Analysis of boot rail collision resistance in rocket sled test system

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Abstract. The shoe-rail resistance to impact of rocket sled was analyzed. Shoe-rail friction resistance was backward calculated with speed, acceleration, weight and gap of shoe-rail. The influencing factor was gain by the continuous contact force model. The relation of shoe-rail resistance to impact with speed, weight and gap of shoe-rail was gained by means of data fitting. Based on the results, the collision resistance coefficient of a new type of sled is calculated. According to the resistance coefficient, the speed of sled is predicted. The predicted results are consistent with the dynamic experimental results.

1. Introduction
During the rocket sled test, the rocket engine was used as the power to simulate the full ballistic process such as launch and flight of the test item. The ground simulation of flight state of weapons and equipment is realized.

When using rocket sled dynamic test, the parameters such as the full ballistic velocity, acceleration, the quality of the sled vehicle, and the engine thrust obtained by external measurement, the equivalent drag coefficient of the sled vehicle calculated by reverse calculation is greater than the equivalent air drag coefficient of the sled vehicle design. So it predict that in addition to air resistance and friction, there is another resistance in the sled test. The sled is in contact with the track through the sled boots when it is running on the track. Due to the uneven track, the sled boots generate tangential friction when they slide at high speed on the track, which is the main reason why the actual drag coefficient of the sled is greater than the design air resistance coefficient.

The relationship between the boot rail collision resistance and the running speed, quality and boot rail gap of the sled is fitted through the dynamic test data, and a new type of sled's collision resistance is calculated by using the boot rail collision resistance calculation model. Using the calculated collision resistance, the speed of the sled is predicted, and the speed of the sled is consistent with the dynamic test speed of the sled.

2. Boot rail collision resistance
There is a gap between the sliding boots and the track (as shown in figure 1). Due to the uneven track and the influence of the roughness of the track surface, the sliding boots continue to collide with the track when the sled is moving at high speed on the track. The normal contact force is generated, and the collision force is converted into tangent friction resistance in the direction of the sled.
2.1. Foot rail contact force model

Based on Hertz theory\cite{1}, Lankarani and Nikravesh proposed a continuous contact model\cite{2,3}. The contact force in the direction of the boot rail is expressed as:

\[
F_N = K \delta^n [1 + \frac{3(1-e^2)}{4} \delta \dot{\delta}^{(c)}] \\
K = \frac{4}{3\pi(\sigma_i+\sigma_j)} (\frac{R_iR_j}{R_i-R_j})^{0.5}
\] (1)

In above formula, $F_N$ is boot rail normal contact force. $K$ is contact stiffness coefficient. $m$ is power index, which is determined by the characteristics of the contact material. $\delta$ is the value of contact deformation. $\dot{\delta}$ is the value of deformation speed after the boot rail contact. $\dot{\delta}^{(c)}$ is boot track collision impact speed. $\sigma_k$ is contact object yield strength. $\sigma_k = (1-v_k^2) / \pi E_k$. $v_k$ is Poisson's ratio and $E_k$ is Young's modulus corresponding to the material in contact with the object. $R_k$ is the contact radius of the collision object. $e$ is the recovery coefficient after the boot rail collision. The value of pure elastic contact is 1, and the value of pure plastic contact is 0.

The energy dissipation caused by plastic deformation during contact with boot Rails is not considered. Therefore, the boot rail contact force is simplified to:

\[
F_N = K \delta^n
\] (2)

S P’Timošenko’s theoretical calculation formula for the comprehensive deformation of the two spheres\cite{4}:

\[
\delta = (5V^2m / 4K)^{2/5}
\] (3)

In the formula, $V$ is collision point collision speed. $m$ is the comprehensive mass of the two cylinders corresponding to the radius of curvature of the collision point.

The contact stiffness $K$ of the collision point reflects the shape characteristics of the collision surface of the collision object. Different surface shapes correspond to different collision stiffness, and the derivation process of this formula has no limit on the surface shape of the object. Therefore, this formula can be further applied to collision problems of different collision surfaces.

The vibration value caused by the boot track gap is $A$, and the wavelength caused by the track is $\lambda$. When the sled vehicle moves at speed $u$ on the track, the orbital excitation is assumed to be harmonic\cite{5,6}:
In the formula, $A$ is the maximum gap between boot rails. In the formula, $\lambda$ is orbital wavelength, and $u$ is sled speed.

When the boot rails collide, the vibration speed $V$ of the sled is:

$$V = z(t) = \frac{\pi A u}{\lambda} \cdot \sin\left(\frac{2\pi u t}{\lambda}\right) \quad 0 \leq t \leq n\lambda / u$$

(5)

From equations (2)-(5), it can be seen that the boot rail contact force $F_N$ is a function related to the quality, speed, and boot rail clearance of the sled:

$$F_N = K' u^a m^m A^A$$

(6)

In the formula, $K'$ is the influence coefficient, which is determined by the type, stiffness, strength, contact shape and size of boot rail. $a_1, a_2, a_3$ are constants which are due to sled running speed, quality and boot rail gap.

2.2. Boot rail collision resistance model

Boot rail shear friction model is [7]:

$$F_i = u(V_i) \cdot F_n \cdot V_i / |V_i|$$

(7)

In the formula, $F_i$ is boot rail shear friction. $u(V_i)$ is boot rail sliding friction coefficient, which is no longer a constant, but a function of the tangent sliding speed.

