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STUDYING THE MOVEMENT OF CIRCULAR EMBEDDING IN A LINEAR VISCOUS-ELASTIC MEDIUM

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Abstract- The presented article is devoted to the study of the unsteady interaction of deformable and rigid bodies with the environment and such issues of great theoretical and practical importance. The study of the movements and vibrations of structures interacting with the environment is one of the most pressing issues in our time. The experience of modern branches of mechanical engineering and construction requires the study of shock waves propagating in the environment of an object to the elements of structures and structures. For this reason, the motion of a circular inclusion in a linear viscoelastic medium was studied in the article. The exact solution of problems concerning the movement of a body in a viscous liquid, as well as in a viscoelastic medium, is associated with great mathematical difficulties. Some similar problems were investigated by the oscillatory motion of a solid body in a viscous liquid compressed at small values of the Reynolds numbers, which at that time were solved using the linear Navier-Stokes equation. Here, the solution of the equation is expressed by scalar and vector potentials. In the question considered in the article, the equations of motion of a body in a linear viscoelastic medium, the initial conditions of which are zero, are first constructed using the integral Laplace transform. Using the principle of congruence, elastic constants are replaced by corresponding viscoelastic complex modules and the reverse transformation is performed. As a result, the reaction force is sought and, for simplicity, it is described in the form of the Macleron order. At the beginning of the problem, the inclusion motion of a viscoelastic medium was studied by the Voigt model, and then by the Kelvin and Maxwell models.

Keywords: Shell, Viscous Fluid, Kelvin and Maxwell Model, Voigt Model, Macdonald Function, Laplace Transform.

1. INTRODUCTION

The question discussed in the article was first posed by D'alembert, and this question is called the D'alembert paradox. That is, with the laminar flow of a liquid, laminarity is disrupted as a result of the impact of an object introduced into the liquid in any form, resulting in turbulence (vorticity). This problem has been identified for water, which is considered a common homogeneous medium. However, further industrial development required that the results obtained for homogeneous incompressible liquid media should generally be investigated for viscous liquid media. For this reason, the effect of a viscous liquid on the insert has been adopted in various models. Despite the fact that the problem considered in the article has been solved for a linear viscoelastic liquid medium, it faces serious mathematical difficulties. The issue under consideration has broad and important applications. In water channels, floating inserts are used to periodically direct the flow of water in different directions. Such designs are also used for periodic adjustment of fuel supply and lubrication systems inside machinery. Since petroleum products are viscous liquid media, Kelvin and Maxwell models are used. On the other hand, the Foight model is used to simplify the problem because it is simpler. The results of applying all three models do not differ much from each other in principle, that is, in the Maxwell model, it is assumed that deformation depends on time (strain rate), whereas in the Kelvin-Voigt model, it is assumed that stress depends on time. It's just that these models differ in the complexity of their mathematical solutions. The problem is theoretical in nature, although using all three models, various equations were obtained that interpret the problem under consideration as physics-mechanical, but equivalent solutions were obtained. The equivalence of the solutions obtained indicates both comparability and reliability of the results obtained.

In this paper, we investigate the non-stationary motion process of a circular embedment in a linear viscoelastic medium. In such a case, the law of commutation of motion is given in advance. In the article, the reaction to the placement by the sphere and medium as well as the reaction moment and longitudinal reaction are determined. The rates of these reactions are complex. Therefore, it is appropriate to use their asymptotic expansion in the form of Maclaurin series. The solution

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of the dynamic problem for the viscoelastic material is obtained from the solution of the corresponding problem for the elastic medium by which is homogeneous applying the Laplace integral transform to these solutions, as well as by replacing the elastic constants with the appropriate viscoelastic complex moduli and applying the compatibility principle has been studied performing the inverse transformation.

In this case, we take different models by choosing the appropriate constants. As a result, the reaction force, moment and longitudinal reaction are determined.

It should be noted that using the obtained results, expressions of these reactions for visco-elastic compressible fluids could be found. In this article we have studied nonstationary movement of circular embedding in a viscous-elastic medium.

2. PROBLEM STATEMENT

Studying the movement of circular embedding moving by the given law in a linear viscous-elastic medium. The following relations characterize the motion of a solid body in a linear viscoelastic medium:

$$a_0 S_{ij} + a_1 \frac{dS_{ij}}{dt} + ... + a_m \frac{d^m S_{ij}}{dt^m} = = b_0 e_{ij} + b_1 \frac{de_{ij}}{dt} + ... + b_n \frac{d^n e_{ij}}{dt^n} \quad (1)$$

$$c_0 \sigma_{kk} + c_1 \frac{d\sigma_{kk}}{dt} + ... + c_l \frac{d^l \sigma_{kk}}{dt^l} = = d_0 \varepsilon_{kk} + d_1 \frac{d\varepsilon_{kk}}{dt} + ... + d_q \frac{d^q \varepsilon_{kk}}{dt^q} \quad (2)$$

where, e_{ij} and S_{ij} are the components of deviatoric deformation and deviatoric stress, respectively. These components are related to ε_{ij} and σ_{ij} stress components in the following form:

$$e_{ij} = \varepsilon_{ij} - \frac{1}{3}\delta_{ij}\varepsilon_{kk} \ , \ S_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk} \quad (3)$$

where,

$$\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33} = 3\sigma$$
$$\varepsilon_{kk} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} = 0 \quad (4)$$
$$\delta_{ij} = \begin{cases} 1 \text{ if } i = j \\ 0 \text{ if } i \neq j \end{cases}$$

