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Forced vibration of the hydro-elastic system consisting of the orthotropic plate, compressible viscous fluid and rigid wall

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Abstract. This paper studies the forced vibration of the hydro-elastic system consisting of the anisotropic (orthotropic) plate, compressible viscous fluid and rigid wall within the scope of the exact equations and relations of elastodynamics for anisotropic bodies for describing of the plate motion, and with utilizing the linearized exact Navier-Stokes equations for describing of the fluid flow. For solution of the corresponding boundary value problem it is employed time-harmonic presentation of the sought values with respect to time and the Fourier transform with respect to the space coordinate on the coordinate axis directed along the plate length. Numerical results on the pressure acting on the interface plane between the plate and fluid are presented and discussed. The main aim in this discussion is focused on the study of the influence of the plate material anisotropy on the frequency response of the mentioned pressure. In particular, it is established that under fixed values of the shear modulus of the plate material a decrease in the values of the modulus of elasticity of the plate material in the direction of plate length causes to increase of the absolute values of the interface pressure. The numerical results are presented not only for the viscous fluid case but also for the inviscid fluid case.

Keywords: compressible viscous fluid; anisotropic plate; interface pressure; forced vibration; hydro-elastic system; fourier transform

1. Introduction

The use of composite materials in ship and submarine building, and as well as water turbine blades requires to study of the problems related to the interaction between the structural members made of composite materials (for instance, such as composite plates and shells) and fluids. It is evident that in these investigations as the first step may be taken the generalization of the classical interaction problems regarding the isotropic plates (or shells) and fluids for the anisotropic plates (or shells) and fluids. Namely this approach is taken in the present paper and it is made the attempt to investigate the forced vibration of the hydro-elastic system consisting of the anisotropic (orthotropic) plate compressible barotropic viscous fluid and the rigid wall. The isotropic plate

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case in this hydro-elastic system was studied in the paper by Akbarov and Ismailov (2017).

Now we consider a brief review of the investigations related to the subject of the present paper and begin this review with the paper by Lamb (1921) which is the first work in this field and studies the natural vibrations of a circular elastic "baffled" plate in contact with still water by utilizing the so-called "non-dimensional added virtual mass incremental" (NAVMI) method was used. Further, this work was developed in the papers by McLachlan (1932), Kwak and Kim (1991), Amabili and Kwak (1996), Amabili (1996), Kwak (1997), Kwak and Han (2000) and many others listed therein. Note that in these works the fluid is modelled as inviscid incompressible one and the motion of the plate is described within the scope of the Kirchhoff hypothesis, and as a result of the investigations it is established the magnitude of the influence of the contact of the plate with the fluid on the values of the natural vibrations of the plate. Moreover, in the paper by Jeong and Kim (2005) it is taken the compressibility of the inviscid fluid into consideration under investigation natural frequencies a circular plate submerged in a bounded fluid. The influence of the incompressible fluid viscosity on the plate vibration is taken into consideration in the papers by Atkinson and Manrique de Lara (2007) and Kozlovsky (2009). The influence of the viscosity of the fluid is also taken into account in the paper by Sorokin and Chubinskij (2008) in which unlike in the previous work the infinite plate model is used, however the plate motion is described within the scope of the various approximate plate theories. The study of the wave propagation problems in "an infinite plate + compressible viscouse fluid" systems was also made in the papers by Bagno *et al.* (1994), Bagno (2015) and others listed therein, the review of which is given in the papers by Bagno *et al.* (1997) and Guz *et al.* (2016) and detailed in the monograph by Guz (2009). However, in these works, unlike to the foregoing papers, the motion of the plate is described within the scope of the so-called three-dimensional linearized equations of wave propagation in elastic bodies with initial stresses and the flow of the fluid is described through the linearized Navier-Stokes equations. Note that within these equations and relations in recent 5 years it was also investigated series problems on the forced vibration of the hydro-viscoelastic and –elastic systems consisting of the viscoelastic (or elastic) plate, compressible viscous fluid and rigid wall the results of which, for instance, are detailed in the papers by Akbarov and Ismailov (2014, 2016, 2017 and 2018). In the paper by Akbarov *et al.* (2017) it is also studied the case where plate materıal is highly elastic and pre-strained in the hydroelastic system under consideration. At the same time, the paper by Akbarov and Panakhli (2017) relates to the forced vibration of the system consisting of the moving plate, viscous compressible fluid and rigid wall. The review of these and other results are given in the survey paper by Akbarov (2018) and some of these results are also detailed in the monograph by Akbarov (2015). It should be noted that the results obtained in these works can also be used as qualitative information on the pressure distribution under dynamic loading of the fluid-structure interaction systems the studying of which was made in the papers by Hadzalic *et al.* (2018), Kelvani *et al.*(2013), Mandal and Maity (2015) and in many others which are listed in these papers.

We recall that in all the reviewed above works it was assumed that the plate material is a homogeneous and isotropic one and therefore the results of these works cannot be applied for the cases where the plate made of composite (or anisotropic) materials is in contact with the fluid the examples for which is discussed in the papers by Shiffer and Tagarielli (2015), Das and Kapuria (2016), Kaneke *et al.* (2018), Gagani and Echtermeyer (2019). Therefore, it appears the need to develop of the foregoing investigations for the cases where the plate material is anisotropic one. Taking into consideration this statement in the present work it is made attempt to investigate the forced vibration of the hydro-elastic system consisting anisotropic (orthotropic) plate, compressible viscous fluid and rigid wall.

2. Formulation of the problem

Consider hydro-elastic system consisting of orthotropic plate-layer, compressible barotropic viscous fluid and rigid wall the sketch of which is shown in Fig. 1. We connect the Cartesian coordinate system $Ox_1x_2x_3$ with the upper face plane of the plate, according to which, the plate occupied the region $\{-\infty<x_1<+\infty;-h<x_2<0;-\infty<x_3<+\infty\}$ and the region $\{-\infty<x_1<+\infty;-h-h_d<x_2<-h;-\infty<x_3<+\infty\}$ is filled with the compressible viscous fluid, where h is the plate thickness and h_d is the fluid depth; at the same time, the plane $x_2=-h-h_d$ is the rigid wall.

It is assumed that the direction of the Ox_3 axis is perpendicular to the Fig. 1 plane and therefore it is not show in this figure. Moreover, it is assumed that along to this line, i.e., under $-\infty<x_3<+\infty$, $x_1=0$ and $x_2=0$ the uniformly distributed time-harmonic forces with intensity P_0 act. Taking this statement into consideration, below we consider plane-strain state in the plate and the plane flow of the fluid in the Ox_1x_2 plane.

We suppose that the material of the plate is the orthotropic one the elastic symmetry axes of which coincide with the coordinate axes Ox_1, Ox_2 and Ox_3, and this supposing is the main one, according to which, the present investigation differs from the investigations carried out in the paper by Akbarov and Ismailov (2017).

Thus, within the foregoing assumptions, we write the field equations and relations for the constituents of the hydro-elastic system under consideration.

The equations of motion for the plate

$$\frac{\partial\sigma_{11}}{\partial x_1}+\frac{\partial\sigma_{12}}{\partial x_2}=\rho\,\frac{\partial^2 u_1}{\partial t^2},\ \frac{\partial\sigma_{12}}{\partial x_1}+\frac{\partial\sigma_{22}}{\partial x_2}=\rho\,\frac{\partial^2 u_2}{\partial t^2}. \tag{1}$$

The elasticity relation

$$\sigma_{11}=a_{11}\varepsilon_{11}+a_{12}\varepsilon_{22},\ \ \sigma_{22}=a_{12}\varepsilon_{11}+a_{22}\varepsilon_{22},\ \ \ \sigma_{12}=2G_{12}\varepsilon_{12}, \tag{2}$$

where

$$a_{11}=\frac{A_{22}}{A_{11}A_{22}-A_{12}^2},\ \ a_{12}=\frac{A_{12}}{A_{11}A_{22}-A_{12}^2},\ \ a_{22}=\frac{A_{11}}{A_{11}A_{22}-A_{12}^2},$$
$$A_{11}=\frac{1-\nu_{13}\nu_{31}}{E_1},\ \ A_{12}=-\frac{\nu_{12}+\nu_{13}\nu_{32}}{E_1},\ \ A_{22}=\frac{1-\nu_{23}\nu_{32}}{E_1}, \tag{3}$$
$$\nu_{13}E_1=\nu_{31}E_3,\ \ \nu_{21}E_2=\nu_{12}E_1,\ \ \nu_{32}E_3=\nu_{23}E_2\ .$$

In (3) the following notation is used: E_1, E_2 and E_3 are the modulus of elasticity of the plate material in the directions of the Ox_1, Ox_2 and Ox_3 axes, respectively, G_{12} is the shear modulus in the Ox_1x_2 plane, ν_{ij} ($i;j$=1,2,3) is the Poisson's coefficient characterizing the shorting (the lengthening) of the material fibers in the Ox_i axis direction under stretching (under compressing) in the Ox_j axis direction; σ_{ij} and ε_{ij}(ij=11;22;12) are the components of the stress and strain tensor, respectively; u_1 and u_2 are the components of the displacement vector in the Ox_1 and Ox_2 axes directions, respectively.

