Computer Simulation of Safety Processes of Composite Structures Rheological Properties

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Abstract*—Mechanical means directly related to the information support path (locators, ob-servation stations, tracking, detection, localization, etc.) require special attention within the technical channels for obtaining information. Their precise and stable performance is of paramount importance. During operation, the instability of the structure occurs when driving on the road, that is, the vibration of the structure. The vibration of the structure during movement is a significant obstacle to im-proving the accuracy of the devices. The influence of the main structural and technological factors on the thermal and stress-strain state, as well as on the performance of large-sized tires, was studied using a comprehensive approach. Modeling of tires with various structural and technological parameters was carried out.Technical solutions in the field of large tires construction, manufacturing technology, and operating modes, have been devel-oped based on complex computational and experimental research, which allowed to provide a decrease in temperature at the design stage, which leads to the in-creased resource. Simulation and calculation are possible only with the use of computer technology and appropriate software. The need to take into account changes in the properties of tire construction materials in the conditions of heating was established by calculation and confirmed by the experiment. o calculate the stress-strain state under conditions of high temperatures, a mathematical model of the moment anisotropic three-layer shell of the tire was used, taking into account the nonlinear deformation of composite materials. The tire is modeled with a three-layer anisotropic shell according to the design features based on the broken line hypothesis for the carcass. The shell is loaded with internal pressure. The movements of the outer layers are independent. The displacements of the middle layer are calculated from the displacements of the outer layers and the curvature changes during deformation. Modeling of the tire with a multilayer shell, material properties of the integral equation with the creep core, taking into account the temperature effect on composite materials of the tire design and implementation in time using numerical methods is possible only with modern computer technology. Calculation at variable parameters and loads, simulation computer modeling, allows to estimate the properties of the structure at the design stage. A simple and convenient environment model for describing the rheological properties of composites under conditions of various loads and elevated temperatures has been developed. The paper presents a model for describing the rheological properties of composite anisotropic materials; the method of determining viscosity and temperature parameters for inelastic materials is shown; the possibility of predicting the behavior of composites in different modes of loads and temperatures is demonstrated.

Keywords*—*safety, computer modeling, large tire, structure vibration, stress-strain state, the method of local variations.

I. INTRODUCTION

Accurate and stable operation of locators, observation stations, tracking, detection, localization,is of paramount importance, which is given attention in the composition of the technical channels of information retrieval, which occurs during the vibration of the structure [1-3].A significant obstacle to improving the accuracy of the devices is the vibration of the structure during movement. The vibration of the structure during movement is a significant obstacle to improving the accuracy of the devices. Technical solutions in the field of construction of large tires, manufacturing technologies and operating modes, which allow to reduce their temperature at the design stage, leading to increased resource, can only be developed based on complex computational and experimental research. Simulation and calculation are possible only with the use of computer technology and appropriate software.

Composites are used in industry. What makes it necessary to model the rheological properties of such materials at different temperatures and types of loads. Viscosity and creep are characteristic of composites and are especially evident in conditions of elevated temperatures. This leads to a close connection of stress, strain, and temperature fields. There are various models for describing the inelastic behavior of materials: from a simple deformation theory that does not take into account the dependence on the speed of loads to rather complex integral models that take into account the hereditary nature of deformation and allow describing reversible and irreversible deformations.

The temperature of *100-120* degrees C in the large tire is achieved through a massive tread up to *12* cm thick and a multilayer frame, where the number of layers along the crown exceeds *50*. Due to the temperature, the creep of rubber cord materials in-creases, which is also significant in the wear and tear of tires [4].

An integrated approach was used to study the influence of the main structural and technological factors on the thermal and stress-strain state, as well as on the perfor-mance of large tires. Tires with different designs and technological parameters were modeled [5-8].

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II. GOALS AND PURPOSE OF THE ARTICLE

To calculate the stress-strain state at high temperatures, a mathematical model of the instantaneous anisotropic three-layer tire shell taking into account the nonlinear deformation of composite materials was used [9-11].