Applying the Laplace integral transform

$$\bar{f}(\omega) = \int_0^\infty (t) e^{-\omega t} dt \quad (5)$$

To the Equations (1) and (2), and taking the initial conditions equal to zero, we obtain the following relations;

$$P_S(\omega)\bar{S}_{ij} = Q_S(\omega)\bar{e}_{ij} \ , \ P_\upsilon(\omega)\bar{\sigma}_{kk} = Q_\upsilon(\omega)\bar{\varepsilon}_{kk} \quad (6)$$

where, P_S, Q_S, P_υ and Q_υ are polynomials dependent on ω. We present complex models of shape and volume change as follows:

$$Y_S(\omega) = \frac{Q_S(\omega)}{P_S(\omega)} \ , \ Y_\upsilon(\omega) = \frac{Q_\upsilon(\omega)}{P_\upsilon(\omega)} \quad (7)$$

In this case, the relations (6) take the following form:

$$\bar{S}_{ij} = Y_S(\omega)\bar{e}_{ij} \ , \ \bar{\sigma}_{kk} = Y_\upsilon(\omega)\bar{e}_{kk} \quad (8)$$

From (8) we obtain:

$$\bar{\varepsilon}_{ij} = e_{ij} + \frac{1}{3}\bar{e}_{kk}\delta_{ij} = \frac{1}{Y_S}S_{ij} + + \frac{1}{3Y_\upsilon}\bar{\sigma}_{kk}\delta_{ij} = \frac{1}{Y_S}\sigma_{ij} - \frac{1}{3}\left(\frac{1}{Y_S} - \frac{1}{Y_\upsilon}\right)\bar{\sigma}_{kk}\delta_{ij} \quad (9)$$

In particular case, from (9) we can write the following expressions

$$\bar{\varepsilon}_{11} = \left(\frac{2}{Y_S} + \frac{1}{Y_\upsilon}\right)\bar{\sigma}_{11} - \frac{1}{3}\left(\frac{1}{Y_S} - \frac{1}{Y_\upsilon}\right)(\bar{\sigma}_{22} + \bar{\sigma}_{33})$$
$$\bar{\varepsilon}_{11} = \frac{1}{Y_S}\bar{\sigma}_{12} \quad (10)$$

The dependences for elastic material are as follows:

$$\bar{\varepsilon}_{11} = \frac{1}{E}\bar{\sigma}_{11} - \frac{\upsilon}{E}(\bar{\sigma}_{22} + \bar{\sigma}_{33}) \ , \ \bar{\varepsilon}_{12} = \frac{1}{2\mu}\bar{\sigma}_{12}$$
$$\bar{\theta} = \bar{\varepsilon}_{kk} = \frac{\bar{\sigma}}{K} = \frac{\bar{\sigma}_{kk}}{3K} \quad (11)$$

Comparing the Equations (11) and (12), we obtain the appropriate elastic and viscous-elastic modules in Table 1.

Table 1. Comparison of elastic and viscoelastic material parameters

module	shear	volume	Young modules	Poisson ratio	Lame coefficient
elastic	μ	K	E	ν	$\lambda - K - \frac{2}{3}\mu$
viscous-elastic	$\frac{1}{2}Y_S$	$\frac{1}{3}Y_\nu$	$\frac{1}{3}\left(\frac{1}{Y_S} + \frac{1}{Y_\nu}\right)^{-1}$	$\frac{Y_\nu - Y_S}{2Y_\nu + Y_S}$	$\frac{1}{3}\left(\frac{1}{Y_S} - \frac{1}{Y_\nu}\right)$

3. PROBLEM SOLUTION

The compatibility principle can be characterized as follows:

The solution of the dynamic problem for a viscoelastic material can be obtained from the solution of the corresponding problem given for an elastic medium by applying the Laplace integral transform to this solution, replacing the elastic constants with viscoelastic complex moduli as given in the table, and performing the inverse transformation. In this case the boundary conditions for both problems must be identical and taken to be equal to zero.

