TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2016, Vol. 16, No.2, 9-14

Calculation of the longevity of elastomeric structural elements

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Received May 27.2016: accepted June 20.2016

Summary. A mathematical model of the process of thermoelastic deformation and dissipative heating of elastomeric structural elements are assumed . The methods of prediction the longevity of structures based on the use of entropy fracture criteria are proposed. For solving of the link thermoelasticity problem of method of successive approximations is used.

Key words. Elastomer, thermoelasticity, longevity, долговечность, fracture criteria.

INTRODUCTION

Elastomeric structural elements are widely used as power elements, dampers, linings, etc. One of the biggest challenges in the design of such devices is to determine their stress-strain state under operating loads and predict their longevity. To analysis the longevity of the rubber elements of designs using different fracture criteria [12, 4, 10, 22, 11, 21].

With a relatively small deformations occur most elastomers essentially nonlinear effects [19, 16]. The rubbers such effects are manifested primarily in the fact that the dependence of the force-deformation is nonlinear. This may be caused by design features rubber parts and the conditions of their installation in the car (so-called effect ends), the asymmetry of the external force, large deformation, structural changes of the material under the action of an external force. In the calculation of structural elements operating under limited strains, as well as the calculation of thin-layer structural elements should be considered weak compressibility of the elastomer. [1].

Highly elastic materials constructions are generally operated under cyclic deformation. This is the effect of the deformation energy dissipation. The rubbers energy dissipation is large enough; in filled rubbers scattered about 4/5 of supplied energy, in unfilled - about 1/2 [6]. Thermomechanical effects lead to degradation of the material, cracks, and ultimately to the failure and fracture design. Moreover, one should consider the dependence of the physical and mechanical characteristics of the material from the time of loading conditions and aggressive environmental effect [5].

In solving the problem of determining the stress-strain state of elastomeric structures must be considered a significant dissipation of deformation energy.

RESEARCH OBJECT

The practice of designing the structure of the elastomeric components required to develop effective methods to predict longevity based on sound thermodynamic fracture criterion. It should take into account the coupling of stress fields and temperature.

RESULTS OF RESEARCH

Elastomers should be presented as a heterogeneous system at the surface and in the volume; anisotropy on the surface caused by surface effects with increased damage of a thin layer of micro and concentration; in the amount of anisotropy due to the heterogeneity of the structure and the presence of a certain level of micro.

Cyclic loading of rubber leads to the formation of submicrocracks, which subsequently turned into micro-cracks; their value is determined by the structure of the material.

Microcracks due to stress relaxation near these dissipate energy, which leads to a sharp increase in temperature (420 K) and the formation of so-called thermomechanical fracture zones; these areas are able to for some time to slow crack growth and to reduce the rate of change in the structure of rubber.

The process of destruction of the rubber is different locality. The rubber structure heterogeneity exists, and hence heterogeneity of the stress fields and temperatures. Therefore, the emergence of sub- micro-cracks and evolutionary transition to micro-cracks, the concentration of the latter and the emergence of macro-cracks is probabilistic in nature. Rapture of metal-rubber system begins in local areas, both in the bulk and on the surface (foci destruction), i.e. in places where the stress and the maximum temperature. In this case, even when main cracks are appeared and develop the metal-rubber system for some time preserves the integrity, stiffness and dissipative characteristics and can match its functionality.

The process of destruction is discrete. In principle, this means that the development of micro- and macro-cracks take place in the form of elementary events occurring abruptly. At the mouth of the moving cracks on the laws of probability are merged sub- and micro-defects and structure of the material changes significantly in a local volume; structure change causes an increase in energy dissipation, which in turn causes even greater structural changes in the material; dissipative heating temperature in the local volume increases until the thermal destruction (melting) rubber; crack temporarily stops the growth and further deformation, ie, with an increase in the rate of accumulation of elastic energy is growing by leaps and bounds. On the surface of the rubber destruction it causes certain fractographic features: grooves, ridges, the next stop of the front cracks, etc.