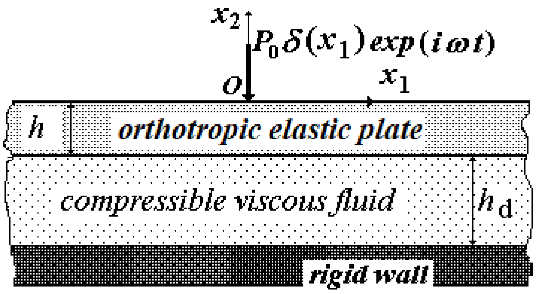


Fig. 1 The sketch of the hydro-elastic system consisting of orthotropic elastic plate, compressible viscous fluid and rigid wall

Finally, we write the strain-displacement relations

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x_1}, \quad \varepsilon_{22} = \frac{\partial u_2}{\partial x_2}, \quad \varepsilon_{12} = \frac{1}{2}\left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\right) \quad . \tag{4}$$

Thus, the equations and relations given in (1)-(4) complete the closed system of the field equations related to the motion of the orthotropic plate.

Now we consider the field equations and relations related to the fluid flow. According to the monograph by Guz (2009), we assume that the motion of the fluid is described with the linearized Navier-Stokes equations which can be written as follows for the case under consideration.

$$\rho_0^{(1)}\frac{\partial v_i}{\partial t} - \mu^{(1)}\frac{\partial^2 v_i}{\partial x_j \partial x_j} + \frac{\partial p^{(1)}}{\partial x_i} - (\lambda^{(1)} + \mu^{(1)})\frac{\partial^2 v_j}{\partial x_j \partial x_i} = 0, \quad \frac{\partial \rho^{(1)}}{\partial t} + \rho_0^{(1)}\frac{\partial v_j}{\partial x_j} = 0,$$

$$T_{ij} = \left(-p^{(1)} + \lambda^{(1)}\theta\right)\delta_{ij} + 2\mu^{(1)}e_{ij}, \quad \theta = \frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2}, \tag{5}$$

$$e_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right). \quad a_0^2 = \frac{\partial p^{(1)}}{\partial \rho^{(1)}} \quad , \quad i; j = 1,2 \quad .$$

where $\rho_0^{(1)}$ is the fluid density before perturbation, $\rho^{(1)}$ is the perturbation of the fluid density, $p^{(1)}$ is the perturbation of the hydrostatic pressure, v_1 and v_2 are the components of the fluid flow velocity vector in the directions of the Ox_1 and Ox_2 axes, respectively, T_{ij} and e_{ij} are the components of the stress and strain velocity tensors in the fluid, a_0 is the sound velocity in the fluid, $\lambda^{(1)}$ and $\mu^{(1)}$ are the coefficients of the fluid viscosity. In (5) it is made summation with respect to the by repeating indices.

As shown in the monograph by Guz (2009), for the solution to the equations in (5) it can be used the following presentation for the velocities v_1, v_2 and the pressure $p^{(1)}$

$$v_1 = \frac{\partial \varphi}{\partial x_1} + \frac{\partial \psi}{\partial x_2}, \quad v_2 = \frac{\partial \varphi}{\partial x_2} - \frac{\partial \psi}{\partial x_1}, \quad p^{(1)} = \rho_0^{(1)}\left(\frac{\lambda^{(1)} + 2\mu^{(1)}}{\rho_0^{(1)}}\Delta - \frac{\partial}{\partial t}\right)\varphi, \tag{6}$$

where the potentials φ and ψ satisfy the following equations.

$$\left[\left(1+\frac{\lambda^{(1)}+2\mu^{(1)}}{a_0^2\rho_0^{(1)}}\frac{\partial}{\partial t}\right)\Delta-\frac{1}{a_0^2}\frac{\partial^2}{\partial t^2}\right]\varphi=0\,,\quad \left(\nu^{(1)}\Delta-\frac{\partial}{\partial t}\right)\psi=0\,,\quad \Delta=\frac{\partial^2}{\partial x_1^2}+\frac{\partial^2}{\partial x_2^2}\,, \tag{7}$$

where $\nu^{(1)}$ is the kinematic viscosity, i.e., $\nu^{(1)}= \mu^{(1)}\,\rho_0{}^{(1)}$.

Assuming that $p^{(1)}=-(T_{11}+T_{22}+T_{33})/3$, it is obtained from the constitutive relations in (5) that

$$\lambda^{(1)}=-\frac{2}{3}\mu^{(1)}\quad . \tag{8}$$

We supply the foregoing field equations with the following boundary, compatibility and impermeability conditions.

The boundary conditions on the upper face plane of the plate

$$\sigma_{21}\big|_{x_2=0}=0\,,\quad \sigma_{22}\big|_{x_2=0}=-P_0e^{i\omega t}\,. \tag{9}$$

The compatibility conditions on the interface plane between the fluid and plate

$$\left.\frac{\partial u_1}{\partial t}\right|_{x_2=-h}=v_1\big|_{x_2=-h}\,,\quad \left.\frac{\partial u_2}{\partial t}\right|_{x_2=-h}=v_2\big|_{x_2=-h}\,,$$

$$\sigma_{21}\big|_{x_2=-h}=T_{21}\big|_{x_2=-h}\,,\quad \sigma_{22}\big|_{x_2=-h}=T_{22}\big|_{x_2=-h}\,. \tag{10}$$

The impermeability conditions on the rigid wall

$$v_1\big|_{x_2=-h-h_{\mathrm{d}}}=0\,,\quad v_2\big|_{x_2=-h-h_{\mathrm{d}}}=0\,. \tag{11}$$

This completes the formulation of the problem under consideration.

3. Method of solution

According to the boundary conditions in (9), we consider the time-harmonic vibration problem and due to this statement all the sought values can be represented with the $e^{i\omega t}$ multiplying, i.e., as $g(x_1,x_2,t)=\bar{g}(x_1,x_2)e^{i\omega t}$. Substituting this presentation into the foregoing equations and relations and replacing the derivatives $\partial(\bullet)/\partial t$ and $\partial^2(\bullet)/\partial t^2$ with $i\omega(\bar{\bullet})$ and $-\omega^2(\bar{\bullet})$, respectively, it is obtained the corresponding equations and boundary and contact conditions for the amplitudes of the sought values. To solve these equations we employ to them the Fourier transform with respect to the coordinate x_1

$$f_F(s,x_2)=\int_{-\infty}^{+\infty}f(x_1,x_2)e^{-isx_1}dx_1 \tag{12}$$

The problem symmetry with respect to the x_1=0 plane allows us to present the original of the sought values as follows

$$u_1 = \frac{1}{\pi}\int_0^\infty u_{1F}(s,x_2)\sin(sx_1)ds, \quad u_2 = \frac{1}{\pi}\int_0^\infty u_{2F}(s,x_2)\cos(sx_1)ds, \quad \sigma_{11} = \frac{1}{\pi}\int_0^\infty \sigma_{11F}(s,y_2)\cos(sy_1)ds,$$

$$\sigma_{22} = \frac{1}{\pi}\int_0^\infty \sigma_{22F}(s,x_2)\cos(sx_1)ds, \quad \sigma_{12} = \frac{1}{\pi}\int_0^\infty \sigma_{12F}(s,x_2)\sin(sx_1)ds,$$

$$\varphi = \frac{1}{\pi}\int_0^\infty \varphi_F(s,x_2)\cos(sx_1)ds, \quad \psi = \frac{1}{\pi}\int_0^\infty \psi_F(s,x_2)\sin(sx_1)ds, \tag{13}$$

$$v_1 = \frac{1}{\pi}\int_0^\infty v_{1F}(s,x_2)\sin(sx_1)ds, \quad v_2 = \frac{1}{\pi}\int_0^\infty v_{2F}(s,x_2)\cos(sx_1)ds, \quad T_{11} = \frac{1}{\pi}\int_0^\infty T_{11F}(s,x_2)\cos(sx_1)ds,$$

$$T_{22} = \frac{1}{\pi}\int_0^\infty T_{22F}(s,x_2)\cos(sx_1)ds, T_{12} = \frac{1}{\pi}\int_0^\infty T_{12F}(s,x_2)\sin(sx_1)ds.$$

Now we consider the determination of the Fourier transforms which enter into the expressions in (13) and first we make this determination for the quantities related to the plate.