Assume that the sphere moves in the medium with the law $z = \frac{t^2}{2}$. Using the relations in the previous chapter, we can determine the influence or reaction force of the elastic medium to the sphere. In this case, the acceleration of the sphere will be constant and $W = 1$. In the case under consideration, it is accepted that the particles of the medium move without leaving the sphere. Then the reaction force is determined as follows:

$$R=\frac{3}{4}\pi\rho r_0^3\left[Ne^{-\chi_1\tau}\sin\chi_2\tau+L\left(1-e^{-\chi_1\tau}\cos\chi_2\tau\right)+\right.$$
$$\left.+B_1\tau+B_2\tau^2\right] \tag{13}$$

where,

$$\tau=\frac{at}{r_0}\ ,\ \chi_1=\frac{2+k}{2}\ ,\ \chi_2=\frac{\sqrt{3k^2-4k+4}}{2}\ ,\ k=\frac{b}{a} \tag{14}$$

$$N=3\left(k^2+k^4-2\right)\left(C_1\sin\chi_2-C_2\sin\chi_2\right)+$$
$$+3\left(2+k-2k^2-k^2\right)\left(D_1\sin\chi_2-D_2\sin\chi_2\right)+$$
$$+4\left(k^2-1\right)\left(E_1\sin\chi_2-E_2\sin\chi_2\right)+$$
$$+\left(1-k\right)\left(M_1\sin\chi_2-M_2\sin\chi_2\right)$$
$$L=3\left(k^2+k^4-2\right)A_0-3\left(2+k-k^2-k^3\right)A_1+$$
$$+8\left(k^2-1\right)A_2-6\left(1-k\right)A_3$$
$$B_1=3\left[\left(k^2+k^4-2\right)A_1-2\left(2+k-2k^2-k^3\right)A_2+\right.$$
$$\left.+8\left(k^2-1\right)A_3-8\left(1-k\right)A_4-k\right]$$
$$B_2=3\left[\left(k^2+k^4-2\right)A_2-3\left(2+k-2k^2-k^3\right)A_2+\right.$$
$$\left.+16\left(k^2-1\right)A_4+\frac{1}{2}\left(1-2k^2\right)\right]$$
$$A_4=\frac{k^2}{8\left(2+k^2\right)}\ ,\ A_3=\frac{k\left(1-2\right)}{\left(2+k^2\right)^2}$$
$$A_2=\frac{-k^4+k^3+2k^2-6k+2}{\left(2+k^2\right)^2}$$
$$A_1=\frac{2\left(k^5+2k^4-11k^3+8k^2+4k-4\right)}{\left(2+k^2\right)^5}$$
$$A_0=\frac{-11k^5+14k^4+28k^3-52k^2+16k+8}{\left(2+k^2\right)^5}$$
$$C_1=\frac{1}{\chi_2}\left[A_0\left(\chi_2\cos\chi_2+\chi_1\sin\chi_2\right)+A_1\sin\chi_2\right]$$
$$C_2=\frac{1}{\chi_2}\left[A_0\left(\chi_1\cos\chi_2+\chi_2\sin\chi_2\right)+A_1\sin\chi_2\right]$$
$$D_1=C_1\chi_1+C_2\chi_2\ ,\ D_2=C_2\chi_1-C_1\chi_2$$
$$E_1=D_1\chi_1+D_2\chi_2\ ,\ E_2=D_2\chi_1-D_1\chi_2$$
$$M_1=E_1\chi_1+E_2\chi_2\ ,\ M_2=E_2\chi_1-E_1\chi_2$$

Accept that the medium is linear viscous-elastic and in the particular case the relations (1)-(2) are in the following form:

$$a_0S_{ij}+a_1\dot{S}_{ij}=b_0b_{ij}+b_1e_{ij}$$
$$c_0\sigma_{kk}+c_1\dot{\sigma}_{kk}=d_0\varphi_{kk}+b_1e_{ij}$$

In this case appropriate complex modules are as follows:

$$Y_S=\frac{b_0+b_1\omega}{a_0+a_1\omega}\ ,\ Y_\upsilon=\frac{d_0+d_1\omega}{c_0+c_1\omega}$$

If $b_0, b_1, a_0, a_1, d_0, d_1, c_0$ and c_1 are non-zero, the relations (12) correspond to the Kelvin model, if b_0 and d_0 are zero, to the Maxwell model, if a_1 and c_1 are, equal to zero, to the Foight model. If for simplicity we accept that the modules (12) are proportional, i.e.

$$Y_S=\delta Y_S \tag{15}$$

Then the viscous- elastic modulus corresponding to the Poisson ratio will be constant number. At the same time,

$$k=\frac{b}{a}=\sqrt{\frac{1-2\nu}{2\left(1-\nu\right)}} \tag{16}$$

By means of Equation (1) and compatibility principle we obtain very complex relations for the rate of reaction force of the elastic medium to the sphere. But taking into account (13) after applying the compatibility principle, the coefficients $\chi_1, \chi_2, N, L, B_1$ and B_2 will remain constant and in this case for the reaction rate we can obtain a simpler expression. To obtain the original of the function $R(t)$ it is convenient to use the Mellin inverse transformation.

Now we study various movements of a cylinder in a linear-viscous medium. To this end, at first, we consider the movement of this cylinder in an elastic medium. It is assumed that the infinite circular cylinder moves in the elastic medium in the direction perpendicular to the generatrix, so that this cylinder moves from the stationary state by the law $x=\frac{t^2}{2}$.