A three-layer anisotropic shell on the hypothesis of a broken carcass line is taken as a tire model. The shell is loaded with internal pressure by force q. The movement of the outer layers is independent. The displacements of the middle layer as the curvature changes during deformation are calculated using the displacements of the outer layers. [12-13].

III. MAIN PART

The statement of the problem is geometrically nonlinear. Transverse shear deformations are taken into account. At elevated temperatures, the relaxation and plastic properties of the cord, rubber, and carcass composite are taken into account. Tire materials, taking into account the influence of temperature, are represented by a rheological model of the environment [14-17].

The performance of the tire material is described by a nonlinear model of the hereditary type of environment:

$$\Psi(\sigma) = \varepsilon(t) - \int_0^t K(t-\tau)\, \varepsilon(\tau)\, T^{\gamma}(t) d\tau \qquad (1)$$

where the relaxation nucleus is selected as the Abel nucleus:

$$K(t-\tau) = \frac{k}{(t-\tau)^{\alpha}}; \quad 0 < \alpha < 1$$

where $\Psi(\sigma)$ - instantaneous deformation curve; α, k, γ - parameters determined by the author's method as a result of experiments; *T(t)* — temperature at the time *t.*

Expression (1) uses the principle of heredity. Three parameters are necessary to fully describe the performance of the material under various load and temperature conditions: α, γ.

The instantaneous strain curve under one loading mode can be used in mode calculations and to predict the behavior of the material. [18-23].

To determine the parameters and type of relationship between stresses and strains, a series of tests for uniaxial tensile at speeds $V_1 = 5\ \mathrm{mm/min}$ and $V_2 = 200\ \mathrm{mm/min}$ were conducted. Samples cut in the circumferential and meridional directions of the tire were used to account for material anisotropy. According to the method, the parameters of the experimental deformation curves of the samples cut in the circumferential direction were found: $k = 0.023$, $\alpha = 0.97$. These parameters were used in the calculation of deformation diagrams of samples cut in the meridional direction. The instantaneous deformation curves $\Psi(\sigma)$ are constructed in both cases. When comparing the calculated and experimental data (Fig. 1. curves 1, 2, 1.), it was found that the same parameters *k, α* describe the deformation diagrams equally well. It was experimentally proven that there is no need to determine the set of heredity nuclei associated with anisotropy for the analysis of the complex stress state of the studied materials. One core is enough, the parameters of which are determined by tests on samples cut in any direction. The only difference is the instantaneous deformation curves, the knowledge of which corresponds to the knowledge of the matrix of elastic modules of anisotropic material for a linear-hereditary medium. Therefore, we can assume that the parameters of the hereditary nucleus do not depend on the direction of cutting samples [24-28].

The temperature parameter was established *γ = 0.55* according to experimental diagrams of deformation at *T=20°* i *T = 120 ºC.* It was used to predict the performance of the material at *T = 70 ºC.*

The experiment and the calculation match well. The values found were also used in the calculations of the deformation diagrams of the samples cut in the meridional direction at *T = 20, 70, 120 ºC.*

The calculations and creep experiments confirmed the possibility of adopting certain parameters for other types of loads (Fig. 2).

For a tire loaded with internal pressure, the permissible deformation levels at operating temperature are *12...15*%. At such levels, a linear model of the environment can be used. The errors, in this case, do not exceed *15*%.

For linear heredity $\Psi(\sigma) = \frac{\sigma}{E}$ equation (1) for uniaxial stress takes the form:

$$\sigma(t) = E\varepsilon(t) - E\int_0^t K(t-\tau)\, \varepsilon(\tau)\, T^{\gamma}(t) d\tau \qquad (2)$$

For an anisotropic case and a complex stress state:

$$\sigma_{ij}(t) = E_{ijke}\varepsilon_{ke}(t) - E_{ijke}\int_0^t K(t-)\varepsilon_{ke}(\tau)\, T^{\gamma}(t) d\tau \quad (3)$$

The temperature effect function can be selected as a normal power function $T^{\gamma}(t)$, where T- the temperature at the moment in time *t*, γ – hereditary model parameter.

