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## Forced harmonic vibrations in a viscoelastic layered bodies lying deformable half-plane

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### Abstract

We consider vibrations of a mechanical system consisting of viscoelastic layers lying on the half-plane and being in plane strain under the influence of vertical harmonic load. Required to find the vertical and horizontal movement and tension layers and half-points. The dynamic state of each of the laminated body, and half by the equations of Lamé continuum mechanics with operator coefficients. The problem is reduced to solving a system of non-homogeneous algebraic equations with complex coefficients, which is solved by Gauss. The change in amplitude displacements and stresses as a function of frequency. In studies of the dynamic stress - strain state introduced the concept of global resonance amplitude (providing the minimum value of the resonant amplitude), which changes radically to nonuniform mechanical systems.

**Keywords:** Oscillations, dissipative heterogeneous system, half space, viscoelastic, body movement frequency and voltage

### Introduction

The dynamics of structures under the influence of the stress cycle of the mechanical energy is absorbed as a result of dissipation mechanism in the material. Therefore, you must take into account the effect of the viscoelastic material. Many materials, such as materials used in road construction on the basis of bitumen, cohesive soils, materials or modern himii-termoplast have distinct viscoelastic properties. Because of the explicit actions viscoelastic materials or designs become actual problems viscoelastic layered foundation vibrations. For the first time a systematic approach to the study of an arbitrary number of layers has been proposed V. Tomsonom<sup>[1]</sup> and N. Haskellom<sup>[2]</sup>. Further development of this theory is presented in L. A. Molotkova<sup>[3]</sup>, I. Dankina<sup>[4]</sup>, II Safarova, V. P. Mayboroda, IE Troyanovskiy *et al.*<sup>[6-11]</sup>. In<sup>[14, 15]</sup> proposed decision of axially symmetric problem of propagation of stress waves in a layer at the half. It is assumed viscoelastic behavior of the layer materials and half according to the concept of complex elastic moduli. The source of voltage harmonic waves is focused normal stress on the surface of the layer.

### Formulation of the problem

Consider a system consisting of a viscoelastic layers lying on the half-plane, and being in plane strain under the action of a vertical load  $p(x, t)$  (Figure 1). Required to find the vertical  $\mathcal{G}_\kappa(x, z, t)$  and horizontal  $u_\kappa(x, z, t)$  move layer pixels and half-plane ( $\kappa = 1, 2, 3 \dots n$ ). Thus to the viscoelastic medium is characterized by Lamé operator modules<sup>[12]</sup>:

$$\tilde{E}_\kappa f(t) = E_{0\kappa} \left[ f(t) - \int_{-\infty}^t R_{E\kappa}(t - \tau) f(\tau) d\tau \right].$$

Here  $f(t)$  – arbitrary function of time;  $R_{E\kappa}(t - \tau)$  – core relaxations,  $E_{0\kappa}$  – Young's module of elasticity instant ( $\kappa = 1 \dots N$ ), if  $R_{E\kappa}(t - \tau) = 0$ , then layered - homogeneous elastic

medium is characterized by constant Lamé  $\lambda_\kappa, \mu_\kappa$ , density  $\rho_\kappa$ , velocities of longitudinal and transverse waves

$$c_{p\kappa} = \left(\frac{\lambda_\kappa + 2\mu_\kappa}{\rho_\kappa}\right)^{1/2}, \quad c_{s\kappa} = \left(\frac{\mu_\kappa}{\rho_\kappa}\right)^{1/2} \quad [13].$$

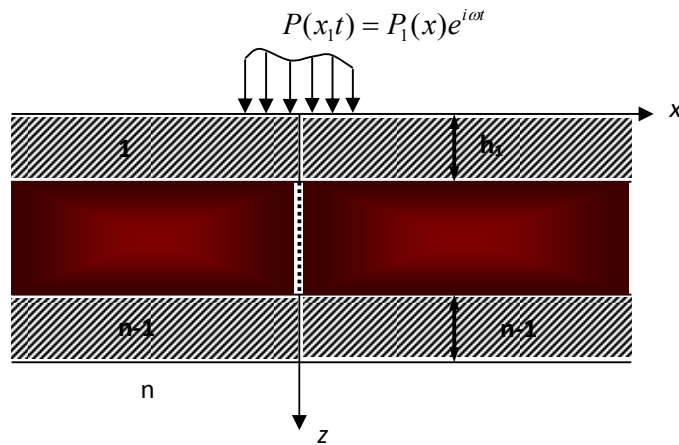


Fig 1: Design scheme

The equations of motion for the second medium can be written as

$$\begin{aligned} \rho_\kappa \frac{\partial^2 u_\kappa}{\partial t^2} &= \frac{\partial \sigma_{11}^{(\kappa)}}{\partial x} + \frac{\partial \sigma_{13}^{(\kappa)}}{\partial z}; \\ \rho_\kappa \frac{\partial^2 g_\kappa}{\partial t^2} &= \frac{\partial \sigma_{33}^{(\kappa)}}{\partial z} + \frac{\partial \sigma_{13}^{(\kappa)}}{\partial x}. \end{aligned} \quad (\kappa = 1, 2, 3, \dots, N) \quad (1)$$