In two-dimensional case, radial and circular displacements in a polar coordinate system are determined for an elastic medium by means of the potentials φ_0 and ψ_0 in the form:

$$u_r=\frac{\partial\varphi_0}{\partial r}+\frac{1}{r}\frac{\partial\psi_0}{\partial\theta}\ ,\ u_\theta=\frac{1}{r}\frac{\partial\psi_0}{\partial\theta}-\frac{\partial\varphi_0}{\partial r} \tag{17}$$

where, the potentials φ_0 and ψ_0 satisfy the following wave equations

$$\Delta\varphi_0=\frac{1}{\alpha^2}\frac{\partial^2\varphi_0}{\partial t^2}\ ,\ \Delta\psi_0=\frac{1}{\beta^2}\frac{\partial^2\psi_0}{\partial t^2} \tag{18}$$

where, r is the distance of the particle from the pole, θ is a polar angle, and t is time.

The velocity of longitudinal and transverse waves is expressed in the following form:

$$\alpha^2=\frac{E\left(1-\upsilon\right)}{\rho\left(1-2\upsilon\right)\left(1+\upsilon\right)}\ ,\ \beta^2=\frac{E}{\rho\left(1+\upsilon\right)} \tag{19}$$

where, E is Young's modulus, υ is Poisson ratio, and ρ is density. We look for the potentials as follows:

$$\varphi_0=\varphi\left(r,t\right)\cos\theta\ ,\ \psi_0=\psi\left(r,t\right)\sin\theta \tag{20}$$

Then Equations (18) are written in the following form:

$$\frac{\partial^2\varphi}{\partial r^2}-\frac{1}{r}\frac{\partial\varphi}{\partial r}-\frac{1}{r^2}\varphi=\frac{1}{\alpha^2}\frac{\partial^2\varphi}{\partial t^2}$$
$$\frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}-\frac{1}{r^2}\psi=\frac{1}{\beta^2}\frac{\partial^2\psi}{\partial t^2} \tag{21}$$

We express the displacement as follows:

$$u_r=a\cos\theta\ ,\ u_0=b\sin\theta \tag{22}$$

Comparing formulas (17) and (22), for the coefficients $a(r,t)$ and $b(r,t)$ we obtain the following relation:

$$a=\frac{\partial\varphi}{\partial r}+\frac{1}{r}\psi\ ,\ b=-\frac{1}{r}\varphi-\frac{\partial\psi}{\partial r} \tag{23}$$

In Equation (21) removing the time by means of the Laplace transform (5), taking into account the initial zero conditions, for $\bar{\varphi}$ and $\bar{\psi}$ we obtain the following Bessel equations:

$$\frac{\partial^2\bar{\varphi}}{\partial r^2}+\frac{1}{r}\frac{\partial\bar{\varphi}}{\partial r}-\left(\frac{1}{r^2}+\frac{\omega^2}{\alpha^2}\right)\bar{\varphi}=0$$
$$\frac{\partial^2\bar{\psi}}{\partial r^2}+\frac{1}{r}\frac{\partial\bar{\psi}}{\partial r}-\left(\frac{1}{r^2}+\frac{\omega^2}{\beta^2}\right)\bar{\psi}=0 \tag{24}$$

Taking into account the boundedness condition at infinity, the solution of Equations (24) will be in the form:

$$\bar{\varphi}=C_1K_1\left(\frac{\omega r}{\alpha}\right)\ ,\ \bar{\psi}=C_2K_1\left(\frac{\omega r}{\beta}\right) \tag{25}$$

where, K_1 is a Macdonald function. The constants C_1 and C_2 in the surface of the cylinder are determined from the "sewing" boundary conditions

$$a=\frac{\partial\varphi}{\partial r}+\frac{1}{r}\psi=x(t)=\frac{t^2}{2}$$
$$b=-\frac{1}{r}\varphi-\frac{\partial\psi}{\partial r}=-x(t)=-\frac{t^2}{2} \tag{26}$$

Applying the Laplace transform to the expressions (26), we obtain the following relations:

$$\begin{cases}\dfrac{\partial\bar{\varphi}}{\partial r}+\dfrac{1}{r}\bar{\psi}=\dfrac{1}{\omega^3} \\ -\dfrac{\bar{\varphi}}{r}-\dfrac{\partial\bar{\psi}}{\partial r}=-\dfrac{1}{\omega^3}\end{cases}\qquad r=r_0$$

In the last system, substituting the Equation (25) for $\bar{\varphi}$ and $\bar{\psi}$, we determine C_1 and C_2:

$$\frac{\omega}{\alpha}C_1K_1'\left(\frac{\omega r_0}{\alpha}\right)+\frac{1}{r_0}C_2K_1\left(\frac{\omega r_0}{\beta}\right)=\frac{1}{\omega^3}$$
$$-\frac{1}{r_0}C_1K_1\left(\frac{\omega r_0}{\alpha}\right)-\frac{\omega}{\beta}C_2K_1'\left(\frac{\omega r_0}{\beta}\right)=-\frac{1}{\omega^3}$$

So,

$$C_1=\frac{\frac{1}{\omega^3}\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)-\frac{1}{\omega^3}\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)}{-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)+\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)}$$

$$C_2=\frac{-\frac{1}{\omega^3}\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)-\frac{1}{\omega^3}\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)}{-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)+\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)}$$

In surface deformation case, the displacements are related to the stresses in the following form:

$$\sigma_r=Q\left[(1-\upsilon)\varepsilon_r+\upsilon\varepsilon_\theta\right]\ ,\ \sigma_{\theta r}=Q\left[(1-\upsilon)\varepsilon_\theta+\upsilon\varepsilon_r\right]$$
$$\sigma_{r\theta}=G\varepsilon_{r\theta}$$

where, $Q=\dfrac{E}{(1-2\upsilon)(1+\upsilon)}$, $G=\dfrac{E}{1+\upsilon}$.