The temperature distribution in the tire is considered to be established. The maximum temperature value is *105-110°*C [29].

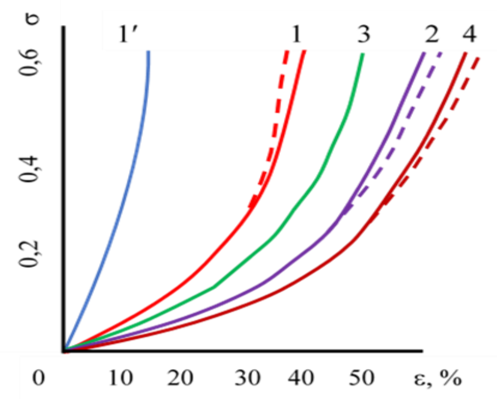


Fig. 1. Instantaneous deformation curve (1′) and diagrams of rubber cord deformation in the meridional direction of the tire under conditions *V = 200(1, 2, 3); 5 mm/min (2); T = 20 (1, 2); 70 (3); 120 ºC (4*) (solid line - experiment, dotted - calculation).

When solving the problem, it is taken into account that as a result of heating the air in the middle of the tire, the temperature rises and, following the gas equation, the internal pressure q_i changes according to the law:

$$q_i = q_0 + (q_0 + 1)(T_t - T_0)/T_0$$

Let's consider that T_t equals to the average integral temperature of the inner surface of the tire, T_0 i q_0 – temperature and pressure of the cold tire [30-33].

The software was developed to perform calculations. The algorithm runs step by step when time increases by equal value. The energy method of solving the problem by the numerical method of local variations is used, which is easily algorithmic and indifferent to the type of nonlinearity.

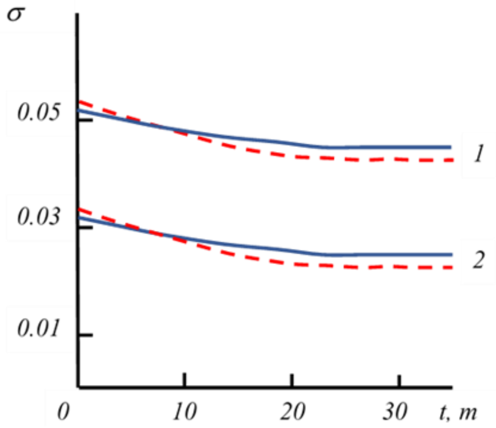


Fig. 2. The stress relaxation curves of the rubber cord in the meridional direction of the tire at $\varepsilon = 10\%(1)$ та $5\%(2)$ (solid line - experiment, dotted - calculation)

At the same time, the principle of a minimum of full energy for a real condition of the system is realized. Deformations and displacements in the tire frame are determined by the displacements found [34-38].

Total shell energy at *t*, taking into account the rheological changes in stresses, is described by the functional $(i, j, k = 1, 2, 3)$

$$Э(t) = \int_V \left[\frac{1}{2} E_{ijke}\varepsilon_{ij}(t)\varepsilon_{ke}(t) - E_{ijke}\varepsilon_{ke}(t)\int_0^t K(t-\tau)\varepsilon_{ke}(\tau)\, T^{\gamma}(t)d\tau\right] dV - \int_{Fc} q_i U_i(t)dFc + q\delta V \tag{4}$$

The coefficients of elasticity in the equation are determined by the theory of reinforcement. The values of displacements vary only at *t*, their change history determines the state of materials at the moment [39-44].

According to established displacements deformations in the tire frame are found. The energy method is used to solve the problem, at which the total energy of the tire shell minimizes. The solution is done using the numerical method of local variations. Assuming a constant temperature distribution in the structure, we solve the problem step by step. Elastic deformations are determined in the first step. Initial deformations received at all previous stages are used at each subsequent step [45-49].