Where  $\rho_\kappa$  - material density,  $\sigma_{ij}^k$  - components of the stress tensor

$$\begin{aligned} \sigma_{11}^{(\kappa)} &= E_{1\kappa} \left( \frac{\partial u_\kappa}{\partial x} + \nu_\kappa \frac{\partial g_\kappa}{\partial z} \right); \\ \sigma_{22}^{(\kappa)} &= E_{1\kappa} \left( \frac{\partial g_\kappa}{\partial z} + \nu_\kappa \frac{\partial u_\kappa}{\partial x} \right), \\ \sigma_{12}^{(\kappa)} &= G_\kappa \left( \frac{\partial u_\kappa}{\partial z} + \frac{\partial g_\kappa}{\partial x} \right). \end{aligned} \quad (2)$$

$$E_{1\kappa} = \frac{\bar{E}_\kappa}{1 - \nu_\kappa^2}, \quad G_\kappa = \frac{\bar{E}_\kappa}{1 + \nu_\kappa}.$$

Movements  $u_\kappa$  and  $g_\kappa$  satisfy one of the following boundary conditions on the surface of the laminated body:

$$\begin{aligned} \text{I. } & \sigma_{33}^1 = -q_1(x, t), \quad \sigma_{13}^1 = -q_2(x, t) \quad \text{at } z=0; \\ \text{II. } & g_1 = q_1(x, t), \quad \sigma_{13}^1 = -q_2(x, t) \quad \text{at } z=0; \quad (3,a) \\ \text{III. } & g = q_1(x, t), \quad \sigma_{13}^1 = -q_2(x, t) \quad \text{at } z=0. \end{aligned}$$

And zero initial conditions

$$u_k = g_k = \frac{\partial u_k}{\partial t} = \frac{\partial g_k}{\partial t} = 0 \quad \text{at } t=0. \quad (3, \bar{6})$$

In the case of exposure to harmonic loads on the surface of the laminated body and the boundaries between layers of viscoelastic run hard contact conditions, then the boundary conditions take the form:

$$\begin{aligned} \sigma_{33}^1(x, 0, t) &= -p(x)e^{-i\omega t}, \\ \sigma_{13}^1(x, 0, t) &= 0, \\ \dots\dots\dots \\ \sigma_{33}^k(x, h_k, t) &= \sigma_{33}^{k+1}(x, h_k, t), \\ \sigma_{13}^k(x, h_k, t) &= \sigma_{13}^{k+1}(x, h_k, t), \\ u_k(x, h_k, t) &= u_{k+1}(x, h_k, t), \\ g_k(x, h_k, t) &= g_{k+1}(x, h_k, t), \kappa = 1.2.\dots.n. \end{aligned} \quad (4)$$

Determining displacement and stress amplitude versus frequency for different parameters planar layered bodies when exposed harmonic load is the main goal of.

**Methods of solution.** The solution of this equation (1) in the form:

$$\begin{aligned} u_\kappa &= U_\kappa(z) e^{i(\gamma x - \omega t)}; \\ g_\kappa &= V_\kappa(z) e^{i(\gamma x - \omega t)}, \end{aligned} \quad (6),$$

$\omega$  – angular frequency, which is a complex value with spectral problems and the actual value for the forced oscillations;  $U_\kappa(z)$  and  $V_\kappa(z)$  - displacement amplitude;  $\lambda=2\pi/\gamma$  - wave length,  $\gamma$ - wave number. Substituting (6) and (1) with (2), we obtain the following ordinary differential equation:

$$\begin{aligned} L_k \frac{dV_k}{dz} - L_{2k} U_k - G_k \frac{d^2 U_k}{dz^2} &= 0; \\ L_k \frac{dU_k}{dz} - L_{3k} V_k - L_{4k} \frac{d^2 V_k}{dz^2} &= 0. \end{aligned} \quad (7)$$

Where

$$\begin{aligned} L_{1k} &= \left( \frac{\bar{E}_k \nu_k}{1 - \nu_k^2} + G_k \right) i\gamma; \quad L_{2k} = \rho_k \omega^2 - \frac{\bar{E}_k}{1 - \nu_k^2} \gamma^2; \\ L_{3k} &= \rho_k \omega^2 - G_k \gamma^2; \quad L_{4k} = \frac{\bar{E}_k}{1 - \nu_k^2}. \end{aligned}$$