Taking into account that;

$$\varepsilon_r=\frac{\partial u_r}{\partial r}\ ,\ \varepsilon_\theta=\frac{1}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{u_r}{r}\ ,\ \varepsilon_{r\theta}=\frac{1}{r}\frac{\partial u_r}{\partial\theta}+\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}$$

Then,

$$\sigma_r=Q\left[(1-\nu)\frac{\partial u_r}{\partial r}+\frac{u}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{\nu}{r}u_r\right]$$
$$\sigma_\theta=Q\left[\frac{(1-\nu)}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{1-\nu}{r}u_r+\nu\frac{\partial u_\theta}{\partial\theta}\right] \tag{27}$$
$$\sigma_{r\theta}=G\left[\frac{1}{r}\frac{\partial u_r}{\partial\theta}+\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}\right]$$

It is assumed that the particles of the medium glued to the embedding move without leaving it. It is case, the pressure of the medium to r_0 radius and unit thickness embedding is as follows:

$$R=r_0\int_0^{2\pi}qd\theta \tag{28}$$

where, q is a specific pressure. Taking into account the symmetry of displacements along the direction of its axis, the quantity q is determined as follows:

$$q=\sigma_r\cos\theta-\sigma_{r\theta}\cos\theta \tag{29}$$

Allowing for (23), we substitute the relations (22) in (27):

$$\sigma_r=Q\left[(1-\nu)\frac{\partial u_r}{\partial r}+\frac{u}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{\nu}{r}u_r\right]=$$
$$=Q\left\{(1-\nu)\frac{\partial}{\partial r}\left[\left(\frac{\partial\varphi}{\partial r}+\frac{1}{r}\psi\right)\cos\theta\right]+\right.$$
$$\left.+\frac{\nu}{r}\frac{\partial}{\partial\theta}\left[\left(\frac{\varphi}{r}-\frac{\partial\psi}{\partial r}\right)\sin\theta\right]+\frac{\nu}{r}\frac{\partial}{\partial\theta}\left[\left(\frac{\partial\varphi}{\partial r}+\frac{\psi}{r}\right)\cos\theta\right]\right\}=$$
$$=Q\left[(1-\nu)\frac{\partial^2\varphi}{\partial r^2}\cos\theta+\frac{(1-\nu)}{r}\frac{\partial\psi}{\partial r}\cos\theta-\frac{(1-\nu)}{r^2}\psi\cos\theta\right]-$$
$$-\frac{\nu}{r}\left[\left(\frac{\varphi}{r}+\frac{\partial\psi}{\partial r}\right)\cos\theta+\frac{\nu}{r}\left(\frac{\partial\varphi}{\partial r}+\frac{\psi}{r}\right)\cos\theta\right]=$$
$$=Q\left\{\cos\theta\left[(1-\nu)\frac{\partial^2\varphi}{\partial r^2}+\frac{(1-\nu)}{r}\frac{\partial\psi}{\partial r}-\frac{(1-\nu)}{r^2}\psi-\right.\right.$$
$$\left.\left.-\frac{\nu}{r}\left(\frac{\varphi}{r}+\frac{\partial\psi}{\partial r}\right)+\frac{\nu}{r}\left(\frac{\partial\varphi}{\partial r}+\frac{\psi}{r}\right)\right]\right\}=$$

$$=Q\cos\theta\left[(1-\nu)\frac{\partial^2\varphi}{\partial r^2}-\frac{\nu}{r^2}\varphi+\frac{\nu}{r}\frac{\partial\varphi}{\partial r}-\frac{(1-2\nu)}{\partial r}\frac{\partial\psi}{\partial r}-\frac{(1-2\nu)}{r^2}\right],$$

$$\sigma_{r\theta}=G\left[\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{\partial u_\theta}{\partial\theta}+\frac{u_\theta}{r}\right]=$$

$$=G\left\{\frac{1}{r}\left[\frac{\partial}{\partial\theta}\left(\frac{\partial\varphi}{\partial r}+\frac{1}{r}\psi\right)\cos\theta\right]+\frac{\partial}{\partial r}\left[\left(-\frac{\varphi}{r}-\frac{\partial\psi}{\partial r}\right)\sin\theta\right]+\right.$$

