Features of the Application of Friction Braking in High-Speed Track Tests

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Abstract. The increase in the speed characteristics of newly developed aircraft models im-poses new requirements on the test bench equipment of rocket-rail tracks, including braking means. In this paper, the method of friction braking in the conditions of a rocket track is considered. A method for calculating the mode of motion of a rocket sled during friction braking and the thermal wear of the friction elements of braking devices occurring at the same time is presented. An example of the calculation of the friction braking of a conditionally specified rocket sled, per-formed according to the presented method, is shown.

1 Introduction

When developing new models of aircraft, it is necessary to test their units and systems under operating conditions. Track tests make it possible to simulate flight conditions for full-scale products and their large-scale models in the entire range of speeds of their application [1, 2].

Braking expands the functionality of track tests, increases their efficiency and informativeness, reduces their time and cost by recycling the stored material part. To ensure effective braking of rocket sleds in a wide speed range, it is advisable to use several types of braking, each of which is involved in an acceptable speed interval for it [3].

This article discusses the application of friction braking in rocket track conditions. A method for calculating the mode of movement of a rocket sled along a rocket-rail track during friction braking, as well as the thermal loading and wear of friction elements of braking devices occurring during this process, is given. An example of calculating the friction braking of a conditionally specified rocket sled according to the presented methodology is demonstrated.

2 Calculation of the rocket sled movement mode during friction braking

Friction braking on the rocket track is carried out with the help of special shoes equipped with friction elements (hereinafter referred to as FE) pressed against the rail guide due to

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powder pressure accumulators or pneumatic accumulators. The source of the braking force is the friction that occurs in the contact zone of the FE and the rail guides. The braking force generated by friction braking devices is equal to the product of the contact pressure p, the area of the FE S and the coefficient of friction f:

$$F_b = pSf \quad . \qquad (1)$$

The acceptable dependence of the coefficient of friction on the velocity for the FE of the rocket sled along the rocket track is given by the:

$$f = ae^{-bv} + c \quad , \qquad (2)$$

where a, b, c are the friction parameters depending on the properties of the material and the contact surfaces of the FE, v is the velocity.

Determining the dependence of the coefficient of friction when modeling the braking process is crucial. Its value will determine the force and thermal effects on the FE, as well as their wear.

The mode of motion of the rocket sled in the braking area is described using the differential equation of translational motion [4]:

$$m\frac{d^2s}{dt^2} = -F_b - F_a - F_{fr} \,, \qquad (3)$$

where m is the mass of the rocket sled; Fb is the braking force; Fa is the force of aerodynamic resistance; Ffr is the friction force of the support shoes.

With an increase in the friction speed, the braking efficiency decreases and the intensity of heat release in the contact zone of the rubbing pair increases [5, 6].

3 Thermal model of friction

The thermal model of friction of the FE of the braking device in contact with the rail guide is presented in the form of a body limited in length L, width W and thickness H in contact with an infinite counterbody (Fig. 1).

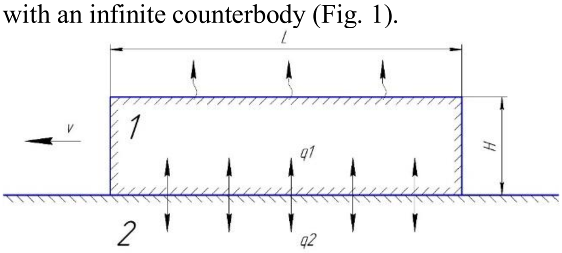

Fig. 1. Thermal model of friction.

The thermal friction process is characterized by the specific intensity of heat release on the nominal area [7, 8]:

$$q(t) = fpv(t) \qquad (4)$$

The heat released in the friction zone per unit of time is distributed into two heat flows with densities q1 and q2. The first flow is directed to the FE of the movable rocket sled 1, the second flow is directed to the rail guide 2.

To calculate the distribution of heat flows between the FE and the rail guide, the conditions of non-ideal thermal contact are applied [9]. The heat flow directed to the FE consists of a fraction of the heat power released by friction, minus the heat flow directed from it to the rail guide, as from a more heated body to a less heated one.

$$-\lambda_1 \frac{\partial T_1(t)}{\partial x} = \alpha_s q(t) - k_r (T_1(t) - T_2(t)) \qquad (5)$$

where as is the coefficient of friction energy distribution; kr is the thermal contact conductance (FE – rail), λ is the coefficient of thermal conductivity.

