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Key words: *material creep, radiation exposure, diffusion processes, neutron irradiation, integral value*

doi:10.5937/jaes0-28088

Cite article:

Vakhneev, S., & Starovoitov, E. [2020]. Damping of circular composite viscoelastic plate vibration under neutron irradiation. *Journal of Applied Engineering Science*, 18(4), 699 - 704.

Online aceess *of full paper is available at: www.engineeringscience.rs/browse-issues*

Istraživanja i projektovanja za privredu
Journal of Applied Engineering Science

Original Scientific Paper

doi:10.5937/jaes0-28088

Paper number: 18(2020)4, 748, 699-704

DAMPING OF CIRCULAR COMPOSITE VISCOELASTIC PLATE VIBRATION UNDER NEUTRON IRRADIATION

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During the irradiation of structural elements with neutrons, ions, electrons, the mechanical properties of materials change. The neutron irradiation is of particular interest. Therefore, the relevance of the study is beyond doubt. The main purpose of this paper is to investigate the vibration damping of a circular composite viscoelastic plate under neutron irradiation. According to existing concepts, two mechanisms of accelerated radiation creep are possible. An initial-boundary value problem of free vibrations damping in a circular linearly viscoelastic sandwich plate under neutron irradiation is considered. It is determined that when the frequency of the perturbing force coincides with higher frequencies of natural oscillations, the periodicity is blurred, although the amplitude of oscillations increases and, in this case, a "false resonance" is observed. An analytical solution is obtained using the averaging method in dynamic viscoelasticity problems. The logarithmic decrement of oscillations is investigated numerically. Its dependence on the intensity of the neutron flux is revealed.

Key words: material creep, radiation exposure, diffusion processes, neutron irradiation, integral value

INTRODUCTION

Three-layer structural elements are used in aerospace and transport engineering, construction, production, and transportation of hydrocarbons. This required the development of appropriate mechanical and mathematical models of quasi-static and dynamic deformation under external force effects of various nature. As a result, a whole direction appeared in the mechanics of a deformable solid, associated with the calculation of the stress-strain state of layered plates, rods, and shells. Recently, attention to the issue of the complex effects of sandwich structural elements in thermal and radiation fields has increased [1]. The problems of strength, stability, dynamic behaviour are considered.

In papers [2-4] transverse vibrations of circular sandwich plates are considered. The kinematic hypotheses for the sandwich plates are accepted in accordance with the broken line hypothesis. In the bearing layers, Kirchhoff's hypotheses are valid, in a light, relatively thick core, Timoshenko's hypothesis about the straightness and incompressibility of the deformed normal is fulfilled. The equations of motion are obtained by variational methods; their solution is constructed in the form of a series expansion in systems of orthonormal eigenfunctions. The natural frequencies were investigated with a rigid termination and with hinged support of the plate contour. Resonance effects arising from the action of an external harmonic load, the frequency of which coincides with one of the natural frequencies of the plate vibrations, were studied in [5-7]. The possibility of occurrence of false resonances is indicated when the load frequency coincides with one of the natural frequencies, but there is no increase in the vibration amplitude [8]. Problems of free vibrations, variable loading, and unsteady vibrations of circular and parabolic cylindrical shells are considered in [9-11]. Deformation of three-layer rods in heat and neutron fluxes was investigated in [12, 13]. The effects of the appearance of additional volumetric deformation and the influence of temperature and integral neutron flux on the mechanical properties of materials are taken into account [14]. Papers [15-17] are devoted to the construction of computational models of complex structure bodies under non-stationary influences and mass transfer. The mechanical properties of steel and composite plates under various impacts, including laser, are described in [18-20].