Thus, after substituting the expressions related to the plate and given in (13) into the equations (1), (2) and (4), and doing some mathematical manipulations we obtain the following equations with respect to the u_{1F} and u_{2F}.

$$Au_{1F} - B\frac{du_{2F}}{dx_2} + \frac{d^2u_{1F}}{dx_2^2} = 0 \quad , \quad Du_{2F} + B\frac{du_{1F}}{dx_2} + G\frac{d^2u_{2F}}{dx_2^2} = 0, \tag{14}$$

where

$$A = X^2 - s^2 a_{11}/G_{12} \quad , \quad B = sa_{12}/G_{12} + s, \quad D = X^2 - s^2, \quad G = a_{22}/G_{12} \quad ,$$
$$X^2 = \omega^2 h^2 / c_2^2 \quad , \quad c_2 = \sqrt{G_{12}/\rho} \quad . \tag{15}$$

As in the paper by Akbarov and Ismailov (2017), introducing the notation

$$A_0 = \frac{AG + B^2 + D}{G}, \quad B_0 = \frac{BD}{G}, \quad k_1 = \sqrt{-\frac{A_0}{2} + \sqrt{\frac{A_0^2}{4} - B_0}} \quad , \quad k_2 = \sqrt{-\frac{A_0}{2} - \sqrt{\frac{A_0^2}{4} - B_0}}, \tag{16}$$

We can write the solution of the Eq. (14) as follows

$$u_{2F} = Z_1 e^{k_1 x_2} + Z_2 e^{-k_1 x_2} + Z_3 e^{k_2 x_2} + Z_4 e^{-k_2 x_2} \quad ,$$
$$u_{1F} = Z_1 a_1 e^{k_1 x_2} + Z_2 a_2 e^{-k_1 x_2} + Z_3 a_3 e^{k_2 x_2} + Z_4 a_4 e^{-k_2 x_2}, \tag{17}$$

where

$$a_1 = \frac{-D - Gk_1^2}{Bk_1^2} \;,\; a_2 = -a_1 ,\; a_3 = \frac{-D - Gk_2^2}{Bk_2^2}, \quad a_4 = -a_3 \,. \tag{18}$$

Substituting the expressions (17) into the Fourier transforms of the Eqs. (4) and (2) we obtain the following expressions for the Fourier transformations σ_{21F} and σ_{22F} of the corresponding stresses which enter the boundary conditions in (9) and contact compatibility conditions in (10).

$$\frac{\sigma_{21F}}{G_{12}} = Z_1\left(k_1 a_1 - s\right)e^{k_1 x_2} + Z_2\left(-k_1 a_2 - s\right)e^{-k_1 x_2} + Z_3\left(k_2 a_3 - s\right)e^{k_2 x_2} + Z_4\left(-k_2 a_3 - s\right)e^{-k_2 x_2} \,,$$

$$\frac{\sigma_{22F}}{G_{12}} = Z_1\left(s\frac{a_{12}}{G_{12}}a_1 + k_1\frac{a_{22}}{G_{12}}\right)e^{k_1 x_2} + Z_2\left(s\frac{a_{12}}{G_{12}}a_2 - k_1\frac{a_{22}}{G_{12}}\right)e^{-k_1 x_2} + \tag{19}$$

$$Z_3\left(s\frac{a_{12}}{G_{12}}a_3 + k_2\frac{a_{22}}{G_{12}}\right)e^{k_2 x_2} + Z_2\left(s\frac{a_{12}}{G_{12}}a_4 - k_2\frac{a_{22}}{G_{12}}\right)e^{-k_2 x_2} \,.$$

This completes the determination of the Fourier transforms of the quantities related to the plate.

Consider also the determination of the values related to the fluid flow and for this purpose we represent the Fourier transforms φ_F and ψ_F as follows.

$$\varphi_F = \omega h^2 \tilde{\varphi}_F \quad , \quad \psi_F = \omega h^2 \tilde{\psi}_F \tag{20}$$

Substituting these expressions into the Fourier transforms of the equations in (7), we obtain

$$\frac{d^2\tilde{\varphi}_F}{dx_2^2} + \left(\frac{\Omega_1^2}{1 + i4\,\Omega_1^2/(3N_w^2)} - s^2\right)\tilde{\varphi}_F = 0 \,,\; \frac{d^2\tilde{\psi}_F}{dx_2^2} - \left(s^2 + iN_w^2\right)\tilde{\psi}_F = 0 \,, \tag{21}$$

where

$$\Omega_1 = \frac{\omega h}{a_0} \quad , \quad N_w^2 = \frac{\omega h^2}{\nu^{(1)}} \,. \tag{22}$$

Note that the dimensionless numbers N_w and Ω_1 in (22) characterize the influence of the fluid viscosity and compressibility, respectively, on the mechanical behavior of the system under consideration. Moreover, note that under writing the equations in (21) and the expressions in (22) the equality in (8) is taken into consideration.

Thus, the solution to the equations in (21) we determine as follows.

$$\tilde{\varphi}_F = Z_5 e^{\delta_1 x_2} + Z_7 e^{-\delta_1 x_2} \,,\; \tilde{\psi}_F = Z_6 e^{\gamma_1 x_2} + Z_8 e^{-\gamma_1 x_2} \,, \tag{23}$$

where

$$\delta_1 = \sqrt{s^2 - \frac{\Omega_1^2}{1 + i4\,\Omega_1^2/(3N_w^2)}} \;,\; \gamma_1 = \sqrt{s^2 + iN_w^2} \,. \tag{24}$$

Substituting these expressions into the representation in (20) and substituting the latter ones into the Fourier transforms of the equations in (6) and (5), we obtain the following expressions for the Fourier transforms of the quantities related to the fluid flow.

$$v_{1F} = \omega h\left[-Z_5 s e^{\delta_1 x_2} - Z_7 s e^{-\delta_1 x_2} + Z_6 e^{\gamma_1 x_2} + Z_8 e^{-\gamma_1 x_2}\right],$$

$$v_{2F} = \omega h\left[Z_5 \delta_1 e^{\delta_1 x_2} - Z_7 \delta_1 e^{-\delta_1 x_2} - Z_6 s e^{\gamma_1 x_2} - Z_8 s e^{-\gamma_1 x_2}\right],$$

$$T_{22F} = \mu^{(1)}\omega\left[Z_5\left(\frac{4}{3}\delta_1^2 + \frac{2}{3}s^2 - R_0\right)e^{\delta_1 x_2} + Z_7\left(\frac{4}{3}\delta_1^2 + \frac{2}{3}s^2 - R_0\right)e^{-\delta_1 x_2} + \right.$$
$$\left. Z_6\left(-s\gamma_1 - \frac{2}{3}s\gamma_1\right)e^{\gamma_1 x_2} + Z_8\left(s\gamma_1 + \frac{2}{3}s\gamma_1\right)e^{-\gamma_1 x_2}\right], \tag{25}$$

$$T_{21F} = -\mu^{(1)}\omega\left[2s\delta_1 Z_5 e^{\delta_1 x_2} - 2s\delta_1 Z_7 e^{-\delta_1 x_2} + (s^2+\gamma_1^2)Z_6 e^{\gamma_1 x_2} + (s^2+\gamma_1^2)Z_8 e^{-\gamma_1 x_2}\right],$$

$$p_F^{(1)} = \mu^{(1)}\omega R_0\left(Z_5 e^{\delta_1 x_2} + Z_7 e^{-\delta_1 x_2}\right),$$

where

$$R_0 = -\frac{4}{3}\frac{\Omega_1^2}{1 + i4\,\Omega_1^2/(3N_w^2)} - iN_w^2. \tag{26}$$