After the introduction of the auxiliary function  $\Phi_\kappa(z)$  relationships

$$U_\kappa = L_{1\kappa} \frac{d}{dz} \Phi_\kappa; \quad V_\kappa = \left[ L_{2\kappa} + G_\kappa \frac{d^2}{dz^2} \right] \Phi_\kappa, \quad (8)$$

we obtain from (8) differential equation of the fourth order

$$\frac{d^4 \Phi_\kappa}{dz^4} + L_{5\kappa} \frac{d^2 \Phi_\kappa}{dz^2} + L_{6\kappa} \Phi_\kappa = 0, \quad (9)$$

$$L_{5\kappa} = -2\gamma^2 + \frac{(3 - \nu_\kappa)\omega^2}{2c_{s\kappa}^2 \Gamma_\kappa};$$

Where

$$L_{6\kappa} = \gamma^2 - \frac{(3 - \nu_\kappa)\omega^2 \gamma^2}{2c_{s\kappa}^2 \Gamma_\kappa} + \frac{\omega^4}{c_{p\kappa}^2 c_{s\kappa}^2 (\Gamma_\kappa)^2};$$

$$\Gamma_{\kappa} = 1 - \Gamma_{\kappa}^C(\omega) - i\Gamma_{\kappa}^S(\omega);$$

$$c_{p\kappa}^2 = (\lambda_{\kappa} + 2\mu_{\kappa}) / \rho_{\kappa}; \quad c_{s\kappa}^2 = \mu_{\kappa} / \rho_{\kappa} -$$

the speed of propagation of longitudinal and transverse waves.

The solution of equations (9) is expressed by the exponential function

$$\Phi_{\kappa}(y) = A_{\kappa}e^{+\alpha_{\kappa}y} + B_{\kappa}e^{-\alpha_{\kappa}y} + C_{\kappa}e^{S_{\kappa}y} + D_{\kappa}e^{-S_{\kappa}y} \quad (10)$$

Where

$$q_{\kappa}^2 = \gamma^2 \left(1 - \frac{c^2}{\bar{c}_{p\kappa}^2}\right); \quad S_{\kappa}^2 = \gamma^2 \left(1 - \frac{c^2}{\bar{c}_{s\kappa}^2}\right),$$

$$\bar{c}_{s\kappa}^2 = c_{s\kappa}^2 \Gamma_{\kappa}, \quad \bar{c}_{p\kappa}^2 = c_{p\kappa}^2 \Gamma_{\kappa},$$

$A_{\kappa}, B_{\kappa}, C_{\kappa}, D_{\kappa}$  - complex arbitrary constants, which are determined from the boundary conditions (4). The arbitrary constants determined from the system of algebraic equations with complex coefficients

$$[C(\omega, c_{s\kappa}, c_{p\kappa}, \Gamma_{\kappa}, h_{\kappa})]\{q\} = \{p\}, \quad (11)$$

where  $[C]$ - square matrix (2k x 2k), which elements consist of exponential functions with complex parameters,  $\{q\}$ - contains unknown, i.e.,  $A_{\kappa}, B_{\kappa}, C_{\kappa}, D_{\kappa}$ ;  $\{p\}$ - it consists of the amplitude of external loads. We define the dependence of the resonance amplitudes  $A_{\eta mj}$  ( $\eta$ -voltage components ( $\sigma_{le}, l, e=1,2,3$ ), and moving  $u_l, m$ - number coordinate, j-number of the resonance frequency) of the parameters of the mechanical system. Depending on the construction of this algorithm includes the construction of the amplitude-frequency characteristics for each component of the displacement and stress amplitude and finding maxima  $A_{\eta mj}$  on each of them. To find the highs and lows Muller method is applicable to the resonance curve [11].

Amplitude - frequency response - a curve described by the equation  $A_{\eta mj} = |A_{\sigma mj}|$ . Her minima and maxima satisfy the equation

$$\frac{\partial A_{\eta mj}(\omega)}{\partial \omega} = 0. \quad (12)$$

It is necessary to find the roots of the equation (12). For this purpose it is necessary to calculate the the left side of (12) at specified values  $\omega = \omega_1, \omega_2, \dots, \omega_n$ . Choosing  $\Delta\omega = 10^{-4} - 10^{-6}$ , by the formula derivatives

$$\frac{\partial A_{\eta mj}(\omega)}{\partial \omega} = \frac{A_{\eta mj}(\omega_j + \Delta\omega) - A_{\eta mj}(\omega_j - \Delta\omega)}{2\Delta\omega} = 0$$