Irradiation of structural elements with neutrons, ions, electrons changes the mechanical properties of materials: hardness, yield strength, plasticity, creep [21]. Neutron irradiation is of particular interest. According to experimental data, the increase in the integral value of the neutron flux (Eq. 1):

$$I = \varphi t \tag{1}$$

(φ – flux level, t – time) within the limits of small deformations, as a rule, leads to an increase in the radiation hardening of the material and an increase in the yield stress. The effect of radiation on the elasticity constants – Young’s modulus, Poisson’s ratio, etc. is insignificant (no more than 1-2%) and will not be taken into account in the future. The first information on the effect of irradiation on creep was obtained when testing uranium in a reactor. The increasing number of point defects under irradiation contributes to the acceleration of the creep of uranium by a factor of 50-100, despite the fact that radiation hardening of the material leads to a decrease in the velocity of dislocation movement. Information on the creep of non-fissile materials is extremely limited. This is due to the difficulties in carrying out experiments to

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measure very small deformations under irradiation conditions in a reactor. Along with the phenomenon of accelerated creep under irradiation, accelerated relaxation of stresses is also observed in both fissile and non-fissile materials [22-24]. So, the aim of the article is to explore the vibration damping of a circular composite viscoelastic plate under neutron irradiation.

ANALYSIS OF NEUTRON IRRADIATION EFFECT ON THE VISCOUS PROPERTIES OF THE MATERIAL

According to existing concepts, two dynamics of accelerated radiation creep are possible. The first dynamic is directly caused by an increase in the concentration of crystal lattice defects, as a result of which diffusion processes are accelerated, in particular, the process of climb of dislocations, since it is known that dislocations are sinks for excess point radiation defects. Another process is associated with the radiation growth of crystals that make up a polycrystalline body. Moreover, the change in the linear dimensions of crystals can be tens of percent. To take into account the effect of neutron irradiation on the viscous properties of the material, we take the relaxation kernel in the (Eq. 2):

$$R_{\phi}(t,\phi) = g(\phi)R(t) \tag{2}$$

where $R(t)$ – relaxation kernel of unirradiated material.

If the intensity of the neutron flux does not change with time, then the value of the function $g(\varphi)$ is constant and in the physical relations of viscoelasticity it can be taken outside the integral sign (Eq. 3):

$$s_{ij} = 2G\left(э_{ij} - g(\phi)\int_0^t R(t-\tau)э_{ij}(\tau)d\tau\right) \tag{3}$$

In the presence of creep curves (Fig. 1) [1], using expression (3), one can obtain a formula for calculating the values of the function $g(\varphi)$ (Eq. 4):

$$g(\phi) = \frac{э_{12}^{(2)} - s_{12}/2G}{э_{12}^{(1)} - s_{12}/2G} = \frac{э_{12}^{(2)} - \varepsilon_{12}(0)}{э_{12}^{(1)} - \varepsilon_{12}(0)} \tag{4}$$

Here the index at the top – curve number, $\varepsilon_{12}(0)$ – instantaneous strain value.

In this case, the obtained value $g(\varphi_0)$ = 1.18, is quite satisfactory corresponding to the experimental data. Consider a circular sandwich plate asymmetric in thickness, the materials of the layers of which in the process of deformation exhibit hereditary linear viscoelastic properties. The coordinate system r, φ, z is associated with the median plane of the core. Carrying layer thicknesses $h_1 \neq h_2$, in lightweight core $h_3 = 2c$.

To describe the kinematics of the plate pack, the hypotheses of the broken normal are accepted: in the bearing layers, the Kirchhoff hypotheses are valid, in the core the normal remains rectilinear, does not change its length, but rotates by some additional angle $\Psi(r, t)$ – shift in the core. perpendicular to the plate, an external perturbing distributed load $q(r, t)$ acts on the outer layer. The plate deflection $w(r, t)$ of the plate and the radial displacement $u(r, t)$ of the median plane of the core close the system of