Finally, substituting the expressions in (17), (19) and (25) into the Fourier transforms of the boundary conditions in (9), the compatibility conditions in (10) and impermeability conditions in (11) we obtain the following system of equations with respect to the unknowns Z_1, Z_2,…, Z_8 which enter the expressions of the Fourier transforms of the sought values.

$$(\sigma_{22F}/G_{12})\big|_{x_2=0} = Z_1\alpha_{21} + Z_2\alpha_{22} + Z_3\alpha_{23} + Z_4\alpha_{24} = -P_0/G_{12},$$

$$\left.\frac{\partial u_{1F}}{\partial t}\right|_{x_2=-h} - v_{1F}\big|_{x_2=-h} = i\omega(Z_1\alpha_{31} + Z_2\alpha_{32} + Z_3\alpha_{33} + Z_4\alpha_{34}) -$$
$$\omega h(Z_5\alpha_{35} + Z_6\alpha_{36} + Z_7\alpha_{37} + Z_8\alpha_{38}) = 0,$$

$$\left.\frac{\partial u_{2F}}{\partial t}\right|_{x_2=-h} - v_{2F}\big|_{x_2=-h} = i\omega(Z_1\alpha_{41} + Z_2\alpha_{42} + Z_3\alpha_{43} + Z_4\alpha_{44}) - \tag{27}$$
$$\omega h(Z_5\alpha_{45} + Z_6\alpha_{46} + Z_7\alpha_{47} + Z_8\alpha_{48}) = 0,$$

$$(\sigma_{21}/G_{12})\big|_{x_2=-h} - (T_{21}/G_{12})\big|_{x_2=-h} = Z_1\alpha_{51} + Z_2\alpha_{52} + Z_3\alpha_{53} + Z_4\alpha_{54} -$$

$$M(Z_5\alpha_{55}+Z_6\alpha_{56}+Z_7\alpha_{57}+Z_8\alpha_{58})=0 \quad ,$$

$$(\sigma_{22}/G_{12})\big|_{x_2=-h}-(T_{22}/G_{12})\big|_{x_2=-h}=Z_1\alpha_{61}+Z_2\alpha_{62}+Z_3\alpha_{63}+Z_4\alpha_{64}-$$

$$M(Z_5\alpha_{65}+Z_6\alpha_{66}+Z_7\alpha_{67}+Z_8\alpha_{68})=0\,, \tag{27}$$

$$v_{1F}\big|_{x_2=-h-h_d}=\omega h(Z_5\alpha_{75}+Z_6\alpha_{76}+Z_7\alpha_{77}+Z_8\alpha_{78})=0\,,$$

$$v_{2F}\big|_{x_2=-h-h_d}=\omega h(Z_5\alpha_{85}+Z_6\alpha_{86}+Z_7\alpha_{87}+Z_8\alpha_{88})=0$$

where

$$M=\frac{\mu^{(1)}\omega}{G_{12}} \quad . \tag{28}$$

It is evident that the expressions of the coefficients $\alpha_{nm}(n;m=1,2,..,8)$ in the equations in (27) can be easily determined from the Eqs. (17), (19) and (25), and the unknowns Z_1, Z_2,…,Z_8 in can be determined via the formula

$$Z_k=\frac{\det\left\|\beta_{nm}^{k}\right\|}{\det\left\|\alpha_{nm}\right\|} \quad . \tag{29}$$

where the matrix $(\beta^k{}_{nm})$ is obtained from the matrix (α_{nm}) by replacing the k–th column of the latter with the column $(0,-P_0/G_{12},0,0,0,0,0,0)^T$.

Now we consider calculation algorithm of the integrals in (13). For this purpose, firstly we discuss the following reasoning. If we take the Fourier transformation parameter s as the wavenumber, then the equation

$$\det\left\|\alpha_{nm}\right\|=0\,, \quad n;m=1,2,\ldots,8\,, \tag{30}$$

coincides with the dispersion equation of the waves with the velocity ω/s propagated in the direction of the Ox_1 axis in the system under consideration.

It is evident that, according to the existence of the fluid viscosity, the equation (30) must have complex roots with respect to the unknown ω/s. However, as usual, the viscosity of the Newtonian fluids is insignificant in the qualitative sense and therefore in some cases within the scope of the necessity of the PC calculation accuracy, in general, the Eq. (30) may have “real roots” and these roots become singular points of the integrated expressions in (13) and in such cases the algorithm for calculation was discussed in monograph by Akbarov (2015) and other works listed in this monograph. According to this algorithm, in the mentioned cases the wavenumber integrals (13) may be evaluated along the Sommerfeld contour examples for which is shown in the monograph by Akbarov (2015). However, in the present investigations under calculation of the integrals in (13) it was not arise the aforementioned “real roots” cases and using the representation $g(x_1,x_2,t)=\bar{g}(x_1,x_2)e^{i\omega t}$, the sought values are determined through the following two types of relations

$$\{\sigma_{22},\sigma_{11},u_2,T_{22},T_{11},\mathrm{v}_2\}=\frac{1}{\pi}\mathrm{Re}\left\{e^{i\omega t}\int_0^{\infty}[\sigma_{22F},\sigma_{11F},u_{2F},T_{22F},T_{11F},\mathrm{v}_{2F}]\cos(sx_1)ds\right\}$$
$$\{\sigma_{21},\sigma_{12},u_1,T_{21},\mathrm{v}_1\}=\frac{1}{\pi}\mathrm{Re}\left\{e^{i\omega t}\int_0^{\infty}[\sigma_{21},\sigma_{12F},u_{1F},T_{21F},\mathrm{v}_{1F}]\sin(sx_1)ds\right\}. \quad (31)$$

Note that under calculation procedures, the improper integrals $\int_0^{\infty} f(s)\cos(sx_1)\mathrm{ds}$ and $\int_0^{\infty} f(s)\sin((s)x_1)\mathrm{d}s_1$ in (31) are replaced by the corresponding definite integrals $\int_0^{S_1^*} f(s)\cos(sx_1)\mathrm{ds}$ and $\int_0^{S_1^*} f(s)\sin((s)x_1)\mathrm{d}s$, respectively. The values of S^*_1 are determined from the convergence requirement of the numerical results.

Under calculation of the mentioned definite integrals, the integration interval [0, S^*_1] is further divided into a certain number of shorter intervals, which are used in the Gauss integration algorithm. The values of the integrated expressions at the sample points are calculated through the equations (17), (19) and (25). All these procedures are performed automatically with the PC programs constructed by the authors in MATLAB.

This completes the consideration of the algorithm which is employed for calculation of the wave-number integrals in (13).

Finally, note that after some obvious changes the foregoing solution method can also be applied for the case where the fluid is inviscid.

4. Numerical results and discussions

For obtaining concrete numerical results we assume that the material of the fluid is Glycerin with viscosity coefficient $\mu^{(1)}$=1,393 kg/(m·s), density $\rho_0^{(1)}$=1260 kg/m^3 and sound speed a_0=1927 m/s (Guz (2009)) and introduce the notation

$$\rho/\rho_0^{(1)}=k_1\ ,\ c_2/a_0=k_2\ ,\ G_{12}=(c_2)^2\rho \quad (32)$$

through which we determine the density and shear modulus of elasticity in the Ox_1x_2 plane of the plate material. Consequently, if we know the density of the fluid, then giving the values for the k_1 we determine the density of the plate material, as well as if we know the sound speed in the fluid, then giving the values for the k_2 we determine the values for the shear modulus G_{12}.

In other words selecting the values for the constants k_1 and k_2 we determine the density and shear modulus of the plate material through the density and sound speed of the fluid material, and an increase in the values of the k_1 (of the k_2) means an increase in the values of the density (of the shear modulus) of the plate material and under fixed value of the fluid density (under fixed sound speed in the fluid).