4 Simulation of friction element heating during braking

Modeling of the process of heat exchange and thermal wear of the FE of the braking device is reduced to solving a linear one-dimensional problem of thermal conductivity with boundary conditions of the second and third kind.

The following assumptions are made in the proposed model:
- The actual friction area is taken as nominal.
- The heat flux is evenly distributed over the friction surface.
- Heat transfer from the side faces of the FE is not taken into account.
- The coefficient of thermal conductivity - constant.

The thermal state of the FE is described using the differential equation of thermal conductivity for one-dimensional unsteady heat transfer without internal energy sources [10, 11]:

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \quad 0 \le x \le H , \qquad (6)$$

where ρ is the density; c is the heat capacity.

Initial conditions:

$t = 0: \quad T = T_0, \quad 0 \le x \le H$

Boundary conditions:

$$x = 0: \quad -\lambda \frac{\partial T}{\partial t} = q_1, \quad t > 0$$

$$x = H: \quad \lambda \frac{\partial T}{\partial t} = k_a (T_a - T_N), \quad t > 0$$

where ka is the heat convection coefficient (FE – air), Ta is the ambient temperature (air).

The temperature distribution in the FE is calculated by solving the differential equation of thermal conductivity in partial derivatives, using the finite difference method based on an implicit four-point scheme (Fig. 2) [12, 13].

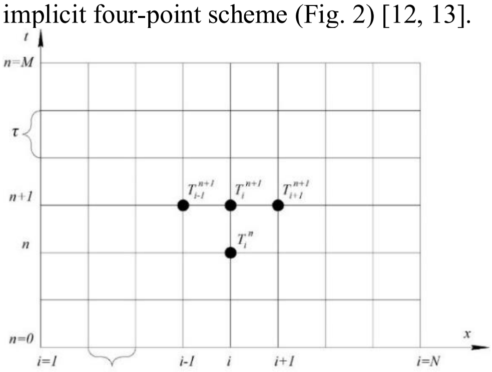

Fig. 2. Implicit four-point difference scheme.

After approximation of partial derivatives by finite differences, equation (6) is transformed into a system of linear algebraic equations:

$$\rho c \frac{(T_i^{n+1} - T_i^n)}{\tau} = \lambda \frac{(T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1})}{h^2}, \quad i = 2,\dots,N-1, \quad n \ge 0 \qquad (7)$$

The system of equations (7) can be represented as three-point difference equations of the second order:

$$A_i \cdot T_{i+1}^{n+1} - B_i \cdot T_i^{n+1} + C_i \cdot T_{i-1}^{n+1} = F_i \qquad (8)$$

$$A_i = C_i = \frac{\lambda}{h^2}, \quad B_i = \frac{2\lambda}{h^2} + \frac{\rho c}{\tau}, \quad F_i = -\frac{\rho c}{\tau} T_i^n .$$

Then the equations (8) are transformed into two-point difference equations of the first order:

$$T_i^{n+1} = \alpha_i T_{i+1}^{n+1} + \beta_i \ . \qquad (9)$$

Run-through coefficients:

$$\alpha_i = \frac{A_i}{B_i - C_i \alpha_{i-1}}, \quad \beta_i = \frac{C_i \beta_{i-1} - F_i}{B_i - C_i \alpha_{i-1}} . \qquad (10)$$

The initial run-through coefficients are determined by approximating the boundary conditions of the II kind for the left wall with an error of O(h2).

$$\alpha_1 = \frac{2a\tau}{h^2 + 2a\tau}, \quad \beta_1 = \frac{h^2}{h^2 + 2a\tau} T_1^n + \frac{2a\tau h q}{\lambda(h^2 + 2a\tau)} \qquad (11)$$

The temperature TN is determined by approximating the boundary conditions of the III kind for the right wall of the *FE* with an error of *O(h2)*:

$$T_N^{n+1} = \frac{\lambda h^2 T_N^n + 2a\tau(\lambda\beta_{N-1} + hk_a T_a)}{\lambda h^2 + 2a\tau(hk_a + \lambda(1 - \alpha_{N-1}))} \qquad (12)$$

Thus, a system of linear algebraic expressions is obtained, which makes it possible to find the temperature distribution in the *FE* of the braking device at various points in time.

5 Simulation of thermal wear of a friction element

With intense heat release, the temperature of the *FE* in the contact area can reach a value at which the strength limit of the material will decrease to the level of the stresses that have arisen in it. The *FE* is subjected to thermal wear due to peeling and removal of the heated layer from the friction surface.

