Optimization of the internal damping rubber elements of the small diameter roller wheel of tracked system

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Abstract. The article presents the formulation and solution of the problem of optimization of the internal damping rubber elements of the small diameter roller wheel of tracked system. The search for the optimal design is based on the results of calculating the stress-strain state of the rubber element caused by the assembly of the roller and loads during subsequent operation. As an objective function, the specific energy of deformation of the rubber was chosen. The geometric parameters of the rubber element of the roller wheel in the initial state and after installation in the structure are taken as variable parameters. Explicit and functional constraints in the form of inequations are imposed on the variable parameters. The results of solving the optimal design problem are presented.

1. Introduction
One of the heavily loaded elements of the tracked system is the roller wheel (or basic running roller), which is subjected to significant dynamic loads during its rolls along the contact surface of the track chain [1–3]. Dynamic loads cause increased dynamic stresses in the contact between the bandage of the roller wheel and the track treadmill, as well as high volumetric stresses that act in the links and pins of the track chain [1, 4 - 6]. High contact stresses contribute to intensive wear of the metal bandage of the roller wheel and the link treadmill. High volumetric dynamic stresses reduce the fatigue strength of links and pins and, together with wear, are the main factors that limit the life of a tracked system.

To reduce dynamic loads, power internal rubber and rubber-metal shock absorbers are installed in the roller wheels of the tracked system [7]. Such elements with a relatively small specific gravity allow providing a reduction in dynamic loads and increasing the durability of the elements of the caterpillar mover.

When designing a caterpillar mover with power rubber-metal elements, it is necessary to take into account the conflicting requirements [6 - 9] imposed on its structure. On the one hand, high requirements are made on the strength and stiffness of the structural elements of the tracked mover, providing a margin
in connection with increased wear. On the other hand, it is necessary to create a structure with a minimum mass. When solving such problems, it is necessary to apply optimal design methods.

In this paper, the formulation and solution of the problem of optimization of the internal damping rubber elements of the roller wheel of tracked systems are presented. Also proposals aimed at improving the structures to increase their durability were made.

2. Features of the use of rubber elements in the constructions of roller wheels

The variety in the geometry of the rubber elements of the roller wheels determines the difference of their stiffness and damping characteristics. The degree of pressing, radial and axial stiffness during secondary loading of rubber elements of the same overall size can differ from each other by several times. This, in turn, determines a wide range of possibilities for their application, allowing for each specific structure of the roller wheel to use the most rational geometric shape of the rubber elements. An optimal combination of rubber and metal elements and a reasonable choice of their structural parameters allow getting the stiffness characteristics which are necessary to reduce dynamic loads.

During operation, rubber elements are subjected to the following types of deformation: deformations associated with the installation and assembly of rubber elements in a roller wheel (rubber elements may be subjected to compression along the end surface), pressing along the inner radius, pressing on the outside radius [7]. Rubber elements can be made in the form of ordinary rubber elements or in the form of rubber-metal, i.e. having metal fittings. When moving along the treadmill of the track, the roller wheel is subjected to shock and dynamic effects in the radial and axial directions associated with the discreteness of the chain design, with vertical vibrations of the tracked vehicle body, with hook load, with speed and uneven road surface.

When assembling, rubber elements undergo large deformations, while the initial shape and geometry of the element changes significantly. As a result, significant stress and strain concentrators appear. As theoretical and experimental studies show, the decisive role in fatigue failure is played by concentrators arising from deformation during secondary loading of rubber elements. The location and the size of the concentrator depend on the initial geometry of the rubber element, the assembly conditions and the loads arising during operation.

The combination of constant and variable mechanical loads as a result of assembly and subsequent radial and axial loading increases cyclic strain and stress in the concentration area and causes fatigue failure of rubber. Moreover, the imposition of secondary inelastic deformations of radial and axial loading on the equilibrium deformations of the assembly significantly changes both the amplitude and average components of local stresses and deformations.