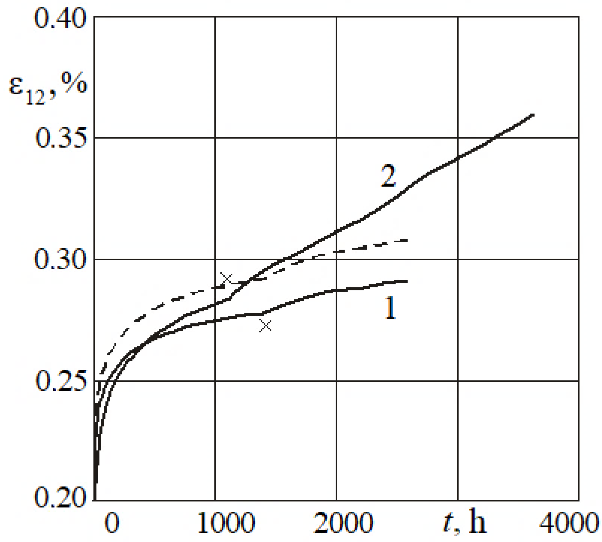

Figure 1: Creep curves of zirconium alloy: solid line – experiment, dotted line – calculation; 1 – not irradiated alloy; 2 – irradiated with a neutron flux of intensity $\varphi_0 = 5 \cdot 10^{16}$ neutron/($m^2 \cdot s$)

the sought functions. The movement occurs in a neutron flux with an intensity φ = const.

It should be noted that vibrations of elastic sandwich plates were considered earlier in [2-7]. Papers [8-10] are devoted to the study of their fluctuations in the heat flow. In [11], a thermo-radiation impact on a sandwich plate was investigated. The equations of a linearly viscoelastic plate vibrations can be formally obtained from the equations of motion of the corresponding elastic plate [3], replacing the elastic parameters G_k with the operators of viscoelasticity (Eqs. 5-6):

$$G_k^* \equiv G_k(1 - R_k^*) \tag{5}$$

$$G_k^* f(t) \equiv G_k\left(f(t) - \int_0^t R_k(t-\tau)f(\tau)d\tau\right) \tag{6}$$

where G_k* – operator of linear viscoelasticity; G_k – shear modulus of elasticity in shear, $R_k(t)$ – relaxation kernels of the materials of the plate layers; $f(t)$ – some function of time.

In this case, in the coefficients a_m*, containing the integral operators $G_k^* \equiv G_k(1-R_k^*)$, formally in the relaxation kernel, it is necessary to introduce the dependence on the neutron flux intensity (Eq. 7):

$$G_k^* f(t) \equiv G_k\big(f(t) - g(\phi)\int R_k(t-\tau)f(\tau)d\tau\big) \tag{7}$$

As a result, we obtain the following system of equations for transverse vibrations of a three-layer viscoelastic plate with a light core (Eqs. 8-10):

$$L_2(a_1^* u + a_2^* \psi - a_3^* w,_r) = 0, \tag{8}$$

$$L_2(a_2^* u + a_4^* \psi - a_5^* w,_r) = 0, \tag{9}$$

$$L_3(a_3^* u + a_5^* \psi - a_6^* w,_r) - M_0 \ddot{w} = -q \tag{10}$$

The following operators are introduced here (Eqs. 11-20):

$$a_1^* = \sum_{k=1}^{3} h_k K_k^+ \tag{11}$$

$$a_2^* = c(h_1 K_1^+ - h_2 K_2^+) \tag{12}$$

$$a_3^* = h_1\left(c+\frac{h_1}{2}\right)K_1^+ - h_2\left(c+\frac{h_2}{2}\right)K_2^+ \tag{13}$$

$$a_4^* = c^2\left(h_1K_1^+ + h_2K_2^+ + \frac{2}{3}cK_3^+\right) \tag{14}$$

$$a_5^* = c\left[h_1\left(c+\frac{h_1}{2}\right)K_1^+ + h_2\left(c+\frac{h_2}{2}\right)K_2^+ + \frac{2}{3}c^2K_3^+\right] \tag{15}$$

$$a_6^* = h_1\left(c^2+ch_1+\frac{h_1^2}{3}\right)K_1^+ + h_2\left(c^2+ch_2+\frac{h_2^2}{3}\right)K_2^+ + \frac{2}{3}c^3K_3^+ \tag{16}$$

$$K_k + \frac{4}{3}G_k^* \equiv K_k^+,\ K_k - \frac{2}{3}G_k^* \equiv K_k^- \tag{17}$$

$$K_k + \frac{4}{3}G_k^* \equiv K_k^+,\ K_k - \frac{2}{3}G_k^* \equiv K_k^- \tag{18}$$

$$L_2(g) \equiv \left(\frac{1}{r}(rg)_{,r}\right)_{,r} \equiv g_{,rr} + \frac{g_{,r}}{r} - \frac{g}{r^2} \tag{19}$$

$$L_3(g) \equiv \frac{1}{r}(rL_2(g))_{,r} \equiv g_{,rrr} + \frac{2g_{,rr}}{r} - \frac{g_{,r}}{r^2} + \frac{g}{r^3} \tag{20}$$