$$\left.+\frac{1}{r}\frac{\partial}{\partial\theta}\left[\left(-\frac{\partial\psi}{\partial r}-\frac{\varphi}{r}\right)\sin\theta\right]\right\}=$$

$$=G\left[\left(-\frac{\partial\varphi}{r\partial r}-\frac{\psi}{r^2}\right)\sin\theta+\left(\frac{\varphi}{r^2}-\frac{1}{r}\frac{\partial\varphi}{\partial r}-\frac{\partial^2\psi}{\partial r^2}\right)\sin\theta\right]+$$

$$+\left(\frac{\varphi}{r^2}+\frac{\partial\psi}{r\partial r}\sin\theta\right)=$$

$$=G\sin\theta\left\{\frac{2}{r}\frac{\partial\varphi}{\partial r}+\frac{\partial\psi}{r\partial r}+\frac{2}{r^2}\varphi-\frac{1}{r^2}\psi-\frac{\partial^2\psi}{\partial r^2}\right\}$$

Then, we obtain the following relations:

$$\frac{\sigma_r}{Q\cos\theta}=(1-\upsilon)\frac{\partial^2\varphi}{\partial r^2}+\frac{\upsilon}{r}\frac{\partial\varphi}{\partial r}-\frac{1-2\upsilon}{r}\frac{\partial\psi}{\partial r}-\frac{1-2\upsilon}{r^2}\psi-\frac{\upsilon}{r^2}\varphi \tag{30}$$

$$\frac{\sigma_{r\theta}}{G\sin\theta}=-\frac{\partial^2\psi}{\partial r^2}-\frac{2}{r}\frac{\partial\varphi}{\partial r}+\frac{1}{r}\frac{\partial\psi}{\partial r}+\frac{2}{r^2}\varphi-\frac{1}{r^2}\psi$$

Applying the Laplace transform to (28) and (30), for determining the reaction force we obtain the following expression:

$$\bar{R}=r_0\int\left(\bar{\sigma}_r\cos\theta-\bar{\sigma}_{r\theta}\sin\theta\right)\Big|_{r=r_0}\partial\theta=$$
$$=\pi\mu r_0\left(\frac{1}{k^2}\frac{\partial\bar{a}}{\partial r}-\frac{\partial\bar{b}}{\partial r}\right)\Bigg|_{r=r_0} \tag{31}$$

where,

$$k=\frac{\beta}{\alpha}=\sqrt{\frac{1-2\upsilon}{2(1-\upsilon)}} \tag{32}$$

Calculate the following expression for $r=r_0$:

$$\left(\frac{1}{K^2}\frac{\partial\bar{a}}{\partial r}-\frac{\partial\bar{b}}{\partial r}\right)\Bigg|_{r=r_0}=\left(\frac{1}{K^2}\frac{\partial\bar{\varphi}}{\partial r}+\frac{1}{K^2 r}\bar{\psi}+\frac{1}{r}\bar{\varphi}+\frac{\partial\bar{\psi}}{\partial r}\right)\Bigg|_{r=r_0}=$$

$$=\frac{\omega}{\alpha}C_1K_1'\left(\frac{\omega r_0}{\alpha}\right)+\frac{1}{r_0}C_2K_1\left(\frac{\omega r_0}{\beta}\right)+\frac{1}{r_0}C_2K_1\left(\frac{\omega r_0}{\alpha}\right)+$$

$$+\frac{\omega}{\beta}C_1K_1'\left(\frac{\omega r_0}{\beta}\right)=C_1\left[\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)+\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)\right]+$$

$$+C_2\left[\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)+\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)\right]=$$

$$=\frac{\frac{1}{\omega^3}\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)-\frac{1}{\omega^3}\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)}{-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)+\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)}\times$$

$$=\frac{\frac{1}{\omega^3}\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)-\frac{1}{\omega^3}\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)}{-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)+\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)}\times$$

$$\times\left[\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\beta}\right)+\frac{K_1}{r_0}\left(\frac{\omega r_0}{\alpha}\right)\right]+$$

$$+\frac{-\frac{1}{\omega^3}\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)-\frac{1}{\omega^3}\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)}{-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\alpha}\right)+\frac{\omega}{\alpha}K_1'\left(\frac{\omega r_0}{\alpha}\right)\frac{\omega}{\beta}K_1'\left(\frac{\omega r_0}{\beta}\right)}\times$$

$$\times\left[\frac{K_1}{r_0}\left(\frac{\omega r_0}{\beta}\right)+\frac{\omega}{\alpha}K_1\left(\frac{\omega r_0}{\beta}\right)\right]$$