The system of algebraic equations (11) is solved by Gauss with the release of the main element. Using the solutions of (6), (8) and (10) we find the expressions for the displacement-th layer

$$u_{\kappa} = i\gamma[A_{\kappa}q_{\kappa} \exp(q_{\kappa}z) - B_{\kappa}q_{\kappa} \exp(-q_{\kappa}z) + C_{\kappa}S_{\kappa} \exp(S_{\kappa}z) - D_{\kappa}S_{\kappa} \exp(-S_{\kappa}z)]e^{i(\gamma x - \omega t)},$$

$$\mathcal{G}_{\kappa} = [-A_{\kappa}q_{\kappa} \exp(q_{\kappa}z) - B_{\kappa}q_{\kappa} \exp(-q_{\kappa}z) - C_{\kappa}\gamma^2 \exp(S_{\kappa}z) - D_{\kappa}\gamma^2 \exp(-S_{\kappa}z)]e^{i(\gamma x - \omega t)}. \quad (13)$$

Movements (13) for the half-satisfy exponential decay coordinate  $z$  ( $z \rightarrow \infty$ ).

As an example, consider the fluctuations layer lying on a half harmonic of the vertical load. Then, the main determinant of the (11) (6x6)  $[C]$ - It takes the following form

$$[C] = \begin{pmatrix} (1 + \bar{s}_1^2) e^{-\bar{\zeta} q_1} & (1 + \bar{s}_1^2) e^{\bar{\zeta} q_1} & -2e^{\bar{\zeta} q_1} & \dots & \dots & 2e^{\bar{\zeta} q_1} & \dots & \dots & 0 & \dots & \dots & 0 \\ -2\bar{q}_1 e^{\bar{\zeta} q_1} & \dots & 2\bar{q}_1 e^{\bar{\zeta} q_1} & \dots & \dots & \left(\bar{s}_1 + \frac{1}{\bar{s}_1}\right) e^{-\bar{\zeta} q_1} & \dots & \dots & \left(\bar{s}_1 + \frac{1}{\bar{s}_1}\right) e^{\bar{\zeta} q_1} & \dots & \dots & 0 \\ (1 + \bar{s}_1^2) e^{\bar{\zeta} q_1} & \dots & (1 + \bar{s}_1^2) e^{-\bar{\zeta} q_1} & -2e^{\bar{\zeta} q_1} & \dots & \dots & 2e^{-\bar{\zeta} q_1} & \dots & \dots & (1 + s^2) \gamma_1 & -2 / \gamma_1 \\ -2\bar{q}_1 e^{\bar{\zeta} q_1} & \dots & 2\bar{q}_1 e^{\bar{\zeta} q_1} & \dots & \dots & \left(\bar{s}_1 + \frac{1}{\bar{s}_1}\right) e^{\bar{\zeta} q_1} & \dots & \dots & \left(\bar{s}_1 + \frac{1}{\bar{s}_1}\right) e^{-\bar{\zeta} q_1} & \frac{2\bar{q}_1}{\gamma_1} & \left(\bar{s} + \frac{1}{\bar{s}}\right) / \gamma \\ e^{\bar{\zeta} q_1} & \dots & e^{\bar{\zeta} q_1} & \dots & \dots & e^{\bar{\zeta} q_1} & \dots & \dots & e^{\bar{\zeta} q_1} & \dots & \dots & -1 \\ \bar{q} e^{\bar{\zeta} q_1} & \dots & \bar{q}_1 e^{-\bar{\zeta} q_1} & \dots & \dots & -\frac{1}{\bar{s}} e^{\bar{\zeta} \bar{s}} & \dots & \dots & -\frac{1}{\bar{s}} e^{\bar{\zeta} \bar{s}} & \dots & \dots & -\bar{q} \\ & & & & & & & & & & & \frac{1}{\bar{s}} \end{pmatrix},$$

Where  $\zeta$  – dimensionless wave number,  $\zeta = \gamma h$ ,  $\gamma_1 = \bar{\mu}_1 / \bar{\mu}$ .

Consider two versions of the mechanical system. For the numerical solution of the problem the following options were used:

$$c_{p1} = 5400m/c, c_{s1} = 3195m/c, c_{s2} = 2300m/c, c_{s3} = 1311m/c, \\ \nu_1 = 0.30, \nu_2 = 0.35, \rho = 0.283MПа c^2 M^{-4}, \rho_0 = 0.126MПа c^2 M^{-4}$$

In the calculations acceptance dimensionless parameters:

$$c_p^1 = \frac{3195}{5400} = 0,5917, c_s^1 = \frac{2300}{5400} = 0,4259, c_s^2 = \frac{1311}{5440} = 0,2428, c_{ss}^2 = \frac{1311}{3195} = 0,4103, \rho_0 = \frac{0,126}{0,283} = 0,4452$$

In the first case considered homogeneous dissipative mechanical system. The calculation results of the first embodiment shown in Figure 2, a, b, c, d. The dimensionless amplitude of the resonance