A comma in the subscript indicates the operation of differentiation by the coordinate following it, the two points at the top – the second time derivative (Eq. 21):

$$M_0 = \sum_{k=1}^{3} \rho_k h_k r_0 \tag{21}$$

where ρ_k – density of the k-th layer material; h_k – material density and thickness of the k-th layer (k = 1, 2, 3), r_0 – radius of the plate.

Let us assume that the relaxation kernels are similar and are expressed through the relaxation kernel of the core (Eqs. 22-23):

$$R_k(\varphi, t) = l_k R_3(\varphi, t) \tag{22}$$

$$l_k = \frac{g_k(\phi)R_k(t)}{g_3(\phi)R_3(t)} \tag{23}$$

In what follows, it is assumed concerning the kernel $R_3(t)$ that it is proportional to some small positive parameter, i.e., it satisfies the condition (Eq. 24):

$$0 \le \int_0^t R_3(\tau)d\tau << 1,\ R_3(\tau) \ge 0 \tag{24}$$

The distributed load $q(r, t)$ is considered small and is represented as a series expansion in terms of the fundamental orthonormal system of eigenfunctions v_n, constructed by solving the corresponding problem of the theory of elasticity [2] (Eqs. 25-26):

$$q(r,t) = \varepsilon_1 M_0 \sum_{n=0}^{\infty} v_n q_n(t) \tag{25}$$

$$v_n \equiv \frac{1}{d_n}\left[J_0(\beta_n r) - \frac{J_0(\beta_n)}{I_0(\beta_n)}I_0(\beta_n r)\right] \tag{26}$$

where v_n – fundamental orthonormal system of eigenfunctions obtained by solving the problem of elasticity theory for the considered plate [2], d_n – normalisation factor; J_0, I_0 – zero-order Bessel and Macdonald functions; β_n – eigenvalues; ε_1 – small parameter.

In the operators of linear viscoelasticity a_m* (m = 1, …, 6), given in (7), we select the relaxation kernel of the core (Eq. 27):

$$a_m^* = a_m - a_m^{'}R_3^*,\ a_m,\ a_m^{'} \tag{27}$$

The solution (plate deflection) of the corresponding system of integro-differential equations (8-10) is supposed to be sought in the (Eqs. 28-30):

$$\psi(r,t) = \sum_{n=0}^{\infty} (b_1 v_{n,r} + C_1 r + C_2/r)\ T_n(t) \tag{28}$$

$$u(r,t) = \sum_{n=0}^{\infty} (b_2 v_{n,r} + C_3 r + C_4/r)\ T_n(t) \tag{29}$$

$$w(r,t) = \sum_{n=0}^{\infty} v_n T_n(t) \tag{30}$$

Integration constants C_1, C_2, C_3, C_4 appear after double integration over the radial coordinate of each of the first two equations of the system (11-20). In what follows, we should assume C_2 = C_4 = 0, based on the smoothness condition at the origin solution. Substitution of expressions (11-30) into the third equation of system (11-20) leads to the following equation for the unknown function $T_n(t)$ (Table 1) (Eq. 31):

$$\begin{aligned} &L_3(a_3(b_1v_{n,r} + C_1 r) + a_5(b_1 v_{n,r} + C_3 r)T_n - \\ &- M_0 v_n \ddot{T}_n =- \varepsilon_1 M_1 v_n q_n + L_3(a_3^{'}(b_1 v_{n,r} + C_1 r) + \\ &+ a_5^{'}(b_2 v_{n,r} + C_3 r) - - a_6^{'} v_{n,r})R_3^* T_n \end{aligned} \tag{31}$$

where (Eqs. 32-34):

$$R_3^* T_n \equiv \int_0^t R_3(t-\tau)T_n(\tau)d\tau \tag{32}$$

$$b_1 = \frac{a_3a_4 - a_2a_5}{a_1a_4 - a_2^2} \tag{33}$$

$$b_2 = \frac{a_1a_5 - a_2a_3}{a_1a_4 - a_2^2} \tag{34}$$

Since the functions v_n are proper for the operator L_3, the relation (Eqs. 35-36), where ω_n – natural vibration frequencies determined through the eigenvalues β_n [2].