After some transformations we obtain

$$\bar{R}=\pi\mu r_0\left\{\frac{1}{k^2}\times\right.$$

$$\times\frac{\left[K_1'(q)\frac{\omega}{\beta}-\frac{1}{r_0}K_1(q)\right]\left[K_1''(p)\frac{\omega^2}{\alpha^2}+K_1'(p)\frac{\omega}{r_0\alpha}-\frac{1}{r_0^2}K_1(p)\right]}{\frac{\omega^4}{\alpha\beta}K_1'(p)K_1'(q)-\frac{\omega^2}{r_0^2}K_1(p)K_1(q)}+$$

$$\left.+\frac{\left[K_1'(p)\frac{\omega}{\alpha}-\frac{1}{r_0}K_1(q)\right]\left[K_1''(q)\frac{\omega^2}{\beta^2}-K_1'(q)\frac{\omega}{r_0\beta}-\frac{1}{r_0^2}K_1(q)\right]}{\frac{\omega^4}{\alpha\beta}K_1'(p)K_1'(q)-\frac{\omega^2}{r_0^2}K_1(p)K_1(q)}\right\}$$

$$\left(\frac{\omega r_0}{\beta}\right)=q\ ,\ \left(\frac{\omega r_0}{\alpha}\right)=p \tag{33}$$

At large values of $|\omega|$ from the expression (33) we obtain the asymptotic expansion for R.

$$\bar{R}=-\pi\rho\left[(1+k)r_0\alpha\frac{1}{\omega^2}+\frac{4k-1-k^\alpha}{2}\frac{\alpha^2}{\omega^3}+...\right] \tag{34}$$

Passing from images to originals, the expansion for the function $R(t)$ in the form of the Maclaurin series will be in the following form:

$$R=-\pi\rho\left[(1+k)r_0\alpha t+\frac{4k-1-k^\alpha}{2}\alpha^2t^2+...\right] \tag{35}$$

Passing to the limit as $k=\beta/\alpha\to 0$ in the Equations (34)-(35) in the compressible liquid for $\bar{R}$ and R we obtain the following formulas:

$$\bar{R}=-\pi\rho\left[r_0\alpha\frac{1}{\omega^2}-\frac{1}{2}\frac{\alpha^2}{\omega^3}+...\right] \tag{36}$$

$$R=-\pi\rho\left[r_0\alpha t-\frac{1}{4}\alpha^2t^2+...\right] \tag{37}$$

Now let us consider rotational movement of the cylinder in an elastic medium changing by the law;

$$\varphi=\frac{u_\theta\big|_{r=r_0}}{r_0}=\frac{t^2}{2} \tag{38}$$

Applying Laplace transform (5) in the following

$$\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_{\theta r}}{\partial r}-\frac{u_\theta}{r}=\frac{1}{\beta^2}\frac{\partial^2 u_\theta}{\partial t^2} \quad (39)$$

we obtain the Bessel equation

$$\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_{\theta r}}{\partial r}-\left(\frac{1}{r^2}+\frac{\omega^2}{\beta^2}\right)\overline{u}_\theta \quad (40)$$

Using the condition of boundedness at infinity, the solution of this equation will be

$$\overline{u}_0 = CK_1\left(\frac{\omega r}{\beta}\right) \quad (41)$$

Using boundary condition (38) we can determine this coefficient C. Then for the reactive moment, we obtain the following expression:

$$\overline{M}(\omega)=\frac{2\pi r_0^3}{\omega_3 K_1\left(\frac{\omega r_0}{\beta}\right)}\left[K_1'\left(\frac{\omega r_0}{\beta}\right)\frac{\omega}{\beta}-\frac{1}{r_0}K_1\left(\frac{\omega r_0}{\beta}\right)\right] \quad (42)$$

where, the formula;

$$M=2\pi r_0^3\mu\left(\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}\right)\Bigg|_{r=r_0} \quad (43)$$

of the reactive moment was used. The asymptotic expansion of (42) will be

$$\overline{M}=-2\pi r_0^2\mu\left[\frac{1}{\beta\omega^2}-\frac{3}{2r_0\omega^3}+...\right] \quad (44)$$

Now, let us consider longitudinal movement of the cylinder in an elastic medium changing by the law;

$$z=u_z\Big|_{r=r_0}=\frac{t^2}{2} \quad (45)$$

Applying the Laplace transform (45) in the following equation

$$\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_{\theta z}}{\partial r}=\frac{1}{\beta^2}\frac{\partial^2 u_z}{\partial t^2} \quad (46)$$

We obtain the Bessel equation;

$$\frac{\partial^2 \overline{u}_z}{\partial r^2}+\frac{1}{r}\frac{\partial \overline{u}_z}{\partial r}-\frac{\omega^2}{\beta^2}\overline{u}_z=0 \quad (47)$$

Using the condition of boundedness at infinity, the solution of this equation will be;

$$\overline{u}_z=CK_0\left(\frac{\omega r}{\beta}\right) \quad (48)$$

Finding the coefficient C from the condition (45), using the formula

$$R=2\pi r_0\,\mu\frac{\partial u_z}{\partial r}\Bigg|_{r=r_0} \quad (49)$$

For the lateral reaction, for $\overline{R}_z$ we can obtain the following expression:

$$\overline{R}_z=2\pi r_0\,\mu\frac{K_0'\left(\frac{\omega r_0}{\beta}\right)\frac{\omega}{\beta}}{\omega_3 K_1\left(\frac{\omega r_0}{\beta}\right)} \quad (50)$$