The main type of the destruction of most of the known rubber vibration isolators in long-term cyclic loading is a fatigue fracture. Laws of this destruction suggest the presence of three main stages. In the first phase longevity t* in local volumes in the material emerging form submicrocracks damage due to external stress field grow to a certain critical value, and then combined into microcracks. The development of such cracks, their merger leads to disruption of the continuity of the local (typical) the amount of change in the structure and the emergence of macro-cracks. For critical power isolators appearance of macro-cracks can serve as a failure; other elements of the signal that a vibration isolator worked most of the time and its residual life of less than 10%. The duration of the first phase of (90-96)% of the time to complete failure. It is said that the longevity of rubber durability under diffuse local destruction or durability, denoted t* is determined by known methods.

As criteria for the destruction of the elastomeric structures may be using different failure criteria: energy criteria [4, 10], the entropy criteria [6], criteria of developing damage [16], and others.

The thermodynamic approach to analysis equilibrium deformation leads to the conclusion that because of the different longevity criteria of elastomeric elements are the most reasonable entropy criterion.

Of all the thermodynamic parameters the entropy criteria of the most complete quantifies the accumulation of irreversible changes. In [2, 9], the proposed entropy durability test in which it is assumed that the local volume of deformable solids is destroyed when the increment of entropy density certain critical ΔS^*, which is characteristic of the material:

$$\int_0^t S(t)dt = \Delta S^*, \qquad (1)$$

where: $S(t)$ – the rate of change of the entropy density equal to the sum of the external and internal flow S_e S_i. source entropy increase. Entropy independence criteria proposed in [8]:

$$\int_0^t \frac{1}{T}\left(\sigma^{ij}\varepsilon_{ij}\right)dt = S^* - S(T_0), \qquad (2)$$

where: σ^{ij} – stress tensor components; ε_{ij} – tensor components irreversible deformation; S^* – limiting density of entropy; $S(T_0)$ – entropy density at the beginning of the creep deformation.

This criterion has the following advantages:

a) allows the calculation for any nature destruction;

b) it is possible to take into account both mechanical and non-mechanical effects;

c) meets the requirement of invariance.

For the thermodynamic description of the destruction of an important task is to choose of complete system of thermodynamic parameters of state. Set these parameters and their number can be different for different models of a continuous medium. Status perfectly elastic medium is completely characterized by the following set of parameters $\{\varepsilon, T\}$ or $\{\sigma, T\}$. To describe the process more complicated than the elastic deformation, these parameters are no longer enough. As a complete set of thermodynamic parameters that describe the irreversible changes in the system, select the following: $\{\varepsilon, T, \lambda\}$ or $\{\sigma, T, \lambda\}$, where λ – a parameter that describes the changes in the system related to the irreversibility; T – temperature; λ – stress tensor; ε – reversible part of the strain tensor.

We write the first law of thermodynamics in the following form:

$$U = \sigma^{ij}\varepsilon_{ij} + divq, \qquad (3)$$

where: U – internal energy density, q – vector of heat flux speed.

The free energy is defined by:

$$F = U - TS, \qquad (4)$$

where: F – the free energy density, S - entropy density.

The entropy density according to [10] can be represented as follows:

$$\dot{S} = \frac{1}{T}\left[\sigma^{ij}\dot{\varepsilon}_{ij} + \frac{\partial f}{\partial G}\dot{G} - div\dot{q}\right]. \qquad (5)$$

The rate of change of entropy can be represented as the sum of the external flow of entropy S_e and speed of generation of entropy within the system S_{i}. Taking into account the experimental research of longevity of elastomeric elements and their products, we consider the criterion of local failure of the equality:

$$\int_0^{t^*}(S_i + S_e)dt = S^* - S_0 = \Delta S^* = const. \qquad (6)$$

Then (Eq. 5) with (Eq. 6) takes the form:

$$\Delta\dot{S} = \int_0^{t^*}\left(\frac{1}{T}\left[\sigma^{ij}\dot{\varepsilon}_{ij} + \frac{\partial f}{\partial G}\dot{G} - div\dot{q}\right]\right). \qquad (7)$$

The equation (Eq. 7) is a criterion equation.

We consider the three-element model of a viscoelastic medium (Fig. 1).