The calculation is performed for the design of a large tire *40.00-57* in case: 1) cold tire with inner pressure of $q_0 = -600$ кПа; 2) heated tire with inner pressure $q_t = -750\ kPa$.

As shown by the software calculations, the distribution of displacement and stress fields close to the constant is observed after *100* minutes from the beginning of deformation. The program runs a cycle with a time step of *5* min., so on the 20-th iteration the values of displacements and stresses are almost the same as those observed in the previous step. For all components of deformations, stresses and displacements in the layers of the three-layer frame model, similar graphs are constructed [50]. It should be noted that there is a gradual decrease in the stress level under a constant field of deformations and displacements, which is consistent with the theory of hereditary elasticity and corresponds to experimental observations. When solving the problem of interaction of the tire with the soil, which also has a nonlinear inheritance of environmental properties, you can use a similar model of type (1) with certain parameters for the soil. For the shell-soil system, the model consists of two functionalities: a functional for the tire (4) and a similarly written functional for the soil:

$$Э_{Г}(t) = \int_{V_Г} \left[\frac{1}{2} E^{Г}{}_{ijke}\varepsilon^{Г}{}_{ij}(t)\varepsilon^{Г}{}_{ke}(t) - E^{Г}{}_{ijke}\varepsilon^{Г}{}_{ke}(t)\int_0^t K^{Г}(t-\tau)\varepsilon^{Г}{}_{ke}(\tau)\, T^{Г}(t)d\tau\right] dV_Г - \int_{Fc} q_i U_i(t)dFc - \int_{Fc}(\sigma_c W_c + \sigma_{c13}U_c + \sigma_{c23}V_c)dFc \tag{5}$$

where $V_Г$ – volume of half-space (soil); F_c − tire and soil contact area; σ_c − contact pressure of the tire shell with the soil; $E^{Г}{}_{ijkl}$ – soil elasticity modules; $T^{Г}(t)$– function of temperature influence for soil.

The contact conditions of the viscoelastic tire and the viscoelastic base (half-space) are written as follows:

$$\sigma_3^{t} = \sigma_3^{s};\quad \sigma_{13}^{t} = \sigma_{c13}^{s};\quad \sigma_{23}^{t} = \sigma_{c23}^{s}. \tag{6}$$

where upper indexes «t» and «s» indicate tire and soil.

Thus, to solve the problem of contact interaction of the tire with the half-space (soil) we have a system (4)-(6).

The problem in this statement is also solved by the method of local variations. The "step-by-step" method is used to account for time: time changes by *t* from *0* to the set value. Deformations can be considered constant at each time interval. The optimal step of *10* min. was chosen for the solution. At the same time, normalization of deformations was observed, which agrees well with the theory of creep and stress relaxation [51-54].

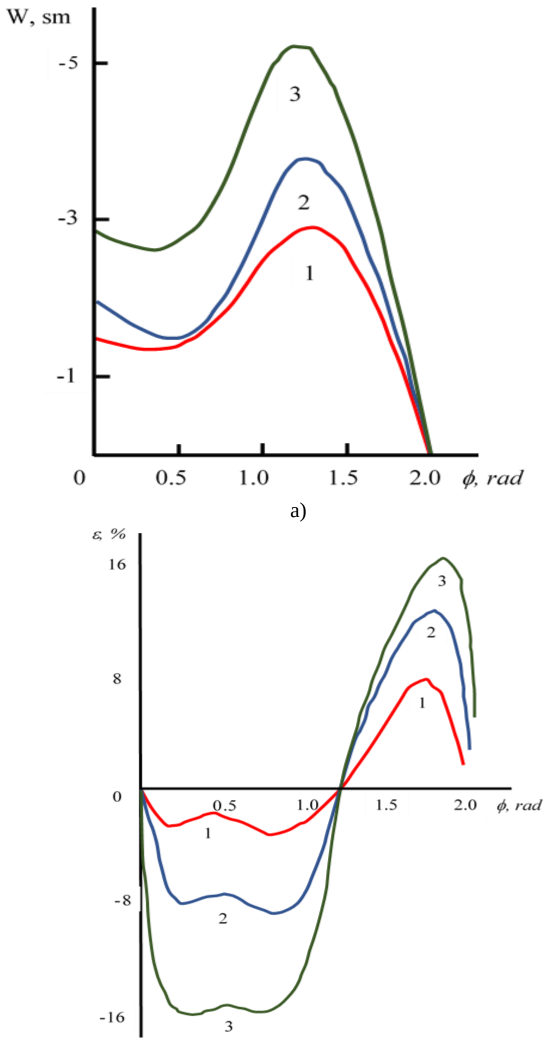
The vibration of the structure during movement is a significant obstacle to improving the accuracy of the devices. Technical solutions in the field of construction of large tires, manufacturing technologies and operating modes, which allow to reduce their temperature at the design stage, leading to increased resource, can only be developed based on complex computational and experimental research. Simulation and calculation are possible only with the use of computer technology and appropriate software [55-58].