The cyclic nature of the modes of operation of the internal damping elements, viscoelastic properties of rubber cause heat generation in the rubber elements. The existing uneven distribution of the temperature field along the length and thickness of the rubber rings is a source of temperature stresses with different gradients within the considered section.

3. Example of the stress-strain state assessment of the internal damping rubber element of the roller wheel with a small diameter

As an example, the design of the roller wheel with internal damping ring (Figure 1), the prototype of which was subjected to field tests, is presented.
The calculation of the stress-strain state of the rubber structural elements shown in Figure 1 included two stages. At the first stage of the calculation, the stress-strain state of the rubber element is due to the assembly of the support roller, that is, under pressing into the outer metal band and subsequent compression in the axial direction. At the second stage, the calculation was performed taking into account the loading by radial force.

For the calculation, a software package was used, the feature of which is the ability to automatically take into account changes in the boundary conditions in the process of deformation. As a result of solving the task of assembly and secondary loading with radial force, the following calculated data were obtained: patterns of displacement of nodes of the finite element model, distribution of stress tensor components over the rubber elements section, distribution of the specific potential strain energy over the section (Figure 2). The figures show a cross section of a rubber element located in the plane of action of the radial force in the compression area.

For the considered construction of the roller wheel, the concentration of tangential stresses and the specific strain energy during assembly (axial compression) is observed in zones 1 - 4. In those zones the rubber elements either come into contact with the sharp edges of the metal parts or are the boundary contact areas between rubber and metal. During secondary loading by radial force the concentration of the specific strain energy is observed in areas 1, 2, and 4. Area 3 is unloaded. Under the action of radial force, the rubber is squeezed out between the metal parts of the rim (zone 1) and a flange rigidly connected to the hub (zone 2).

Field tests of the considered experimental support roller showed that the durability of rubber elements is 2000 hours. The first fatigue cracks were observed in the areas of concentration of specific strain energy (Figure 2, b). Subsequent operation was accompanied by delamination of the rubber from the metal base in zones 2 and 4, an increase in temperature, and thermomechanical destruction of the rubber elements along the line connecting zones 1 and 4.

The considered internal damping rubber elements of have an irrational design, since during assembly and secondary loading with radial force there is an uneven distribution of stresses and specific strain energy.
energy over the cross section of the rubber element. The distribution of these parameters has distinct concentration areas.

4. Proposal approach of optimal design of rubber elements of roller wheels to increase their durability

A reserve for increasing the operability of the construction of small diameter roller wheels with internal rubber damping element is the use of deformation limiters.

When designing the elements of the internal damping of the roller wheel of the caterpillar mover it is necessary \([6, 7]\):
- to provide the possibility of placing rubber elements in the construction of the roller wheel;
- to ensure the absence of an influx of rubber on the metal elements of the roller wheel;
- to eliminate the possibility of penetration of the abrasive between the metal and the rubber element;
- to ensure that the tangential stresses caused by the assembly do not exceed the permissible values;
- to provide characteristics of radial and axial stiffness of the rubber elements of the roller wheel, allowing to reduce dynamic loads;
- the temperature of the rubber elements must not exceed the permissible values;
- to provide for the design of the roller wheel to limit the radial deformation of the rubber elements;
- to minimize the mass of the unsprung part of the roller wheel, i.e. weight of metal bandage.

To assess the fatigue endurance of a rubber element under a complex mechanical loading regime (simultaneous action of dynamic and static stress), equations based on the energy criterion are used \([10, 11]\). The equation for describing the dependence of the fatigue endurance of rubber on the strain energy has the following form \([10]\):

\[
N = \left( \frac{W_p k_r}{W} \right)^{n_r},
\]

where \(N\) is the number of loading cycles before the crack; \(n_r\) - the coefficient of fatigue endurance of rubber; \(W_p\) is the fracture work under single loading; \(W\) is the strain energy under cyclic loading; \(k_r\) - the coefficient of the change of strength from temperature.

