Simulation of movement of a high-speed stage of a monorail rocket train along an elastic guide, taking into account wave processes in it and conditions at the sliding contact

V I Erofeev*, S I Gerasimov and I A Odzerikho
Mechanical Engineering Research Institute of RAS, Nizhny Novgorod, Russia

* erof.vi@yandex.ru

Abstract. The processes of changing the mechanical characteristics of the material, intensive plastic deformations and the entrainment of material from the working surfaces are studied at high-speed sliding of loads along the rail guides of the rocket track.

For the acceleration of the payload when setting up experiments on a rocket track, generally, rocket trains of the following two types are used: monorail and duorail trains. Monorail trains have higher engine packaging densities and better quality design factors as compared to duorail trains, due to they may achieve higher acceleration rates. However, in some cases the movement of high-speed stages of monorail rocket trains (usually the last or the penultimate one) is attended with the significant wear of the working surfaces of their support shoes and the roll exceeding allowable values as well as failures of shoes and damage to the rail guide.

The said anomalies in the movement of high-speed stages of rocket trains occur because of a number of peculiar features available in the dynamics of the interaction of high-speed objects along a rail guide. The most significant ones are: wave processes in the guide [1-6] and conditions on the sliding contact of the working surfaces of the stage support shoes with the guide.

The interaction of a moving object with a rail guide at high sliding speeds is characterized by the frictional heating of working surfaces up to temperatures close to the melting point of the material of rubbing bodies. As a result thereof, in layers adjacent to the contact boundary some changes occur in the mechanical characteristics of the material as well as the intensive plastic deformation and material entraining from the working surfaces.

This paper deals with the study of these processes.

A distinctive feature of high-speed friction is the intensive heat generation in the area of rubbing surface contact. The specific intensity of the heat generation per a unit of contact area shall be [7]:

\[ q = K_{mp} p_k V_s, \] (1)

where \( K_{mp} \) is friction coefficient, \( p_k \) is the nominal contact pressure, \( V_s \) is the sliding speed.

Under the conditions of short-term high-speed friction processes there is not enough time for the materials of the contacting pair to warm up to the full depth. Only surface layers adjacent to the
contact area are involved in the heat absorption. Based on the assessments performed the effective depth of the heat pulse penetration into the shoe body is 0.2-0.5 mm.

As the friction surface temperature increases the contact saturation occurs and the nominal contact pressure reaches the value of material hardness $HB$ at the contact surface temperature.

The increasing temperature of the friction surface causes the loss of mechanical properties in the material of the working surfaces of the support shoe. The dependences of hardness $HB$ and elasticity modulus $E$ of the shoe material (steel 30 HGSA) on the temperature are shown in Figure.1 [8, 9].

![Figure 1. Dependences of the elastic modulus (solid line) and hardness (dotted line) on the temperature.](image)

At a certain temperature of the heated layer the contact pressure will become equal to the current value of the material hardness and the heated layer entrainment will begin from the working surface of the shoe. As it follows from the physics of the phenomenon the higher is the contact pressure, the lower is the temperature of the heated layer on the working surface of the shoe. It is also confirmed by the results of metallographic and chemical studies of the friction surface of the support shoe [10].

The heat balance equation for the contact area shall have the form [11]:

$$K_q q dt = (T_k - T_i) C_p \rho_h dh,$$

where $K_q$ is the heat flow sharing ratio, $C_p$ is the heat capacity of the shoe material, $\rho_h$ is the shoe material density, $T_i$ is the mean temperature of the layer with thickness $dh$, $T_k$ is the initial temperature of the shoe material.

Change in the friction surface temperature results in changing the mechanical properties of the surface layers of rubbing bodies, which determine the value of the friction coefficient. Given the linear character of the change in the friction coefficient from the current hardness of the friction surface [12] and taking into account the contact pressure equality to the current hardness there may be obtained

$$K_{mp} = K'_{mp} \frac{p_i}{p_k},$$
where with * parameters are marked for which value $K_x$ is determined under the experimental conditions.

Having inserted the expression for the specific intensity of the heat generation (1) into the heat balance equation (2) with consideration of expression (3) there may be calculated the motion velocity of the boundary of the layer heated up to temperature $T_s$ when the material is carried away, i.e., in fact, the rate of material entrainment from the working surface of the shoe

$$\frac{dh}{dt} = \frac{K_u}{(T_s - T_0)} \rho_p \frac{V_s}{p_k},$$

(4)

where $K_u = \frac{K_x K_{wp}}{C_p \rho_p}$ is the coefficient of wear for working surfaces of the shoe.

Under conditions of the experiment during 2 second with sliding velocity $V_s$ varied within the range of 500-890 m/s, contact pressure $p_k$ varied within the range of 0-18 MPa and the resulting wear reached 16 mm, the calculated value for the heat flow shearing coefficient $K_u$ was 0.21 and the wear factor was: $1.1 \times 10^{-9}$ m$^2$deg./H.

The result obtained does not contradict the physics of the phenomenon. A portion of heat transferred from the friction area to the shoe is used to heat the entrained material, some heat is dissipated in space through radiation and serves to heat the deeper lying layers of the shoe due to heat conduction. Based on the results, 21% of the heat generated due to friction in the contact area is used for heating of the entrained material and 79% is lost because of the thermal conductivity and radiation and serves for heating of the rail guide.

Thus, knowing the sliding speed $V_s$, the temperature dependences of the contact pressure $p_k(t)$, material hardness $HB(t)$ and elasticity $E(t)$, it is possible to estimate for the heated layer in the sliding contact area the values of temperature $T_s$, elasticity modulus $E_s$, ware rate for shoe work surfaces $h$, friction coefficient $K_{wp}$.

The consideration for the conditions on the sliding contact in the simulation of the interaction of the high-speed stage with a rail guide has enabled to achieve the satisfactory adjustment of the results of the stage dynamics calculation with the experimental results. Figure 2 shows the calculated stage roll as a continuous curve. The results of the roll measurements during the real experiment on the rocket track are indicated by single points. The stage velocity on the roll measurement segment was 1450 m/s, the stage roll angle was 8 degrees.

![Figure 2. Dependence of the stage roll angle on the distance travelled by the stage along a rail guide: calculation (solid line).](image-url)
Thus, the paper shows that the interaction of a moving object with a rail at high sliding speeds is characterized by the frictional heating of working surfaces up to temperatures close to the melting point of the material of the rubbing surfaces. As a result thereof, in layers adjacent to the contact boundary some changes occur in the mechanical characteristics of the material as well as the intensive plastic deformation and material entrainment from the working surfaces. It has been established that knowing the sliding speed, temperature dependences of the contact pressure, the material hardness and the elastic modulus it is possible to calculate for the heated layer in the sliding contact area the values of temperature, elasticity modulus, wear rate for shoe work surfaces and the friction coefficient.

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