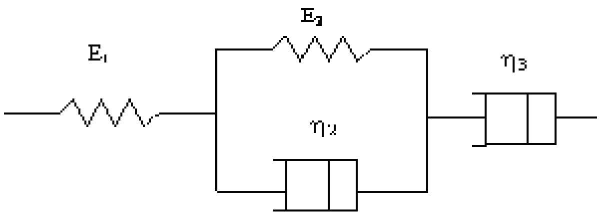

Fig. 1. Three-element model of a viscoelastic continuum

Complicating the structure of the model, you can get a good temporal relationship between stress and strain. In this case, the limit can be considered a model with an infinite number of elastic and viscous elements, which increases the order of the differential operator and complicates its application in solving practical problems. . Stresses-strain relations can be installed by means of integral equations of state. Proportionality between the increment of strain and stress in the integral equations is set with the function that is called the kernel of the equation. The most widely used in the calculation of the elastomeric construcnions obtained relaxation core Rabotnova [20].

Considering the aging behavior of the material on the basis of the above scheme, for its third element have $\sigma(t) = \eta_3(t)\varepsilon^p(t)$, from whence:

$$\varepsilon^p(t) = \frac{\sigma(t)}{\eta_3(t)}. \quad (8)$$

The function $\eta_3(t)$ can be represented as $\eta_3(t)=\eta_3(0)\varphi=\eta_{30}\varphi$, where φ – aging function of the curve corresponds to the changes in time $E = E(t)$ – the modulus of elasticity. To calculate the durability you need an analytic representation of the function. A common approximation of the experimental data for elastomers is exponential dependence [9]:

$$\varphi(t) = \frac{E(t)}{E(0)} = \exp\left[\left(k_1 - k_2\int_0^t W(t)dt\right)t\right], \quad (9)$$

where: k_1, k_2 – coefficients of the approximation, $W(t)$ – function proportional accumulated over time t strain energy.

To determine the longevity of elastomeric constructions the following calculation procedure is used:

1. Calculation of the stress-strain and temperature conditions of the elastomeric structure.
2. Determination of the danger point.
3. The decision of criterion equation (Eq. 7) in a dangerous point.

Construction of the elastomers employed in dynamic loading conditions, are subject to intense heating of dissipative. Sources of heat in this case are the stress and strain rate in the viscoelastic body.

To study the thermal stress state of such structures is supposed to joint problem solving thermoelasticity, and thermal conductivity of the method of finite elements onto [3, 15].

Based on the law of conservation of energy, the variational equation of thermoelasticity Bio as a generalization of the Lagrange variational principle has the form:

$$\iiint_{V_k} \delta F\sqrt{g}\,d\xi^1 d\xi^2 d\xi^3 - \iiint_{V_k} \vec{P}\delta\vec{u}\sqrt{g}\,d\xi^1 d\xi^2 d\xi^3 - \iint_{S_k} \vec{q}\delta\vec{u}\,ds = 0. \quad (10)$$

The variation of free energy is calculated by the formula:

$$\delta F = \delta W - \sigma^{ij}_{(\text{т})}\delta\varepsilon_{ij}, \quad (11)$$

where: $\delta W = \sigma^{ij}\delta\varepsilon_{ij}$ – a variation of the elastic deformation energy.

State law weakly compressible elastomeric accept a generalized Hooke's law:

$$\sigma^{ij} = \int_0^{\varepsilon_{kl}} 2\mu\left(G^{mi}G^{nj} - \frac{1}{3}G^{mn}G^{ij}\right)d\varepsilon_{mn} - \int_0^{G^*} B\left(\sqrt{I_3\left(G^*\right)} - 1\right)dG^{ij} \quad (12)$$

where: μ – shear modulus; G^{ij} – components of the metric tensor of the deformed volume; B – modulus of dilatation; I_3 – third invariant of the strain measures G^*.

