \int_0^t C \left[ R_c \rho + \frac{1}{2} (\rho^2 - R_1^2) \ln \frac{1 + R_c/\rho}{1 - R_c/\rho} \right] dt$$

$$\Delta Z = f_0^t C \left[ R_c \rho + \frac{1}{2} (\rho^2 - R_1^2) \ln \frac{1 + R_c/\rho}{1 - R_c/\rho} \right] dt$$
According to elastic mechanics [4], the contact stress between the unit body and the contact center of the brake pad is also the maximum contact stress \( Q_0 \) on the contact surface.

\[
Q_0 = \frac{3P}{2\pi R_c^2} \tag{12}
\]

By substituting equation (12) into equation (11), the result is

\[
\Delta Z = \int_0^t k v P \frac{3\rho}{2R_c} [R_c \rho + \frac{1}{2} (\rho^2 - R_c^2) \ln \frac{1 + R_c / \rho}{1 - R_c / \rho}] dt \tag{13}
\]

Define,

\[
D = \frac{3\rho}{2R_c^2} [R_c \rho + \frac{1}{2} (\rho^2 - R_c^2) \ln \frac{1 + R_c / \rho}{1 - R_c / \rho}] \tag{14}
\]

Then the equation (13) can be conducted to

\[
\Delta Z = \int_0^t k v P D dt \tag{15}
\]

By comparing the equation (15) and equation (2), it is indicated that the two equations are very similar. For the contact friction of two horizontal plane surfaces, the pressure \( P_n \) in the equation (2) is along the vertical direction. But for the pressure between two non-planar surfaces in contact, its value and direction are various with its position on the contact surface. It is a variable, which causes the integral in the equation (15) to have a term \( D \) compared with the integral in the equation (2). Because \( k, v, \) and \( P \) are all greater than 0, thus if \( D > 1 \), the \( \Delta Z \) calculated by the equation (15) is greater than the one calculated by the equation (2). This means the friction and wear of the unit body of the bionic brake drum to the brake pad is greater than that of the non-bionic brake drum. Therefore, whether \( D \) is greater than 1 is the focus for analyzing.

Assume that,

\[
E = \ln \frac{1 + R_c / \rho}{1 - R_c / \rho} \tag{16}
\]

Then the equation (14) can be conducted,

\[
D = \frac{3\rho}{2R_c^2} [R_c \rho + \frac{1}{2} (\rho^2 - R_c^2) E] \tag{17}
\]

During the braking process, the point unit body is pressed into the surface of the brake pad under the action of the pressure \( P \). Because the elastic modulus of the brake drum and brake pad material are very high, the elastic deformation of their contact is small, as well as the depth of the unit body pressed into the brake pad. The contact surface radius \( R_c \) formed by both of them is also small. Therefore:

\[
\frac{R_c}{\rho} < 1 \tag{18}
\]

By power series expanding the Equation (16), then,

\[
E \approx 2\frac{R_c}{\rho} \left[ \frac{R_c}{\rho} + \frac{1}{3} \left( \frac{R_c}{\rho} \right)^3 + \frac{1}{5} \left( \frac{R_c}{\rho} \right)^5 + \cdots + \frac{1}{2n+1} \left( \frac{R_c}{\rho} \right)^{2n+1} + \cdots \right] \tag{19}
\]

Consider the equation (18), from the equation (19),

\[
E \approx 2 \frac{R_c}{\rho} \tag{20}
\]

By substituting equation (20) into equation (17), the result is

\[
D = \frac{3\rho}{2R_c^2} (2R_c \rho - \frac{R_c^3}{\rho})
\]

\[
D = \frac{3}{2} \frac{\rho^2}{R_c^2} - 1 \tag{21}
\]

Based on the equation (18)

\[
\frac{\rho^2}{R_c^2} > 1
\]
\[
\frac{2\rho^2}{R_c^2} > 2 \\
\frac{2\rho^2}{R_c^2} - 1 > 1
\]

Therefore, based on the equation (21)

\[
D > 1.5
\]

(22)

Based on the equation (22), by comparing the equation (15) and equation (2), it is indicated that the friction wear of the brake pad based on point unit bionic brake drum is more than 50% higher than the friction wear based on the traditional non-bionic brake drum.

4. Conclusion

This paper analyzes the interaction between the point unit body on the bionic brake drum and the brake pad, and obtains the contact stress distribution law of their interaction. Besides, the friction and wear of the unit body on the brake pad according to the stress distribution law has been calculated. Regardless of other factors, just considering the changes in the surface shape, the friction wear of the point unit body on the brake pad is increased by more than 50%. Although some assumptions and approximations have been made in the analysis, the results will have certain deviation, the trend of change can be confirmed, which means that the point unit body on the bionic drum will increase the friction and wear of the brake pad. For a traditional ordinary brake drum, its contact surface with the brake pad can be approximately regarded as a plane contact, and the pressure is perpendicular to the contact surfaces. After implementation of the bionic brake drum, from a macro point of view, the pressure between the bionic brake drum and the brake pad shows no change. However, due to the addition of the small convex unit bodies on the surface of the bionic brake drum, the contact surface between the bionic brake drum and the brake pad is no longer the original plane contact. The value and direction of the pressure between the contact surfaces have become variable, and the original pressure also cannot represent the contact pressure between two surfaces anymore. The contact pressure between their surfaces will increase, thereby increasing the friction and wear of the brake pad. This is one of the main reasons why the bionic brake drum increases friction and wear on the brake pad.

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