The temperature of *100-120* degrees C in the large tire is achieved through a massive tread up to *12* cm thick and a multilayer frame, where the number of layers along the crown exceeds *50*. Due to the temperature, the creep of rubber cord materials increases, which is also significant in the wear and tear of tires.

To study the influence of the main design and technological factors on the thermal and stress-strain state, an integrated approach was applied, as well as on the performance of large tires. Tires with different designs and technological parameters are modeled based on the developed model. [59-60].

IV. CONCLUSION

The most general principle that can be the basis of research on the rheological properties of inelastic materials is the principle of heredity. The article formulates and describes a mathematical model based on the specified principle, which describes the behavior of composite materials in different modes of loads and temperatures. The mathematical model is an integral equation with a creep core. The kernel of the model is chosen in the form of an Abel kernel. The parameters of the Abel kernel are determined using experiments on samples of anisotropic composites.



a)

b)

Fig. 3. Frame deflection (a) and shear deformation between layers (b) in the meridional section (from rim to rim) under the condition of elastic deformation ($q_0 = -600$ kPa) (1); under the condition of viscoelastic deformation of the "cold" ($q_n = -600$ kPa, t=100 min) (2) under the condition of viscoelastic deformation of the "heated" tire ($q_t = -750$ kPa, t=100 min) (3).

Inelastic materials, in particular, composites are widely used in the manufacturing. This necessitates the development and research of mathematical models to describe the rheological properties of such materials at different temperatures and types of loads. Viscosity and creep are characteristic of composites and are especially evident in conditions of elevated temperatures. This leads to a close connection of stress, strain, and temperature fields.

A simple and convenient environment model for describing the rheological properties of composites under conditions of various loads and elevated temperatures has been developed.

The paper presents a model for describing the rheological properties of composite anisotropic materials; the method of determining viscosity and temperature parameters for inelastic materials is shown; the possibility of predicting the behavior of composites in different modes of loads and temperatures is demonstrated.

For inelastic materials, in particular, composites, the behavior of which largely depends on the time and speed of loading, the issue of the effect of temperature on mechanical properties is very important.

The assumption that the instantaneous strain diagram is independent of temperature is an advantage of the proposed model. The model takes temperature into account in a legacy type equation. The model is most commonly used in linear viscoelasticity compared to the time-temperature analogy.

A significant obstacle to improving the accuracy of instruments is the vibration of structures. Operating modes are developed on the basis of calculation and laboratory work in technical solutions for the design of large tires and their manufacturing technologies, which allows to reduce the temperature, which leads to an increase in tire life.. Simulation and calculation are possible only with the use of computer technology and appropriate software. The need to take into account changes in the properties of tire construction materials in the conditions of heating was established by calculation and confirmed by the experiment. Modeling of the tire with a multilayer shell, material properties of the integral equation with the creep core, taking into account the temperature effect on composite materials of the tire design and implementation in time using numerical methods is possible only with modern computer technology. Calculation at variable parameters and loads, simulation computer modeling, allows to esti-mate the properties of the structure at the design stage.

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