In the case of combined action of temperature and load, the deformation occurring represented as the sum of the elastic $\varepsilon^{(\text{у})}_{ij}$ and thermal corresponding $\varepsilon^{(\text{у})}_{ij}$:

$$\varepsilon_{ij} = \varepsilon^{(\text{у})}_{ij} + \varepsilon^{(\text{т})}_{ij}, \qquad \varepsilon^{(\text{т})}_{ij} = \alpha^{(\text{т})}_{ij}\left(T - T_0\right), \quad (13)$$

where: $\alpha^{(\text{т})}_{ij}$ – tensor linear thermal expansion; T – solid point temperature; T_0 – initial temperature

The contravariant stress tensor components are represented as:

$$\sigma^{ij} = \sigma^{ij}_{(\text{у})} - \sigma^{ij}_{(\text{т})}, \quad (14)$$

where: $\sigma^{ij}_{(\text{у})}$ – stress tensor components caused by movements of the body; $\sigma^{ij}_{(\text{т})}$ – thermal stresses.

The heat equation can be represented in the form of variations of Lagrange equation when considering the stationary heat conduction problems:

$$\delta W = \int_V \left(w_0\delta T + \lambda^{ij}T_{,i}\delta T_{,j}g^{ij}\right)dv + \int_{S_1} q\delta T ds + \int_{S_2} h\left(T - \theta\right)\delta T ds = 0, \quad (15)$$

where: ρ – density; c – heat capacity; λ^{ij} – thermal conductivity tensor; of w_0 – power internal heat sources; of q – the intensity of the heat flow; h – coefficient of heart transfer; T_0 – ambient temperature.

Temperature field of self-heating of the elastomeric structure is determined by the following algorithm:

1. The problem of thermoelasticity for a given amplitude of oscillation.

To solve highly nonlinear problem using the method of successive approximations [11].

At each iteration, the load increment is made and solved the linearized equation at a given temperature:

$$\left[K^{ij}\right]\left\{u_j\right\}=\left\{P^i\right\}+\left\{Q^i\right\}, \tag{16}$$

where: $[K^{ij}]$ – the global stiffness matrix of the structure; $\{u_j\}$ – generalized displacement vector; $\{P^i\}$ – load vector by the forced displacement of the body surface; $\{Q^i\}$ – thermal load vector.

Then check the condition of equilibrium. If equilibrium conditions are not met, then the residuals are added to the right side of the system. If a satisfactory solution to the iterative process is repeated.

After reaching the start-up parameters (applied force) limit the procedure ends.

2. Calculate the power of internal sources of heat as the averaged fluctuation according to the formula for the cycle:

$$w_0=\frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}}\sigma^{ij}(t)\dot{\varepsilon}_{ij}(t)dt\ , \tag{17}$$

\

where: ω – rate fluctuations.

3. The temperature of self-heating to determine the onset of thermal equilibrium between the structure and the environment by solving stationary problem of heat conduction:

$$[H]\{T\}=-\{R\}, \tag{18}$$

where: $[H]$ – global matrix structure of thermal conductivity; $\{T\}$ – generalized vector of nodal temperatures; $\{R\}$ – equivalent vector heat load.

4. To account for the stress fields and temperature connectivity solutions the process is repeated from step 1. A satisfactory solution is obtained since the first approximation.

As a result of the implementation of the algorithm we obtain the nodal temperature field, the field intensity of the internal sources and thermal stress in the centers of finite elements, which are the source of data for determining the durability.

A mechanical stresses and temperature have greatest influence on the longevity of elastomers. If there are n points with different values of the specific strain energy U_1, U_2, U_3,... U_n and different temperatures T_1, T_2, T_3,... T_n, calculation is made for the longevity of all the n points. In most cases there is no need to calculate for each point of the durability of the structure. The calculation is carried out with respect to a dangerous point, ie, one in which degradation starts first.

Practically dangerous point is determined as follows: two selected points $O_1(U_1, T_1)$ and $O_2(U_2, T_2)$, where at one point U_1=max, а в другой , and the other T_2=max and the calculation is made for these points.

Criteria equation of state under cyclic loading is of the form:

$$\Delta S_T T=$$

$$=\int_0^{t^*}\left[\frac{U\mu\sin^2\omega t}{\eta_0}\exp\left(k_2\omega^2\sin^2\omega t-k_1-div\,q\right)\right]dt\ , \tag{19}$$

where: U – the specific strain energy, T – absolute temperature, η_0 – the initial value of the viscosity coefficient, t – time, ω – loading rate, ΔS_T – critical increment of entropy density.