$$\begin{aligned} &L_3(a_3(b_1 v_{n,r} + C_1 r) + a_5(b_1 v_{n,r} + C_3 r) - a_6 v_{n,r}) = \\ &=- M_0 \omega_n^2 v_n \end{aligned} \tag{35}$$

$$\omega_n^2 = \frac{\beta_n^4}{M^4} \tag{36}$$

Table 1: Eigenvalues for the clamped plate

Number n	Eigenvalue β_n	Number n	Eigenvalue β_n
0	3.196	8	28.279
1	6.306	9	31.420
2	9.439	10	34.561
3	12.577	11	37.702
4	15.716	12	40.844
5	18.856	13	43.985
6	21.997	14	47.126
7	25.138		

By analogy, the operator on the right-hand side of (31), can be written as (Eq. 37):

$$\begin{aligned} &L_3(a_3^{'}(b_1 v_{n,r} + C_1 r) + a_5^{'}(b_1 v_{n,r} + C_3 r) - a_6^{'} v_{n,r}) = \\ &=- M_0 \omega_n^{'2} v_n \end{aligned} \tag{37}$$

where quantities of the frequency type ω'_n are determined through the generalised eigenvalues β'_n by similar (Eq. 38):

$$\omega_n^{'2} = \frac{(a_1^{'}a_6^{'} - a_3^{'2})(a_1^{'}a_4^{'} - a_2^{'2}) - (a_1^{'}a_5^{'} - a_2^{'}a_3^{'})^2}{a_1^{'}(a_1^{'}a_4^{'} - a_2^{'2})M_0}\beta'^4 \tag{38}$$

SOLUTION OF THE DYNAMIC VISCOELASTICITY PROBLEM

The values β'_n, as well as the eigenvalues β_n, follow from the transcendental algebraic equations obtained when the boundary conditions [2] are satisfied if the parameters am are replaced by a'_m. It should be noted that when sealing the edge of the plate $\beta'_n = \beta_n$. To solve equation (31), we apply the averaging method proposed in [3] for dynamic problems of viscoelasticity. In this case, it is assumed that the last term of the equation contains a small parameter ε, which should be set equal to unity in the final results since the smallness of the integral terms is ensured by condition (24). Therefore, in the following $R_3(t)$ is replaced by $\varepsilon R_3(t)$. As a result, for the function $T_n(t)$ form (31) we obtain the (Eqs. 39-40):

$$\ddot{T}_n + \omega_n^2 T_n = \varepsilon_1 q_n + \varepsilon \omega_n k_n \int_0^t R_3(t-\tau) T_n(\tau) d\tau \quad (39)$$

$$k_n = \omega_n^{'}/\omega_n \quad (40)$$

Equations of this type have been studied for the case of small forces (25). As applied to our problem, we have (Eq. 41):

$$T_n = \left[A_n \cos \omega_n \left(1+\frac{1}{2}R_{cn}\right)t + B_n \sin \omega_n \left(1+\frac{1}{2}R_{cn}\right)t\right] \times \times \exp\left(-\frac{1}{2}\omega_n R_{sn} t\right) + \frac{2}{\omega_n}\sqrt{\frac{q_{1n}^2+q_{2n}^2}{R_{cn}^2+R_{sn}^2}} \cos(\omega_n t + \phi_1 - \phi_2) \quad (41)$$