In the 1980s, a famous expert in tribology from Soviet Union, studied a large number of experiments to study different materials at medium and low speeds (speeds of 0. 004-25m/s, pressure 0. 0008-0.17MPa). Friction coefficient was change under conditions. When sliding at medium and low speeds, friction is mainly caused by local adhesion and shear in the contact area. Friction resistance is manifested as surface heat, but this heating effect will not have a great impact on the overall friction mechanism [8,9]. According to the elastic-viscous contact theory and test data of the friction surface, the relationship between speed and friction coefficient is proposed:

$$u(V_i) = (a+b|V_i|) \cdot e^{-c|V|} + d$$

(8)

In the formula: $a, b, c, d$ are coefficients, which are determined by the sliding material and positive pressure.

The variation of friction coefficient between metal friction materials under high speed and high pressure with sliding speed is studied, and the high speed and high pressure of friction coefficient still satisfy the variation rule of formula(8). The friction coefficient decreases with the increase of sliding speed under high contact pressure, and the higher the pressure, the smaller the friction coefficient. The friction coefficient changes tend to flatten at high speed. Therefore, it can be considered that the sliding friction coefficient is constant when the boot rail slides at high speed[10,11]. From this, it can be seen that the boot rail collision resistance mainly depends on the boot rail contact force. The influencing factors are the speed, quality, and boot rail gap of the sled. The key of boot rail collision resistance analysis is to determine the index of $a_1, a_2, a_3$.

3. Data fitting and verification of results
3.1. Data fitting
The purpose of the data fitting is to determine the relationship between boot rail collision resistance and quality, running speed and boot rail clearance of the sled by using the existing boot rail collision resistance [11].

The sled is mainly subjected to rocket thrust $T$ and drag $R$ (including air resistance $R_a$ and boot rail collision resistance $F_t$), sleigh motion equation expressed as:

$$ T - ma = R_a + F_t $$

(9)

For the existing test data fitting, it was found that (as shown in figure 2):

$$ T - ma = nu^2 $$

(10)

In the formula, $n$ is a fixed constant, the value of $n$ is only related to the type of sled. As the same type of sled $n$ is basically the same.

In formula (10), $R_a = C_D A_p u^2 / 2 = n_1 u^2$, $n_1$ is the equivalent aerodynamic drag coefficient of the sleigh car. $n_1$ is only related to the type of sled. As the same type of sled, $n_1$ is basically the same, as shown in figure 2.

So, from formulas (9) and (10) express of $F_t$ was gained:

$$ F_t = (n - n_1)u^2 = n_2 u^2 $$

The value of $n_2$ is only related to the type of sled, and the same type of sled, $n_2$ is basically the same.

From $F_t = [u(V_t)K' m^{a_2} A^{a_2}]u^{a_2} = n_2 u^2$, $a_4 = 2$ is gained. As the same type of sled, boot rail collision resistance is proportional to the square of speed.

When the sled is running, the gap between the boot and the track is the same. At this time, $A^{a_1}$ is a constant. Express of $F_t$ is:

$$ F_t = [u(V_t)K' u^2 A^{a_1}]m^{a_2} = n_3 m^{a_2} $$

(11)

In the formula, the gap between the sliding boot and the track is the same, and $n_3$ is a constant.
For the first, second, and third types of sled vehicles, the data fitting of the two-track sled vehicles was found. The values of $a_2 = 0 - 10$ are introduced into the above formula to fit the data. It is researched that when the value of $a_2$ is 0.6, the value of $n_3$ was basically the same. The value of the two-track sled vehicle was 0.003, and the value of the single-track sled vehicle was 0.0015. See figure 3 for details.

\[ \frac{3.2^{a_2} + 1.6^{a_2}}{1.3^{a_2} + 1.2^{a_2}} = \frac{0.003}{0.0015} \]

From this fitting: $a_2 = 1.2$

From this, the relationship between boot rail collision resistance and the quality, running speed, and boot track gap of the sled is:

\[ F_t = u(V_e) K u^m m^a A^b = k'' u^2 m^{0.6} A^{1.2} \]

$k''$ is a constant.

According to equation (11) and fitting results, the calculation expression of the boot rail resistance of the twin-track sled is:

\[ F_t = 1.26 \times 10^{-3} \times u^2 \times m^{0.6} \times A^{1.2} \]

3.2. Validation of the results

According to the relationship of the collision resistance coefficient of the boot rail, the collision resistance coefficient of the boot rail of the sled was calculated as 0.42. According to the engine thrust, the quality of the sled, the air resistance coefficient, and the boot rail collision resistance coefficient, the maximum speed of the sled is predicted to be 300m/s. The predicted results are consistent with the actual dynamic test results (see figure 4), and the correctness of the calculation method is verified.
4. Conclusion
Due to the objective track roughness and uneven smoothness, the actual boot rail collision resistance generated by the sled is much higher than the static friction force. Through data fitting, the relationship between boot rail collision resistance and the quality, speed and boot rail clearance of skis is obtained. The boot rail collision resistance is proportional to the 0.6 power of the sled mass, the 1.2 power of the boot rail gap, and the square of the speed of the sled. The relationship between the mass, speed and clearance of sled is based on the existing data fitting. Due to the small amount of data, the accuracy of the fitting numerical value needs to be further improved. But this fitting method is correct. The calculation method of boot rail collision resistance was verified by dynamic test, which laid the foundation for the design and ballistic calculation of the subsequent sled.

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