We introduce the notation:

$$I=\int_0^{t^*}\left[\frac{U\mu\sin^2\omega t}{\eta_0}\exp(k_2\omega^2\sin^2\omega t-k_1)-divq\right]dt\ . \tag{20}$$

where: the unknown is the upper limit of integration – the required durability.

To solve the equation (Eq. 7) perform numerical integration using the trapezoid rule:

$$f\left(t^*\right)=\frac{U\mu\sin^2\omega t}{\eta_0}\exp\left(k_2\omega^2\sin^2\omega t-k_1-div\,q\right), \tag{21}$$

where: the unknown is the upper limit of integration – the required durability.

I represent as a function of time:

$$f\left(t^*\right)=\frac{U\mu\sin^2\omega t}{\eta_0}\exp\left(k_2\omega^2\sin^2\omega t-k_1-div\,q\right), \tag{22}$$

and transforming the (Eq. 7) with (Eq. 22) we obtain the following equation:

$$f(t^*)-\Delta S_T T=0\ . \tag{23}$$

Solving nonlinear equation (Eq 23), using the bisection method define longevity – t^*.

The critical level of entropy can be found by the empirical formula:

$$\Delta S_T=a\cdot\exp[b(T_H-T_0)]\ , \tag{24}$$

where: a and b – constant coefficients, $T_н$ = 293K, T_0 – design temperature.

For the true time to failure is necessary to multiply the resulting longevity – t^* by a factor of time-temperature shift – a_T determined by the following formula:

$$\lg a_T=-\frac{c_1(T_0-T)}{c_2+T_0-T}\ , \tag{25}$$

where: c_1 = 12, c_2 = 101,6 K.

The parameters c_1, c_2 are determined from a creep experiment at different temperatures for rubber [14].

On the basis of the considered method calculated the cylindrical shock absorbers. Elements with a complex shape of the free surface VR is a constructive development of hollow cylinders. In order to improve the stability of the last developed a series of parametric vibration isolators [6, 19].

Consider the problem of cyclic deformation at a predetermined frequency and amplitude shock VR -201 and VR-103 (Table 1).

Table 1. Rubber isolators type VR

Type isolator	Nominal dimensions	
	outside diameter, $D_н$, mm	height h, mm
VR -201	100	80
VR -103	120	148

Shock absorbers are made of rubber stamps 1562. The elastic constants and parameters of relaxation: μ=0.51 MPa, ν=0.4999, ω=68s^{-1}, λ=0,15 Wт/(m·K), α= – 0.6, β=0.914, χ=0,35. On the surfaces of the shock absorber heat exchange occurs with metal fittings and air, respectively, with the coefficients H_1=H_2=40m^{-1} and H_3=5240m^{-1}

To determine the stress-strain state and stiffness parameters of elements with complex free form surfaces accurate analytical methods are not applicable because of the insurmountable difficulties at present in the solution of nonlinear systems of differential equations in partial derivatives for solving boundary value problems thermoviscoelasticity. Numerical methods are used, the main of which is the finite element method (FEM) [17, 23]. The specific formulation Thermoviscoelasticity problems with its use are given in [7, 13]. The results of calculation of stress-strain state can determine the stiffness in compression elements VR type (Fig. 2).

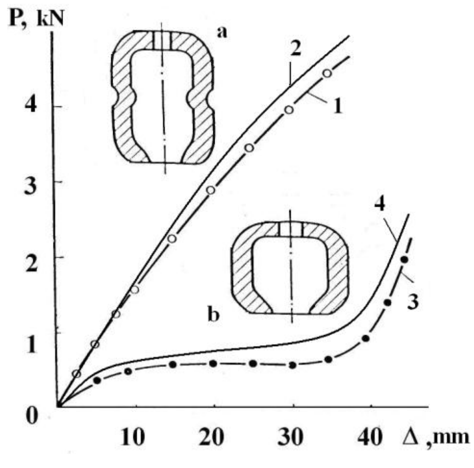

Fig. 2. Force versus displacement for the rubber elements: a – VR103: 1 – experimental data [6]; 2 – numerical solution, b – VR201: 3 – experimental data [6]; 4 – numerical solution

The algorithm of numerical solution of heat conduction problem for elements with complex shapes such as the free surface of BP based on the decision [3], using as the main method - the finite element method in combination with the method of stepwise integration.