Moreover, we introduce the following ratios which characterize the anisotropy of the plate material.

$$E_1/G_{12}, E_1/E_2,\ \ E_2/E_3,\ \ E_1/E_3, \quad (33)$$

and assume that

$$\nu_{12} = \nu_{13} = \nu_{23} = 0.3, \quad \nu_{21} = \nu_{12}\frac{E_1}{E_2}, \; \nu_{31} = \nu_{13}\frac{E_1}{E_3}, \; \nu_{32} = \nu_{23}\frac{E_2}{E_3}. \tag{34}$$

Moreover, assume that

$$E_1 = E_3 \tag{35}$$

and in this way we have two ratios E_1/G_{12} and E_1/E_2 through which we characterize the influence of the anisotropy of the plate material on the values of the stresses and velocities appearing as a result of the dynamic loading of the plate with the time-harmonic forces acting on the plate.

In the present investigations we will consider the numerical results illustrating the influence of the k_1, k_2, E_1/G_{12} and E_1/E_2 on the frequency response of the interface dimensionless stress $T_{22}h/P_0$. Note that, according to the convergence investigations carried out in the paper by Akbarov and Ismailov (2017), under obtaining numerical results it is assumed that $S^*_1=9$ the interval $[0, S^*_1]$ is divided into 2000 shorter subintervals in each of which it is used the Gauss integration algorithm with ten sample points.

The convergence of the numerical results in the selected numbers of the subintervals and in the selected length of the integration interval was illustrated not only in the paper by Akbarov and Ismailov (2017) but also in the papers by Akbarov and Ismailov (2016, 2018) and in others listed therein. Therefore, we do not consider here results illustrated the convergence of the numerical results. The trustiness of the used PC programs which are used under obtaining the numerical results which will be discussed below is tested with obtaining in the particular cases the known results and with agreeing the obtained results with the physico-mechanical consideration. After establishing the mentioned testing procedure (we do not give here examples for such testing) we obtain numerical results for the case under consideration.

Thus, we consider and analyze numerical results illustrating the influence of the k_1, k_2, E_1/G_{12} and E_1/E_2 on the frequency response of the interface dimensionless stress $T_{22}h/P_0$ at point $x_1/h=0$ which acts on the interface plane between the plate and fluid. Note that under this consideration we will distinguish two cases with respect to the vibration phase ωt, i.e., we will consider separately the cases where $\omega t=0$ and $\omega t=\pi/2$. The selection of these two cases for consideration is in connection with the following situation. The investigations carried out in the papers by Akbarov and Ismailov (2016, 2017 and 2018) show that in the inviscid fluid case with respect to the vibration phase ωt the stress T_{22} has its absolute maximum (zero) value under $\omega t=0+n\pi$ (under $\omega t=\pi/2+n\pi$). However, in the viscous fluid case the stress T_{22} has its absolute maximum (zero) value under $\omega t=(\omega t)'+n\pi$ (under $\omega t=(\omega t)''+n\pi$) where the value of the $(\omega t)'$ (the value of the $(\omega t)''$) is very near to the 0 (to the $\pi/2$) and the values of $(\omega t)'$ and of $(\omega t)''$ depend on the problem parameters. If we considered the stress value at $\omega t=(\omega t)'$ and $\omega t=(\omega t)''$ then there would be many confusions for describing the values of the $(\omega t)'$ and $(\omega t)''$ for each selected values of the problem parameters. Taking the foregoing discussions into consideration we decide to calculate the values of the stress T_{22} for values of the $\omega t=0$ (under which the values of the T_{22} become is very near to its absolute maximum ones) and of the $\omega t=\pi/2$ (under which the values of the T_{22} become is very near to its zeroth).

Now we begin to analyze the numerical results and first, we assume that $k_1=k_2=1$, $E_1/E_2=1.5$ and consider the influence of the ratio E_1/G_{12} on the frequency response of the $T_{22}h/P_0$ in the case where $\omega t=0$. The graphs of this response are given in Fig. 2 in the cases where $h_d/h=2$ (Fig. 2(a)),

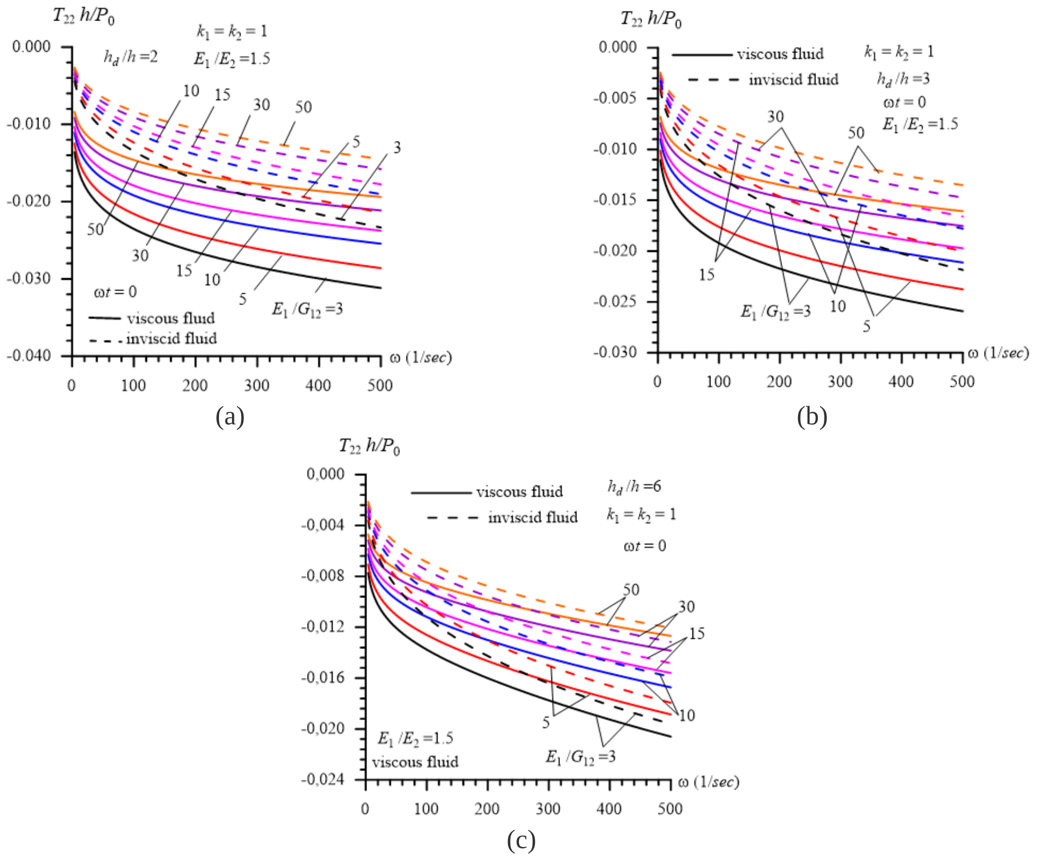


Fig. 2 The influence of the ratio E_1/G_{12} on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the case where ωt=0, k_1=k_2=1, E_1/E_2=1.5 under h_d/h=2 (a), 3 (b) and 6 (c)

3 (Fig. 2(b)) and 6 (Fig. 2(c)). Simultaneously, in Fig. 2 it is given the mentioned frequency response for the case where the selected fluid (Glycerin) is modelled as a Newtonian viscous fluid, but also for the case where this fluid is modelled as a Newtonian inviscid fluid and the graphs related to this inviscid fluid case are drawn with the dashed lines.