Here R_{cn}, R_{sn} – cosine and sine Fourier images of the relaxation kernel $k_n g_3(\Phi) R_3(t)$ (Eqs. 42-46):

$$R_{cn} = k_n g_3(\phi) \int_0^\infty R_3(\tau) \cos(\omega_n \tau) d\tau \quad (42)$$

$$R_{sn} = k_n g_3(\phi) \int_0^\infty R_3(\tau) \sin(\omega_n \tau) d\tau \quad (43)$$

$$q_{1n} = \frac{1}{\omega_n} \lim_{T\to\infty} \frac{1}{T} \int_0^T q_n(t) \sin(\omega_n t)\, dt \quad (44)$$

$$q_{2n} = \frac{1}{\omega_n} \lim_{T\to\infty} \frac{1}{T} \int_0^T q_n(t) \cos(\omega_n t)\, dt \quad (45)$$

$$\phi_1 = arctg\frac{R_{sn}}{R_{cn}};\ \phi_2 = arctg\frac{q_{1n}}{q_{2n}} \quad (46)$$

The constants of integration A_n, B_n are determined from the initial conditions of the plate motion (Eqs. 47-48):

$$A_n = \int_0^1 w(r,0) v_n r dr - \frac{2}{\omega_n}\sqrt{\frac{q_{1n}^2+q_{2n}^2}{R_{cn}^2+R_{sn}^2}} \cos(\phi_1 - \phi_2) \quad (47)$$

$$B_n = \frac{1}{\omega_n\left(1+\frac{1}{2}R_{cn}\right)}\left[\frac{\omega_n R_{sn}}{2} A_n + 2\sqrt{\frac{q_{1n}^2+q_{2n}^2}{R_{cn}^2+R_{sn}^2}} \sin(\phi_1 - \phi_2) + + \int_0^1 \dot{w}(r,0) v_n r dr\right] \quad (48)$$

Thus, the transverse vibrations of a circular sandwich plate, the layers of which have linear viscoelastic properties, are described by expressions (23-25) taking into account (26-43) and the fact that (Eqs. 49-50):

$$v_{n,r} = -\frac{\beta_n}{d_n}\left[J_1(\beta_n r) - \frac{J_0(\beta_n)}{I_0(\beta_n)} I_1(\beta_n r)\right] \quad (49)$$

$$\{C_1, C_3\} = \{b_1, b_2\}\frac{\beta_n}{d_n}\left[J_1(\beta_n) - \frac{J_0(\beta_n)}{I_0(\beta_n)} I_1(\beta_n)\right] \quad (50)$$

Numerical results were obtained for a plate clamped along the contour, the layers of which are made of composite materials D16T-fluoroplastic-D16T. The necessary natural vibration frequencies ω_n were calculated using the eigenvalues from the table and the layer parameters $h_1 = h_2 = 0.01$, $c = 0.05$. When summing up the series (28-30), we were limited to the first six terms, since the subsequent ones (up to 100) add a total correction of less than 0.1%. The required parameters of elasticity of materials and material functions are taken from [12-14].

Figure 2 shows the increase in the vibration amplitude (deflection in the centre of the plate) with time at the frequency of the external load ω_k, which coincides with the first and second frequencies of natural vibrations (Eqs. 51-52):