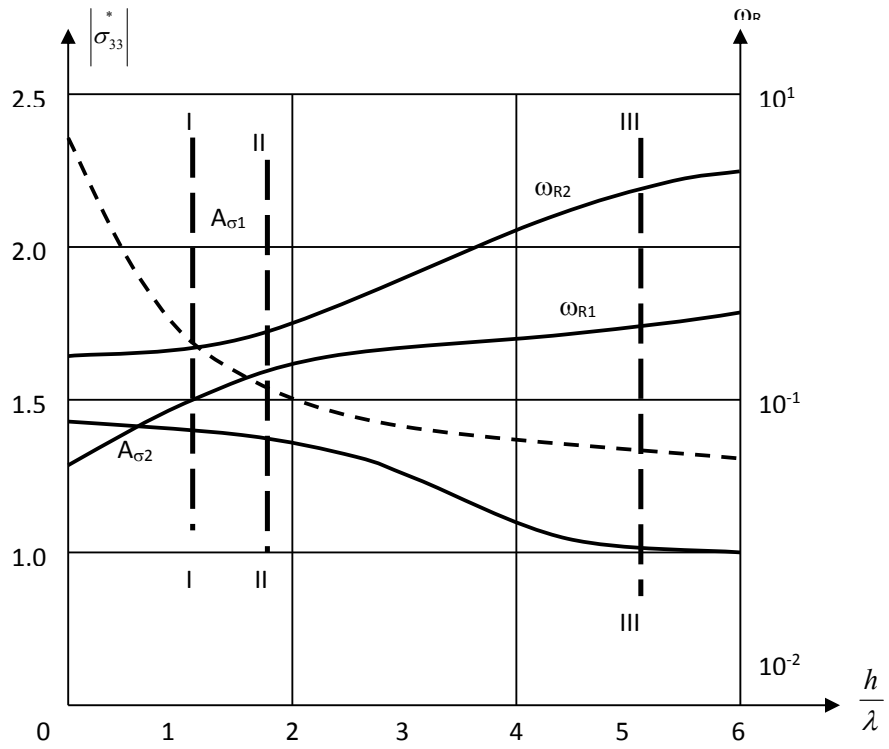
$$|A_{\sigma 33jk}| = \left| \frac{A_{\sigma 33jk}}{\sigma_p} \right| \left| A_{\sigma 33jk} \right| -$$

voltage amplitude,  $|\sigma_p|$  – the amplitude of the voltage load current) on the parameter  $h/\lambda$  It changed monotonically (Figure 2a). The corresponding amplitude characteristics -chastity voltages for the three sections (Figure 2a) are shown in Figure 2, b, c, d. This amplitude -chastity characteristics are fully consistent with the results of [7].

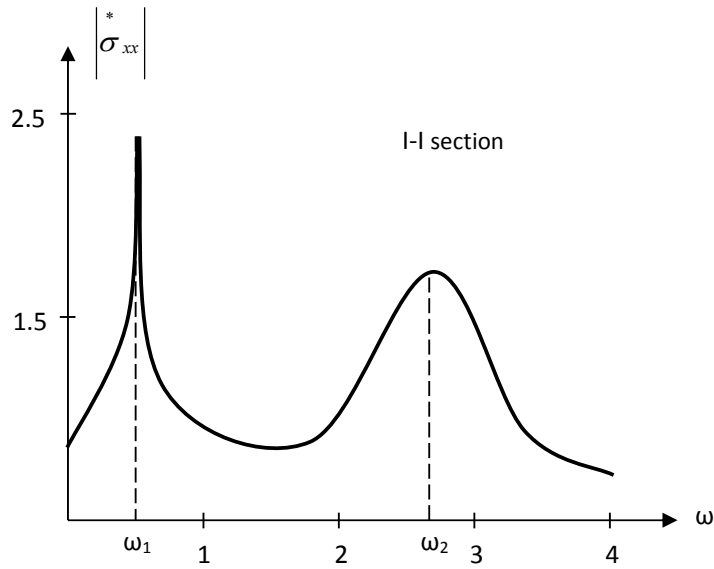
In the second embodiment, the resilient layer:  $R_1 = 0$ , other parameters coincide with those adopted above. The calculation results are presented in Figure 3, a, b, c, d, according to which at maximum approximation of the natural frequencies of the corresponding amplitudes  $|A_{\sigma 3311}|$  and  $|A_{\sigma 3312}|$  become equal [11]. Addition  $|A_{\sigma 33jk}|$  a parameter  $h/\lambda$  It turned out to be non-monotonic for inhomogeneous dissipative mechanical systems. The damping properties of the system as a whole are determined by the maximum amplitude of the resonance with forced vibrations (let's call it global resonance amplitude). The intensity of the dissipative processes in the system, the higher the lower the global resonance amplitude:

$$\delta_{\sigma_k} = \max_{\omega} ( |A_{\sigma_{jk}}| ), \quad k=1,2,\dots,N. \quad (14)$$

In dissipative homogeneous system performs the role of global amplitude for all values of the first resonant amplitude. In dissipative inhomogeneous system as a global amplitude acts depending on the value of the parameter as the first and second resonant amplitude. "Turn the Tables" occurs when the characteristic value of the parameter at which the real part of the natural frequencies of the closest.