Thus, it follows from the results given in Fig. 2 that an increase in the values of the ratio E_1/G_{12} causes a decrease in the absolute values of the interface normal stress $T_{22}h/P_0$. This means that an increase in the values of the modulus of elasticity E_1 of the plate material in the Ox_1 axis direction (this is because, according to the relations in (32), the shear modulus G_{12} has a fixed value under k_1=k_2=1 for the fixed values of the fluid density and fluid's sound velocity) causes to decrease of the absolute values of the pressure acting on the interface plane. The comparison of the results given in Fig. 2(a), Fig. 2(b) and Fig. 2(c) between each other shows that an increase in the fluid depth causes to decrease in the absolute values of the stress $T_{22}h/P_0$. Note that this conclusion is in agreement in the qualitative sense with the corresponding one obtained in the paper by Akbarov and Ismailov (2017) and with the well-known mechanical considerations. Moreover, the comparison of the results obtained for the viscous fluid case (solid lines) with the corresponding ones obtained for the inviscid fluid cases (dashed lines) shows that the fluid viscosity also causes to increase the absolute values of the interface pressure between the plate and fluid and the

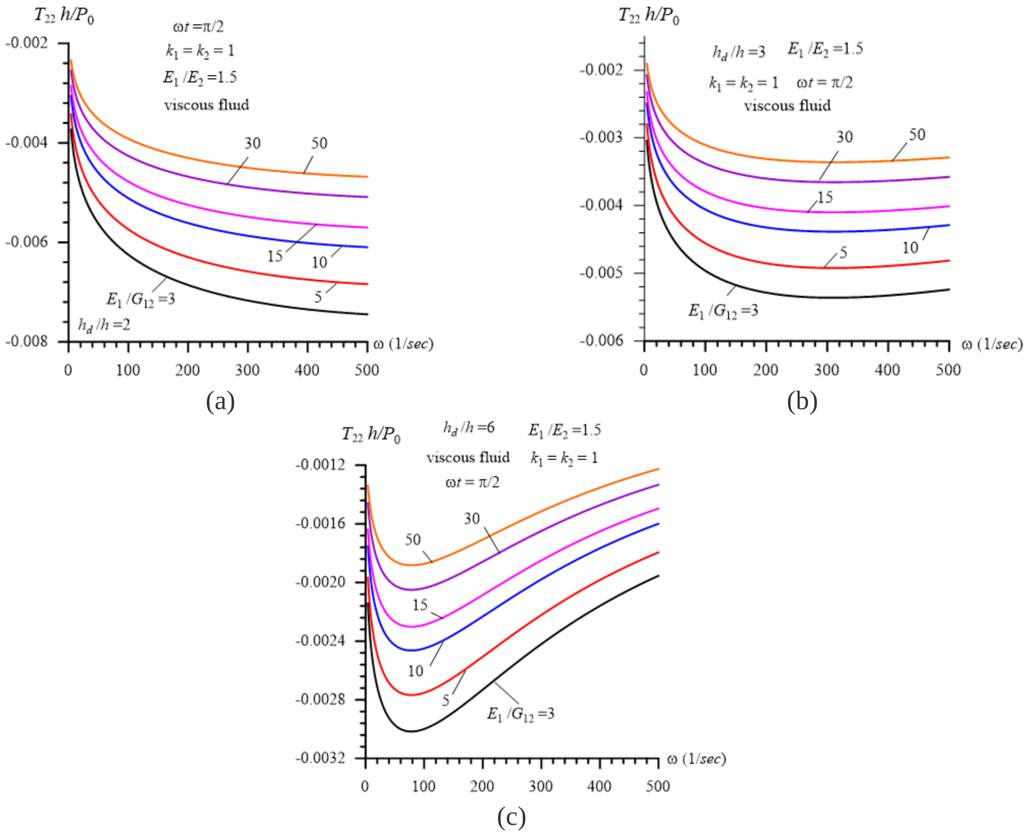


Fig. 3 The influence of the ratio E_1/G_{12} on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the case where $\omega t=\pi/2$, $k_1=k_2=1$, $E_1=E_2=1.5$ under $h_d/h=2$ (a), 3 (b) and 6 (c)

magnitude of this increase becomes more considerable with decreasing of the fluid depth, i.e., with decreasing of the ratio h_d/h. At the same time, it follows from the results given in Fig. 2 that an increase in the values of the ratio E_1/G_{12} causes to decrease of the difference between the results obtained for the viscous and inviscid fluid cases.

Now we consider the results obtained under $\omega t=\pi/2$ within the scope of the assumptions which accepted under calculating of the results illustrated in Fig. 2. Note that these results are given in Fig. 3 for the cases where $h_d/h=2$ (Fig. 3(a)), 3 (Fig. 3(b)) and 6 (Fig. 3(c)).

Note that in Fig. 3 the results related to the inviscid fluid case do not illustrated because in the inviscid fluid case, as it has noted above, in the case where $\omega t=\pi/2$ the values of the stress T_{22} are equal to zero. It follows from the results in Fig. 3 that the character of the influence of the ratio E_1/G_{12} on the values of the stress under consideration in the qualitative sense is the same as in the case considered in Fig. 2. Moreover, it follows from the Fig. 3 that in the considered change range of the frequency ω the character of the dependence between the stress T_{22} and ω becomes non-monotonic with the ratio h_d/h.

Now we consider the results illustrated the influence of the ratio E_1/E_2 on the frequency response under consideration and looking ahead note that this influence is insignificant. This conclusion is also proven with the results given in Fig. 4 which show the graphs of the frequency response constructed for various values of the ratio E_1/E_2 in the case where $k_1=k_2=1$, $E_1/G_{12}=5$

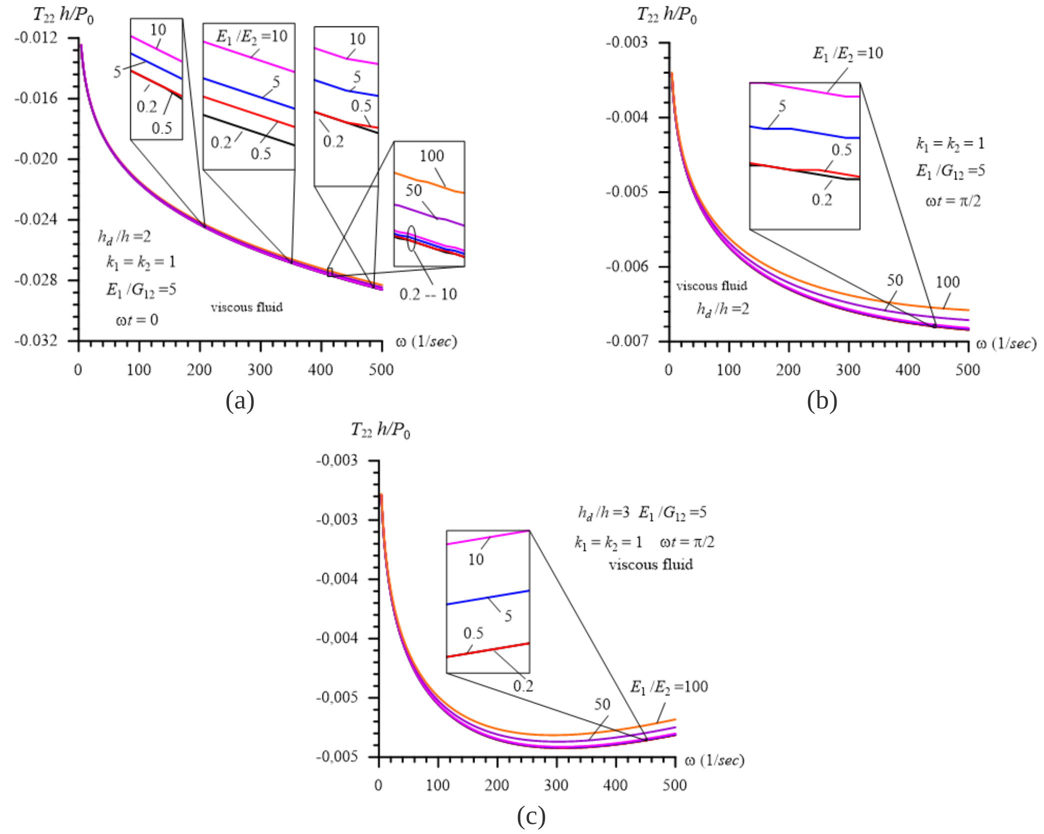


Fig. 4 Examples on the influence of the ratio E_1/E_2 on the frequency response of the dimensionless interface stress in the case where $k_1=k_2=1$, $E_1/G_{12}=5$ under $\omega t=0$, $h_d/h=2$ (a); $\omega t=\pi/2$, $h_d/h=2$ (b) and $\omega t=\pi/2$, $h_d/h=3$ (c)

under $\omega t=0$, $h_d/h=2$ (a); $\omega t=\pi/2$, $h_d/h=2$ (b) and $\omega t=\pi/2$, $h_d/h=3$ (c). It follows from the analyzes of these graphs that despite the fact that the mentioned influence is insignificant nonetheless an increase in the values of the ratio E_1/E_2, i.e., a decrease in the values of the modulus of elasticity of the plate material in the Ox_2 axis direction causes to decrease in the absolute values of the pressure acting on the interface plane between the plate and fluid.