The asymptotic expansion of the latter will be as follows:

$$\overline{R}_z=-\frac{2\pi r_0\,\mu}{\beta}\left[\frac{1}{\omega^2}+\frac{1}{2}\frac{\beta}{r_0}\frac{1}{\omega^3}+...\right] \quad (51)$$

Passing to the originals in (51), for $\overline{R}_z$, we obtain the following expansion in the form of Maclaurin series:

$$R_z=-2\pi r_0\,\rho\beta t-\frac{1}{2}\pi\rho\beta^2t^2+... \quad (52)$$

Assume that the medium is linear viscous- elastic and satisfies the relations (13). In this can the appropriate complex modules are determined by formulas (14). The speed of the function is rather complex; therefore, it is difficult to find in the elastic medium the original of reaction for the cylinder. Therefore, applying the compatibility principle, from asymptotic expansion (34) we find the original of in function $R(t)$ for small values of time.

For simplicity we accept that modules (13) are proportional, i.e. formula (15) is satisfied. Then thee to viscous - elastic modulus ν_1 corresponding to the Poisson ratio will be a constant number. At the same time, the modules k corresponding to (16) will be the constant k_1. Furthermore, in the expansion (34) at large values of $|\omega|$ and α should be replaced by the following modules:

$$\alpha_1=\lim_{\omega\to\infty}\sqrt{\frac{1}{\rho}\left[\frac{1}{3}\left(Y_\nu-Y_S\right)+Y_S\right]}= \\ =\lim_{\omega\to\infty}\sqrt{\frac{1}{3\rho}\left(Y_\nu+2Y_S\right)}=\lim_{\omega\to\infty}\sqrt{\frac{1+2\delta}{3\rho}\frac{b_0+b_1\omega}{a_0+a_1\omega}} \quad (53)$$

In the particular case, for the Kelvin and Maxwell $(\alpha\neq 0)$ model we obtain:

$$\alpha_1=\sqrt{\frac{(1+2\delta)b_1}{3\rho\alpha_1}} \quad (54)$$

In the case when the Foight model $\alpha_1=0$, for the quantity α_1, we get the following expression

$$\alpha_1=\sqrt{\frac{(1+2\delta)b_1\omega}{3\rho\alpha_0}}=\sqrt{A\omega} \quad (55)$$

Therefore, based on the accepted assumptions, in the case of Kelvin or Maxwell modulus, for the reaction R we obtain expansion from (55) by substituting k with k_1, for viscous-elastic materials substituting the speed α of longitudinal waves with the appropriate spell α_1. For the Fight model from (34) we obtain the following expression:

$$\overline{R}=-\pi\rho+\left[(1+k_1)r_0\sqrt{A}\frac{1}{\omega^2}+\frac{4k_1-1-k_1^2}{2}A\frac{1}{\omega^2}+...\right] \quad (56)$$

Then from (35) we obtain the following expansion:

$$\overline{R}=-\pi\rho+\left[\frac{2(1+k_1)r_0\sqrt{A}}{\sqrt{\pi}}\sqrt{t}+\frac{4k_1-1-k_1^2}{2}At+...\right] \quad (57)$$

4. CONCLUSIONS

The lateral reaction of the embedding (cylinder) in the Kelvin or Maxwell viscous-elastic medium and during rotational movement the moment and longitudinal reaction can be obtained from the expansions (44) and (52) respectively. In this case, the β speed of the considered material of the transverse waves should be replaced by the appropriate momentary elasticity, by the β_1 speed. When the medium is a viscous-elastic Fight medium, reactive moment and longitudinal reaction can be determined by means of the compatibility principle, from the expansion (57) obtained from (44) and (51).

Finally, we can note that by means of formula (34) and the composability principle, we can determine the reaction of viscous-elastic liquid to the circular embedding. In this case, the tangential stress in this viscous-elastic medium (Y_S=0) equals to zero, volumetric change is expressed by means of the Kelvin, Maxwell or Voigt model.

1. The paper investigates the unsteady motion of a cylindrical insert in a linear viscoelastic medium. Here the problem is solved for the case of preliminary transmission of the law of motion change. The normal reaction force of the structure and the medium to the insert and the torque it creates are determined.
2. Since the rate of action of the reactionary forces is difficult, it was found that using the asymptotic separation of the Macleron order shows the accuracy of the solution.
3. It is proved that the solution of dynamic problems for viscoelastic media is obtained from solving the corresponding problems for elastic media by applying the Laplace integral transformation.
4. Having determined the elastic constants characterizing the medium, it is possible on the basis of the principle of coherence, replacing the corresponding viscoelastic media with complex modules and performing the reverse transformation.
5. It is proved that the approximation allows you to apply different models by choosing constants.

Thus, as a result, it is possible to determine the strength of the reaction, the moment of the reaction and the longitudinal reactions in various cases.

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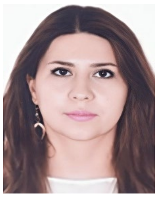

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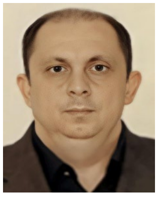

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