**Fig 2a.** The dependence of the amplitude of the resonance  $h/\lambda$  (dissipative homogeneous system)



**Fig. 2b.** Amplitude - frequency characteristics (I-I section) (dissipative homogeneous system)

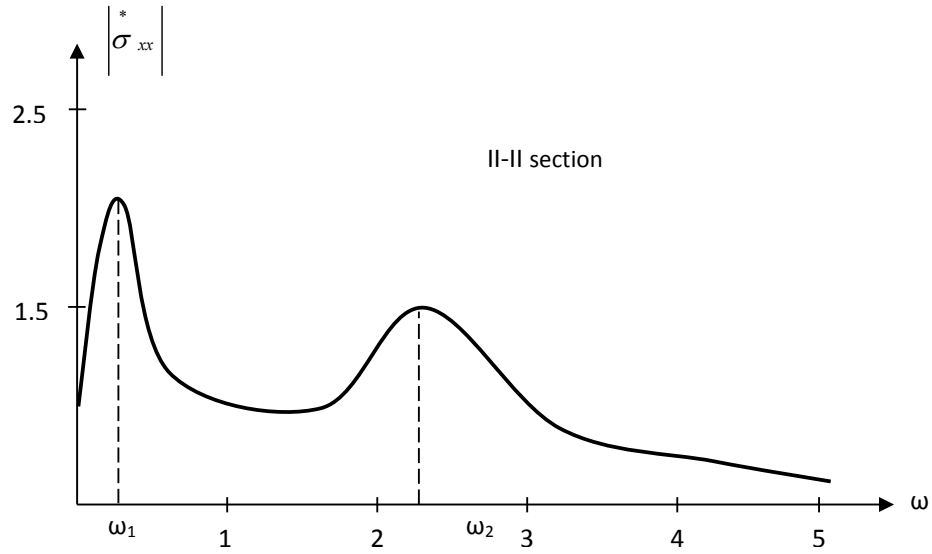


Fig. 2c. Amplitude - frequency characteristics (II-II section) (dissipative homogeneous system)

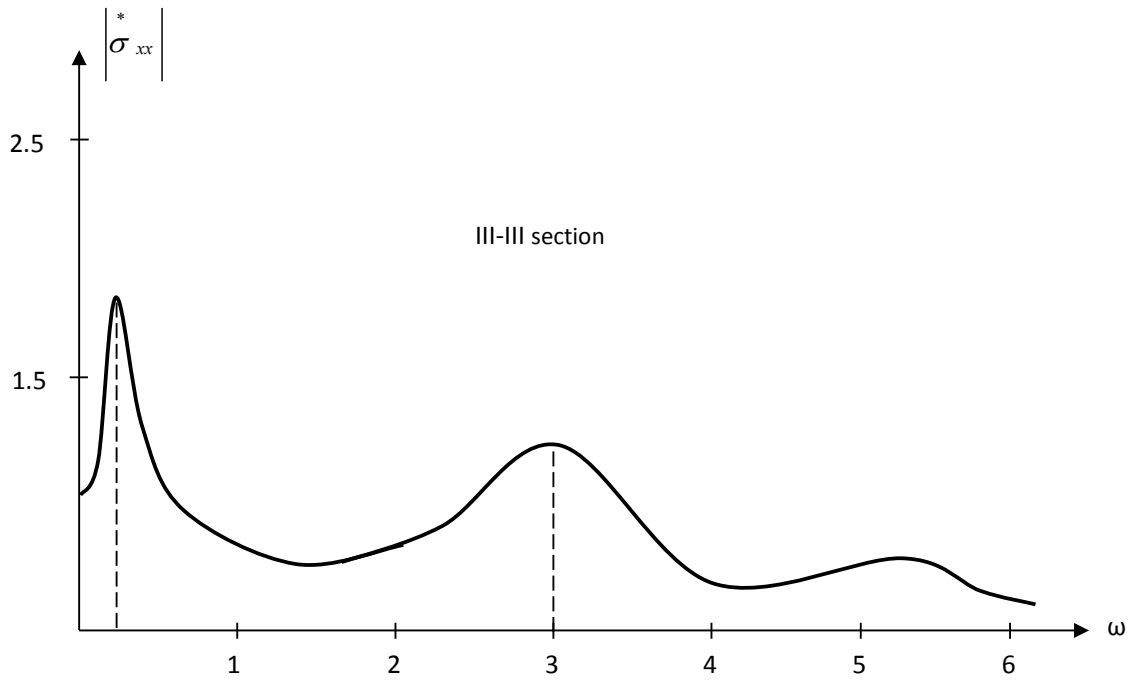


Fig 2g. Amplitude - frequency characteristics (III-III section) (Dissipative homogeneous)