Now we consider numerical results illustrated the influence of the coefficient k_1 under $k_2=1$ (the influence of the coefficient k_2 under $k_1=1$) on the frequency response under consideration and for this purpose we consider the graphs given in Figs. 5 and 6 (given in Figs. 7 and 8) which are constructed in the cases where $\omega t=0$ and $\omega t=\pi/2$ respectively. Note that in these figures the graphs grouped by the letters a, b and c relate to the cases where $E_1/G_{12}=5$, 10 and 50 respectively. Moreover, under obtaining the results given in these figures it is assumed that $E_1/E_2=5$ and $h_d/h=2$.

According to the relations in (32), a decrease (an increase) in the values of k_1 under fixed k_2, $\rho_0^{(1)}$ and a_0 means a decrease (an increase) in the values of the plate material density ρ. However, as in this change the shear wave velocity in the plate material must remain constant therefore shear modulus G_{12} of the plate material must also decrease (increase) proportionally to ρ or proportionally to k_1. Thus, it follows from the results illustrated in Figs. 5 and 6 that within the

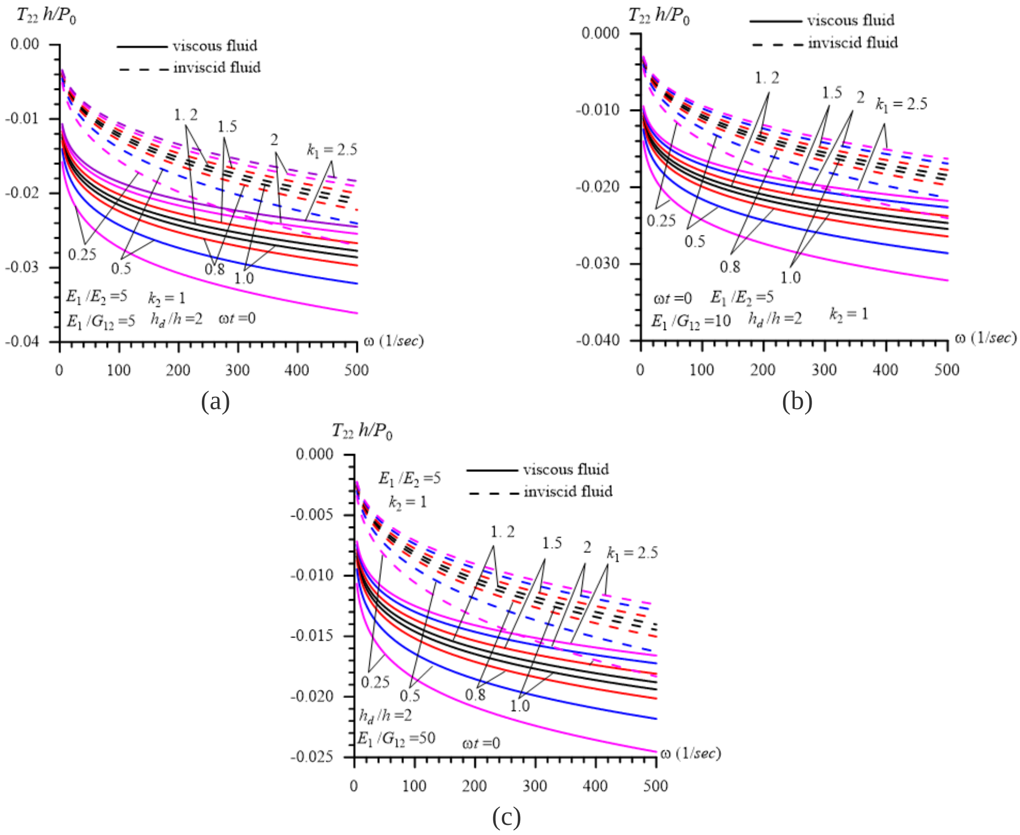


Fig. 5 The influence of the values k_1 on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the cases where E_1/G_{12}=5 (a), 10 (b) and 50 (c) under k_2=1, ωt=0, h_d/h=2 and E_1/E_2=5

framework of the foregoing statements, a decrease in the density of the plate material with respect to the density of the fluid causes to increase of the absolute values of the interface pressure which

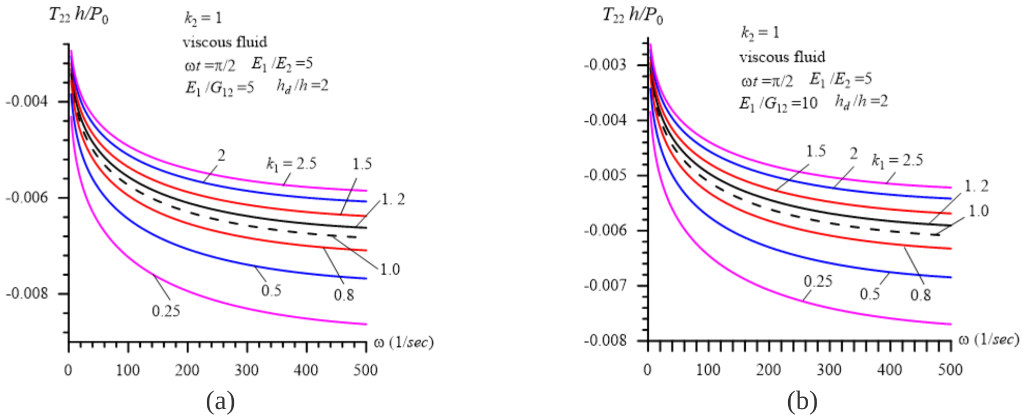
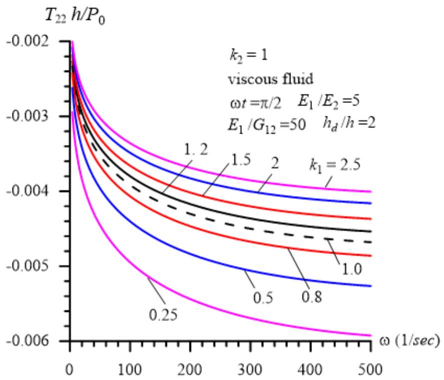
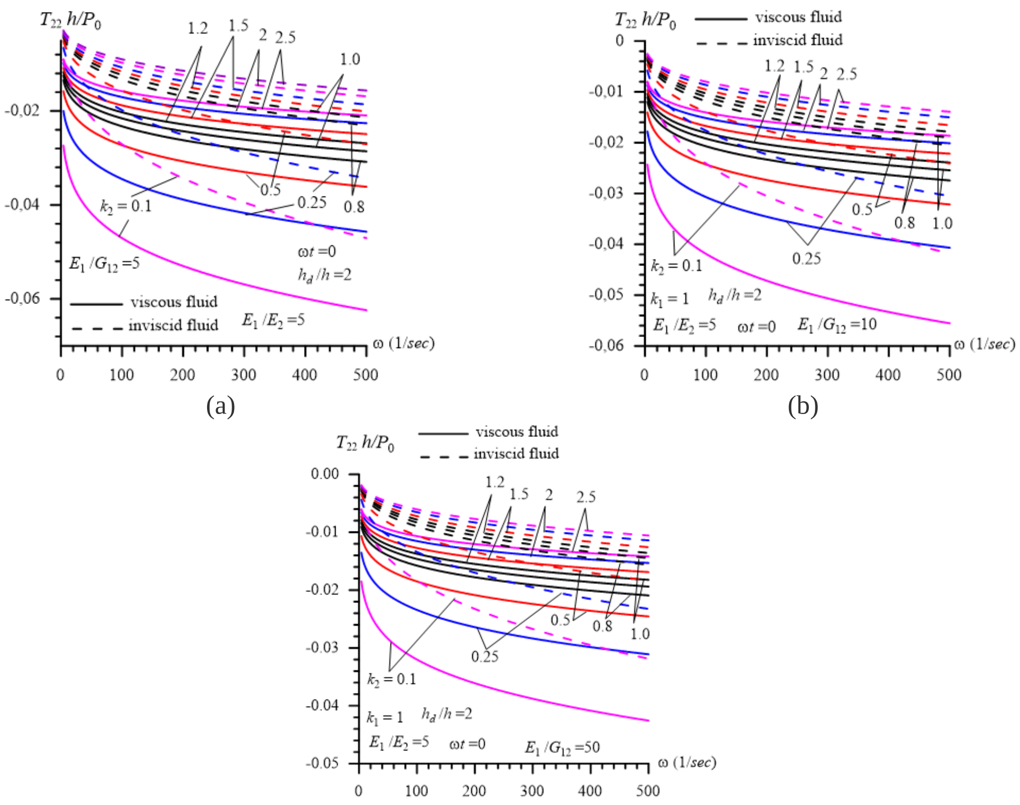