The calculation of wear is performed by catching the front in the node of the spatial grid [14, 15]. A uniform spatial grid with a step h and an uneven time grid with a step τn+1 are introduced, which is determined so that the *FE* boundary shifts by one step of the spatial grid as a result of wear (Fig. 3). The heating time of the layer thickness h to the critical temperature T_{cr} is determined:

$$\tau_{n+1} = \frac{h^2 \rho c (T_k^n - T_{k+1}^n)}{q_k^n h - \lambda(T_{k+1}^n - T_{k+2}^n)}, \qquad T_k^n = T_{cr} \qquad (13)$$

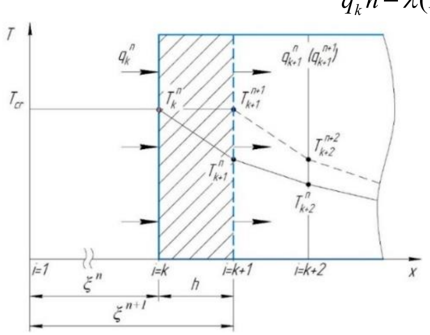

Fig. 3. Temperature field of the surface layer of the FE.

During the time τn+1, the leftmost layer of the FE with thickness h is completely warmed up to the temperature Tcr and removed. The temperature field of the remaining part of the FE is calculated using the thermal conductivity equation:

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \quad \xi^{n+1} < x < H \qquad (14)$$

Initial conditions:

$t = t^n: \quad T = T^n, \quad \xi^{n+1} < x < H$

Boundary conditions:

$$x = \xi^{n+1}: \quad -\lambda \frac{\partial T}{\partial t} = \frac{1}{2}(q_k^n + \lambda \frac{T_{k+1}^n - T_{k+2}^n}{h}) \qquad (15)$$

$$x = H: \quad \lambda \frac{\partial T}{\partial t} = k_a (T_a - T_N) \qquad (16)$$

As a result of the calculation, the parameters of the movement of the rocket sled, the amount of wear and the temperature distribution over the thickness of the FE of the braking device during braking are determined.

6 An example of calculation of friction braking parameters

Find the braking distance and wear of a FE (length - 0.3 m; width - 0.1 m, thickness - 0.03 m), made of steel with a carbon content of 0.15 % when braking a rocket sled weighing 250 kg moving along a rocket track at a speed of 200 m / s. The contact pressure is 10 MPa.

The calculation results are presented in the form of graphs in Fig. 4 and 5.

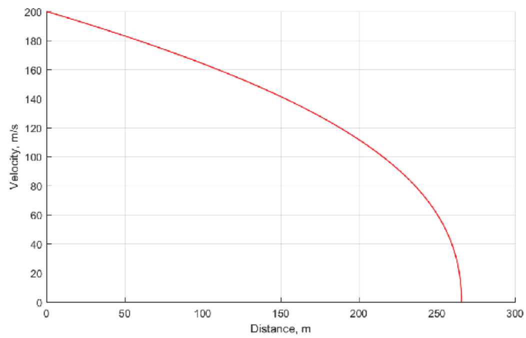

Fig. 4. Dependence of the rocket sled speed on the path.

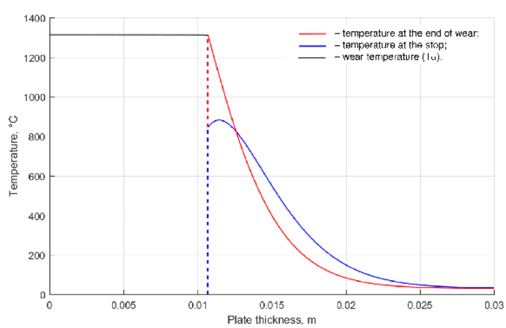

Fig. 5. Temperature distribution in the FE of the braking device by its thickness.

Under the given conditions, the calculated braking distance of the rocket sled was 265.5 m, while the wear of FE in thickness was 10.7 mm.

7 Conclusion

The assessment of the braking means capabilities used on the rocket-rail track is carried out using computational methods. In this paper, a mathematical model method of the friction braking devices operation is proposed. The presented method makes it possible to determine the mode of movement of the rocket sled, the thermal effect on the friction elements of braking devices and the amount of their wear during friction braking. According to the presented method, an algorithm implemented in the MATLAB software was developed.

It is known from previous studies that the effectiveness of friction braking devices decreases with an increase in the friction speed: the developed braking force decreases, the thermal wear of friction elements increases. Consequently, in high-speed track tests, friction braking can be applied in the speed range acceptable for it, for example, for the final stop of the rocket sled after the application of other types of braking ineffective at low speeds.

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