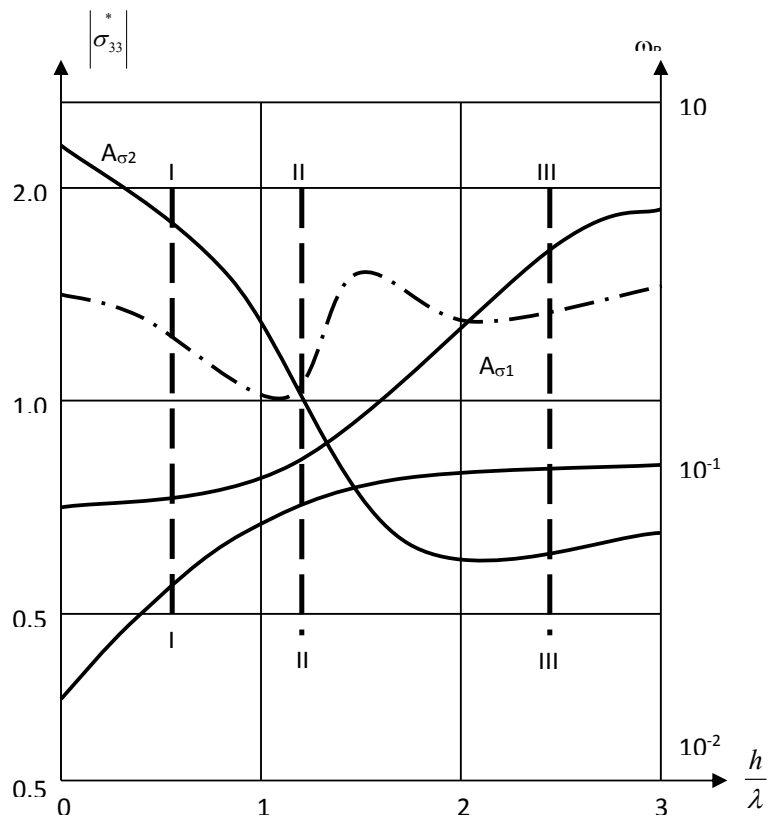


Fig. 3a. The dependence of the amplitude of the resonance  $h/\lambda$  (dissipative heterogeneous mechanical system)

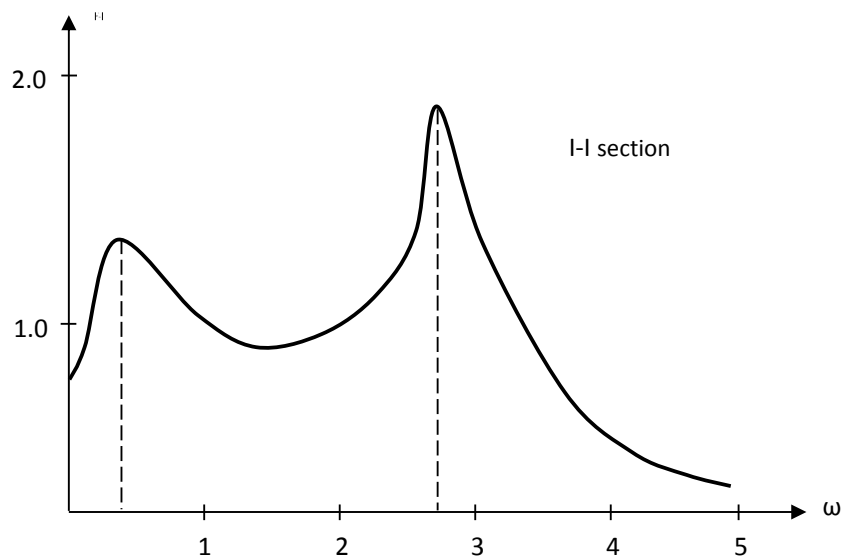


Fig. 3b. Amplitude - frequency characteristics (I-I cross section) (Dissipative heterogeneous mechanical system)