Fig. 6 The influence of the values k_1 on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the cases where E_1/G_{12}=5 (a), 10 (b) and 50 (c) under k_2=1, ωt=π/2, h_d/h=2 and E_1/E_2=5



(c)

Fig. 6 Continued



(c)

Fig. 7 The influence of the values k_2 on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the cases where E_1/G_{12}=5 (a), 10 (b) and 50 (c) under k_1=1, ωt=0, h_d/h=2 and E_1/E_2=5

appear between the plate and fluid. Moreover, from these results follows that in the cases where k_1<1 the magnitude of the mentioned decrease becomes more considerable than that in the cases where k>1.

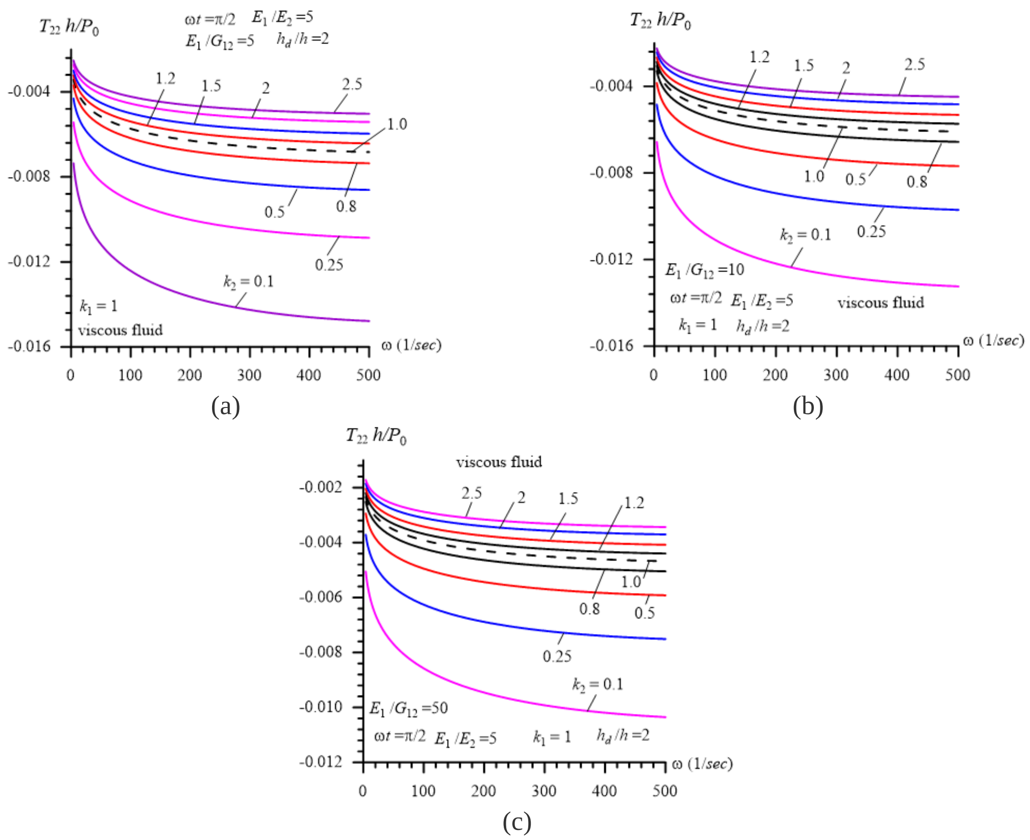


Fig. 8 The influence of the values k_2 on the frequency response of the dimensionless interface stress $T_{22}h/P_0$ in the cases where E_1/G_{12}=5 (a), 10 (b) and 50 (c) under k_1=1, $\omega t=\pi/2$, h_d/h=2 and E_1/E_2=5

Also, it follows from the relations in (32) that, under fixed values of the k_1, $\rho_0^{(1)}$ and a_0 a decrease (an increase) in the values of the coefficient k_2 means a decrease (an increase) in the values of the shear wave propagation velocity c_2. However, in this case as the density remain constant and is equal to the density of the fluid therefore the change in the values of the k_2 means the change in the values of the shear modulus G_{12} proportionally to $(k_2)^2$. Thus, within these frameworks, it follows from the Figs. 7 and 8 that, an increase (a decrease)in the values of the k_2 causes a decrease (an increase) in the absolute values of the interface pressure.

This completes the consideration analyses of the numerical result and the concrete conclusions which follow from these results will be given in the following section.

5. Conclusions

Thus, in the present paper the time-harmonic forced vibration of the hydro-elastic system consisting of the orthotropic plate, compressible (barotropic) viscous fluid and rigid wall is studied and this study is made by employing the exact equations of elastodynamics for anisotropic bodies under describing the motion of the plate and the linearized Navier-Stokes equations under describing the fluid flow. The main aim in the present investigation is the study of the influence of the anisotropy of the plate material on the pressure appearing on the interface plane between the fluid and plate. As fluid is taken Glycerin and the shear modulus and the density of the plate material are determined by the density of this fluid and by the sound speed of that through introducing the coefficients k_1 and k_2. Numerical results on the frequency response of the interface normal stress acting on the interface plane between the plate and fluid are presented and discussed. These results are presented not only viscous fluid case but also for the inviscid fluid case, i.e. for the cases where the Glycerin is modelled as compressible inviscid fluid. The analyses of these numerical results allow us to make some concrete conclusions on the character of the influence of the plate material anisotropy on the aforementioned frequency response.

-An increase in the values of the modulus of elasticity E_1 of the plate material in the direction of plate length under constant values of the shear modulus G_{12} of this material causes to decrease of the absolute values of the interface pressure;

-Under fixed values of the G_{12}, the influence of the change of the ratio E_1/E_2 (where E_2 is the modulus of elasticity of the plate material in its thickness direction) on the interface pressure is insignificant, nonetheless, an increase in the values of the ratio E_1/E_2 causes a decrease in the absolute values of the mentioned pressure;

-Under constant value of the ratios G_{12}/ρ, G_{12}/E_2 and E_1/E_2 (where ρ is the density of the plate material) a decrease in the values of the plate material density ρ, i.e., a decrease in the values of the coefficient k_1 causes an increase in the absolute values of the interface pressure mentioned above;

-Under fixed values of the plate material density ρ and under fixed values of the ratios G_{12}/E_2 and E_1/E_2 a decrease in the values of the shear modulus G_{12} of the plate material, i.e., a decrease in the values of the coefficient k_2 causes an increase in the values of the interface pressure;

-The foregoing conclusions occur not only for the viscous fluid case but also for the inviscid fluid case;

-The foregoing conclusions hold not only for the values of the interface pressure calculated for the vibration phase $\omega t=0$ near to which this pressure has its absolute maximum with respect to ωt but also for the values of the pressure calculated for the vibration phase $\omega t=\pi/2$ near to which the pressure has its zero;

-A decrease of the fluid depth causes to increase significantly the magnitude of the influence of the fluid viscosity on the values of the interface pressure.

It follows from the foregoing results and conclusions that the anisotropy of the plate material which is in contact with fluid can change significantly the vibration behavior of this plate and therefore, investigations of the influence of the plate material anisotropy on the forced or natural vibration of the corresponding hydro-elastic systems must be developed for the other type dynamic problems and for the more high change range of the frequency of the vibration of the external forces which in the present paper is selected as $4(1/sek) \leq \omega \leq 500(1/sek)$.

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