$$(a) - \omega_k = \omega_0 \quad (51)$$

$$(b) - \omega_k = \omega_1 \quad (52)$$

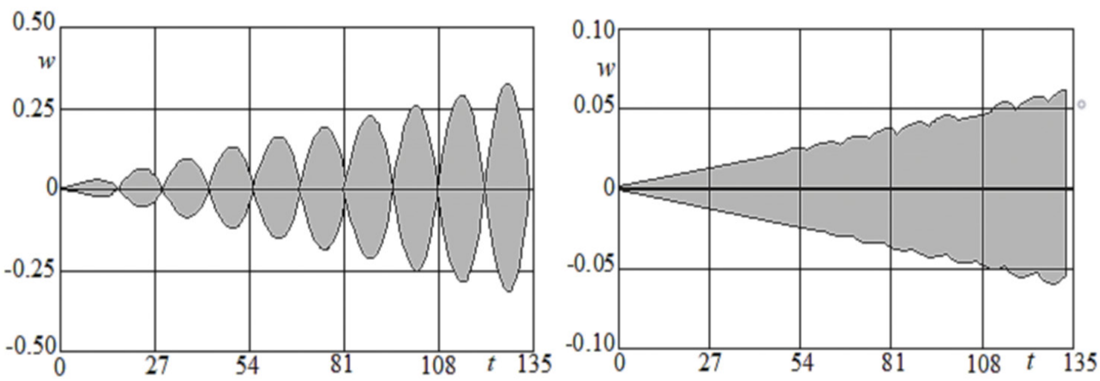

Figure 2: Change in the amplitude of oscillations in time at resonance

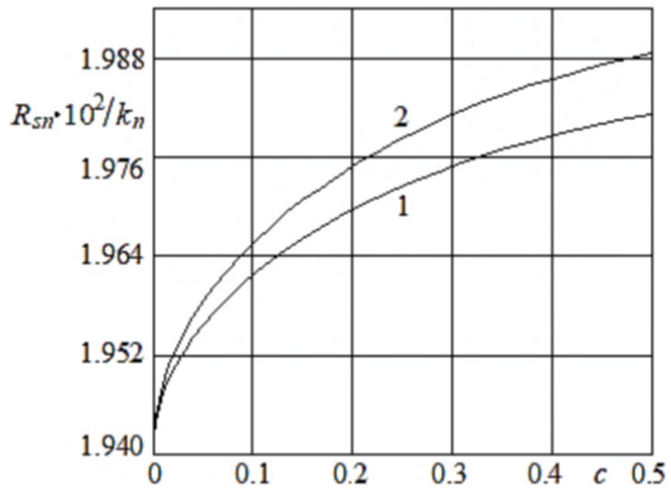

Figure 3: Logarithmic decrement of oscillations:
1 – before irradiation of the plate with neutrons,
2 – after irradiation

The amplitude of the surface load intensity acting on the entire surface of the plate, q_0 = 50. The number of oscillations in the indicated time interval is very large, therefore the process in the figures is graphically indistinguishable.

In the first of these figures, the periodicity of oscillations with a frequency close to ω_0 is preserved. However, when the frequency of the perturbing force coincides with higher frequencies of natural oscillations, the periodicity is blurred, although the amplitude of oscillations increases. The so-called “false resonance” is observed. Moreover, the higher the natural frequency coincides with the resonant frequency, the lower the rate of increase in the deflection over the accepted time interval. In the above case, the maximum deflection at the frequency $\omega_k = \omega_1$ is approximately six times less than at $\omega_k = \omega_0$.

The logarithmic decrement of oscillations R_{sn}, which characterises the damping ability of the sandwich plate materials, was also investigated numerically (Fig. 3). Duralumin was taken as the material of the bearing layers, the core was fluoroplastic. The corresponding mechanical and rheonomic characteristics are given in [2].

CONCLUSIONS

The use of hereditary physical equations of state makes it possible to properly describe the creep during the deformation of the materials of the rod layers. The effect of the neutron flux leads to the acceleration of the creep of the viscoelastic materials of the layers. An analytical solution to the initial-boundary value problem of viscoelasticity for circular sandwich plates is constructed according to the well-known solution to the problem of the theory of elasticity, taking into account the creep of the materials of the layers and the effect of radiation exposure. The system of orthonormal eigenfunctions is constructed for two types of boundary conditions: rigid fixing and free support of the plate contour. It is shown that the logarithmic decrement increases nonlinearly with increasing core thickness. If we assume $g(\varphi)$ = 1.18, then the logarithmic decrement of oscillations, which characterises the damping capacity of a sandwich plate in neutron flux, increases by an average of 20%. This allows us to conclude that the neutron irradiation accelerates the oscillation damping.

Thus, the proposed formulation of the boundary value problem, the considered solution methods, the obtained analytical and numerical results allow us to study the stress-strain state during vibrations of viscoelastic sandwich plates in neutron flux, in the case of carrying out the corresponding exact engineering calculations.

ACKNOWLEDGEMENTS

The work was carried out with the financial support of the RFBR grant 19-01-00675.

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Paper submitted: 21.08.2020.
Paper accepted: 20.10.2020.