In the case of a complex stress-strain state, the strain energy is determined using the Treolar potential \([10]\), which is a function of the invariants (or components) of the tensor of the measure of finite strains and depends on the coordinates. Estimation of the highest value of the specific strain energy is associated with the determination of finite strains, which are a solution to the boundary value problem with a system of nonlinear partial differential equations. To solve this problem, an algorithm based on a step-by-step procedure is used. The numerical implementation of the algorithm is performed using the finite element method \([12]\). In addition to assessing the stress-strain state, the results obtained are used to determine the stiffness characteristics of rubber elements.

Thus, in the problems of optimal design of the internal damping rubber elements of the roller wheels of caterpillar systems, the objective function and functional constraints imposed on the variational parameters are not set analytically, but in the form of an algorithm. To solve such problems, optimization methods related to direct search methods are used \([13-15]\). In this paper, to solve optimization problems, the complex Box method is used \([13, 14]\). This approach is a modification of the Nelder – Mead simplex method \([15]\), which allows one to take into account the constraints on various parameters, both explicitly and functional limitations.

The formulation of the problem of optimal design of the internal damping rubber element on the example of the small diameter roller wheel (Figure 3) will be considered. As the objective function, the maximum value of the specific strain energy during secondary loading with radial force will be chosen.
Variational parameters $x_j$ are: the coordinates of the nodal points of the cross section, which determine the shape of the rubber element and geometric dimensions prior to assembly in the initial undeformed state (Figure 3, b); the value of compression acting on the rubber elements in the axial direction after assembling the roller.

The mathematical formulation of the optimization problem has the form: to find a vector $\vec{x}$ that minimizes the objective function

$$Z = \min_\Omega \left[ \max_\Omega (W) \right],$$

where $\Omega$ is the cross section zone of the of the element with a variational boundary $\Gamma$.

Constraints on variational parameters (geometric) are set by the system of inequations:

$$x_j^- \leq x_j \leq x_j^+ , \quad (j=1, 2, \ldots, m),$$

where $x_j^-$, $x_j^+$ are the limits of variation of the components of the vector $\vec{x}$; $m$ – the number of independent parameters.

Functional constraints are set by the system of inequations:

$$F_z [\tau_{rz}] > 0;$$

$$\max_\Omega (|\tau_{rz}|) - [\tau_{rz}] < 0;$$

$$K_{r_{\min}} \leq K_r \leq K_{r_{\max}};$$

$$K_{Z_{\min}} \leq K_Z \leq K_{Z_{\max}},$$

where $F_z$ - the axial force providing the necessary friction force; $\tau_{rz}$ - the tangential stresses due to assembly; $K_{r_{\min}}, K_{r_{\max}}$ - the lower and upper limits of radial stiffness; $K_{Z_{\min}}, K_{Z_{\max}}$ - the lower and upper limits of axial stiffness.

5. Calculation results

As a result of solving the optimal design problem, a cross-sectional shape of the rubber element of the internal depreciation of the track roller is obtained (Figure 4, a). The tangential stresses caused by the deformation of the rubber elements in the axial direction during assembly of the roller (Figure 4, b) are less than the permissible values. The objective function - the specific strain energy caused by the secondary loading of rubber elements by radial force (Figure 4, c) - decreases at least four times in comparison with the previously considered design (Figures 1, 2) with a radial displacement (6 mm) and 12 times with an additional limiter of the radial deformation of rubber elements due to structural measures.
6. Conclusions

As a result of solving the optimal design problem, the shape and design parameters of the internal damping rubber element of the roller wheel of the tracked system were calculated. which made it possible to reduce the specific strain energy under radial loading to 0.05 MJ/m$^3$. This value is 4 times less than the same parameter of the existing roller when exposed to radial forces of the same magnitude. In this case, the radial stiffness of the rubber elements of the roller wheels of the optimal and existing design is the same.

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