Experimental distribution of temperature fields [3, 7] and the results of calculations performed by the field of temperatures for the elements VR are shown in Fig. 3.

Field distribution study dissipative heating temperature in the shock absorbers shows that the maximum values are set in the central regions

Assessment of the longevity of the local rubber vibration isolators such as VR is manufactured in accordance with the general calculation algorithm, using the criterion of entropy dissipative type [6]. According to [16], the time to failure of any local volume rubber array t* is determined by expression (Eq. 20).

The longevity of the rubber components such as VR can be determined in points with a maximum temperature of dissipative heating, pre-calculated in the same points value of the dissipation function.

In Table 2 the values of the durability of vibration isolators such as BP, taking into account the maximum values set the temperature $T^*_{\max}$ at load operation: a_0 = 0,003 m; ω = 94 s^{-1} [6] are presented.

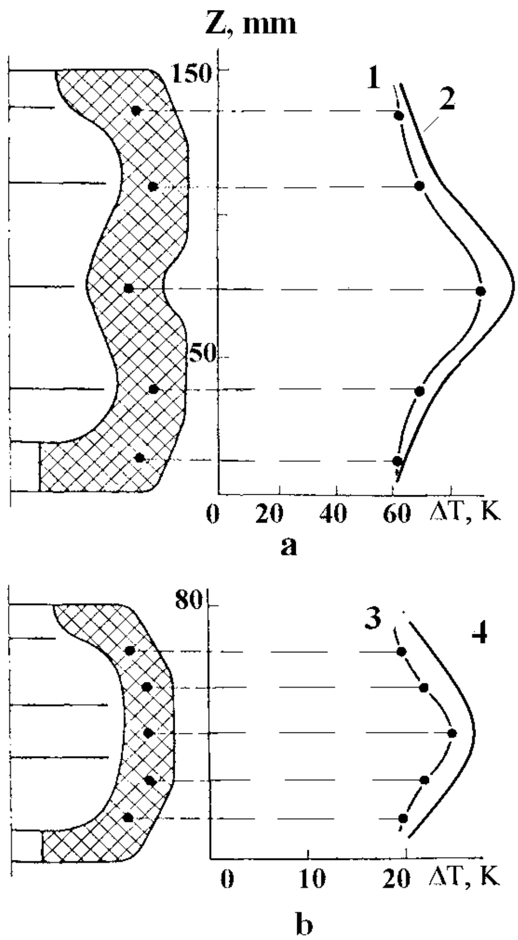

Fig. 3. Distribution of temperature fields in the elements at the frequency of oscillation 13.3Gts:

a – the amplitude A = 10mm: 1 - experimental data [16]; 2 - numerical solution, b – amplituda A = 10mm: 3 - experimental data [6]; 4 - numerical solution.

Table 2. The values of *t** vibration isolators such as VR, taking into account temperature

Type VR	$T^*_{\max}$,°C	t^*, h
VR-201 [6]	29,035	19722
VR -201	33.651	19102
VR -103 [6]	68.211	17415
VR -103	71.322	16987

Analysis of the results shows that the proposed method allows the solution, satisfactory agreement with the experimental data obtained by other authors.

CONCLUSIONS

1. A method for solving the problem of thermoelastic cyclic deformation geometrically and physically nonlinear elastomers, based on the method of successive approximations.
2. Significant dissipation of deformation energy causes a significant self-heating elastomeric designs.
3. On the basis of the entropy criterion analyzed durability elastomeric structures.

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РАСЧЕТ ДОЛГОВЕЧНОСТИ ЭЛАСТОМЕРНЫХ ЭЛЕЕНТОВ КОНСТРУКЦИЙ

Ю. Козуб, Г. Козуб

Аннотация. Представлена математическая модель процесса термоупругого деформирования и диссипативного разогрева эластомерных элементов конструкций. Предложена методика прогнозирования долговечности конструкций, основанная нп применения энтропийного критерия разрушения. Для решения связанной задачи термоупругости используется метод последовательных приближений.

Ключевые слова: эластомер, термоупругость, долговечность, критерий разрушения.