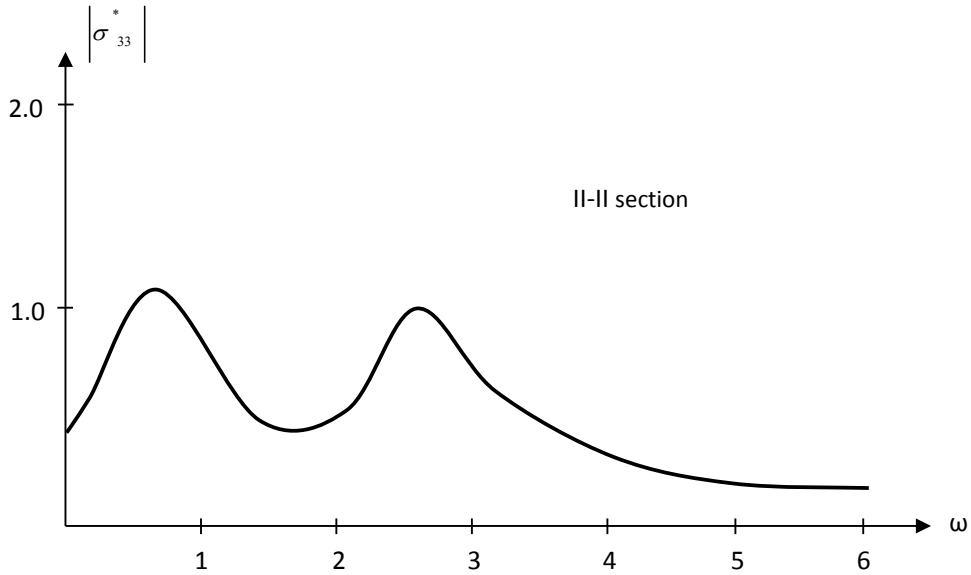


Fig. 3c. Amplitude - frequency characteristics (II-II cross section) (Dissipative heterogeneous mechanical system)

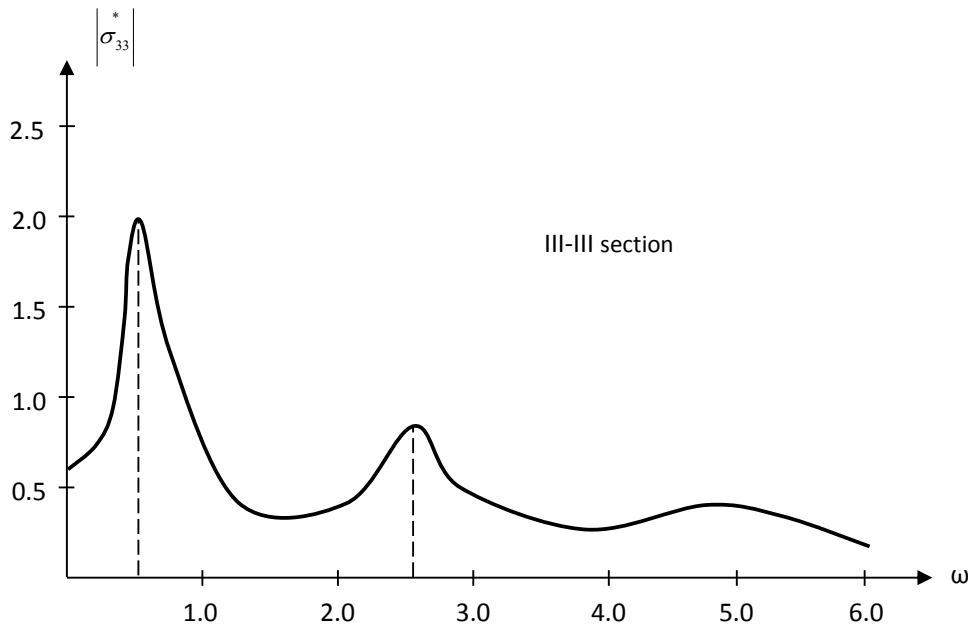


Fig. 3g. Amplitude - frequency characteristics (III-III section) (Dissipative heterogeneous mechanical system)

At this value of the global resonant amplitude is minimal and therefore dissipative processes in the system occur most intensively, and global damping coefficient has a pronounced maximum (or minimum) [7, 8, 9, 11]. From the simulation results can be seen that the minimum value of the amplitude of the voltage is achieved in the second sections for inhomogeneous dissipative mechanical systems (Figure 3, c).

**Conclusions**

1. The damping properties of the mechanical system with forced oscillations is determined by the maximum resonant amplitude (global resonance amplitude). The intensity of the dissipative processes in the system, the higher the global lower resonant amplitude (Figure 3, c). In a homogeneous dissipative mechanical system, the role of the global amplitude values for all parameters performs first resonance amplitude, and dissipative inhomogeneous -to depending on the size of (the global amplitude) setting both the first and second resonant amplitude.
2. "Change roles" occurs when the characteristic value of the parameter at which the real part of the natural frequencies of the closest. At this value of the global resonant amplitude is minimal and therefore dissipative processes in the system occur most intensively, and global damping coefficient has a pronounced maximum [7, 8, 9, 11].

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