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Issue **Article**

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VIBRATIONS OF A CYLINDRICAL BODY IN A VISCOELASTIC MEDIUM

Abstract*: This article considers the diffraction of harmonic waves on an elliptical cylindrical cavity made of an elastoplastic material. The problem of diffraction on elliptical cylindrical bodies with a concave shape, affected by an elastoplastic medium, and their specific features have not yet been sufficiently studied in terms of methodology, algorithm, and program creation. The aim of this research is to develop a methodology and algorithm for studying the dynamic deformation of an elliptical cylindrical body with a concave shape in an elastoplastic medium. The equations describing the diffraction process are formulated using the Mate function. It is established that the frequency of oscillations in an elliptical cavity depends not only on the Poisson's ratio but also on the aspect ratio of the ellipse.*

Key words*: elliptic cylindrical space, displacement wave diffraction, Mate equation, Puasson coefficient, specific fluctuations.*

Language*: English*

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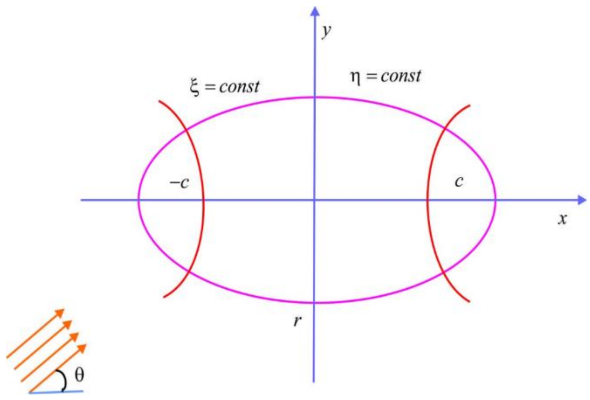
Introduction

The problem of studying the mutual influence of underground structures with the ground is considered important. Different types of underground structures can be used to solve this problem. In recent years, the construction of underground communications has been actively carried out in seismic zones. Therefore, it is necessary to assess the reliability of such structures (tunnels, pipelines, underground roads, etc.) under the influence of seismic and landslide processes, and studies the state of deformation and strengthening [1-3]. To study the state of underground structures under seismic influence, there are two main methods: experimental research and theoretical analysis [4, 5]. The methodology, algorithm, and program for studying the diffraction and special properties of elastic materials in elliptical cylindrical bodies interacting with each other and a vibrating environment has not been sufficiently solved [6-9]. In addition, there is no established scientific basis for studying the special properties of non-dissipative cylindrical bodies. The methodology, algorithm, and program for studying the diffraction and special properties of non-dissipative cylindrical bodies has not been sufficiently resolved [10, 11]. Various theoretical concepts have been proposed to address these issues of non-dissipative cylindrical bodies with either a segmented or non-segmented design, with the results (approximate and precise) requiring further scrutinization and utilization.

2.Methods

2.1. Purpose of the study

The purpose of the research is to develop a methodology and algorithm for studying the dynamic deformation state of a cylindrical body consisting of an ellipsoidal neck section located in a rubber-elastic environment under the influence of harmonic vibrations, and to obtain and analyze quantitative results (Figure 1). This article discusses the problem of diffraction of harmonic waves on an elliptical cylindrical cavity in an elastic medium, and presents a method for solving this problem and the numerical results. The connection between deformation and distortion is expressed by the Bolzmann-Volterra integral. The diffraction of harmonic waves in an elliptical cavity is related to the problem of the theory of elasticity in a purely deformed state. The problem of the relationship between elasticity and deformation in the elastic medium is solved by using the Lame equation for a deforming solid.



1- Figure. Schematic representation of an elliptical cavity.

The equations that express the processes of diffraction are derived using the wave equation and are solved using the Math function. Finite results are obtained and analyzed. The diffraction of elastic and acoustic waves on cylindrical bodies with a smooth profile has been widely studied by domestic and foreign scientists. The problem of the diffraction of elastic waves on isotropic elastic cylindrical bodies with a smooth profile has been investigated in works [12,13] where the mutual influence of the elastic waves is considered.

2.2. Method of laying and solving the issue

Let's suppose that an elliptical cavity is given in an elliptic coordinate system in an elastic medium (Figure 1). Let a harmonic pulse (SH pulse) propagate along the OX axis at an angle to the major axis of the elliptical cavity. The pulse front is parallel to the Z axis. The problem under consideration relates to the mechanics of deformable solid bodies and is a boundary value problem in the theory of elasticity. Under these conditions, the following relationships hold.

$$u = v = 0,\ w = w(x, y, t) = w(\xi, \eta, t) \quad . \qquad (1)$$

The connections between the strengthening and deformation in physics are described by the Boltzmann-Volterra integral and can be expressed as follows:

$$\sigma_{ij} = \tilde{\lambda}_c \varepsilon_{kk} \delta_{ij} + 2\tilde{\mu}_c \varepsilon_{ij} (i, j, k = 1, 2, 3) \ , \qquad (2)$$

Here $\sigma_{ij}, \varepsilon_{ij}$ – respectively, components of the tension and deformation Tensor, $\tilde{\lambda}_c$, $\tilde{\mu}_c$ -Volterra operator [14]:

$$\tilde{\lambda}_c \phi(t) = \lambda_{0c} \left[\phi(t) - \int_{-\infty}^{t} R_{c\lambda}(t-\tau)\phi(\tau) d\tau \right];$$

$$\tilde{\mu}_c \phi(t) = \mu_{0c} \left[\phi(t) - \int_{-\infty}^{t} R_{c\mu}(t-\tau)\phi(\tau) d\tau \right].$$

Here $\lambda_{0c}, \mu_{0c}, R_{c\lambda}, R_{c\mu}$ –

Lame parameters and nuclear relaxation of the environment,

$\phi(t)$ - time arbitrary function. Using the main equations of the dynamics of deformations, we derive the following w equation for the elastic medium in terms of the displacement dynamics.

$$\Delta w - \int_{-\infty}^{t} R_{c\lambda}(t-\tau) \Delta w(\tau) d\tau = \frac{1}{c_{cs}^2} \frac{\partial^2 w}{\partial t^2}. \qquad (3)$$

If we use the relationships (1) and (2) mentioned above, then we can identify the deformations that occur in the environment due to the impact of compression forces. They can be described as follows:

$$\sigma_{\xi z} = \frac{\mu_{0c}}{H} \frac{\partial w}{\partial \xi} - \frac{\mu_{0c}}{H} \int_{-\infty}^{t} R_{c\mu}(t-\tau) \frac{\partial w(\tau)}{\partial \xi} d\tau, \qquad (4)$$

$$\sigma_{\eta z} = \frac{\mu_{0c}}{H} \frac{\partial w}{\partial \eta} - \frac{\mu_{0c}}{H} \int_{-\infty}^{t} R_{c\mu}(t-\tau) \frac{\partial w(\tau)}{\partial \eta} d\tau.$$

Here $H = c\sqrt{ch^2 \xi - \cos^2 \eta}$, $2c$ – focal length; *w*-displacement of ambient points at displacement. Assuming conditions for being free of deformations caused by compression on an elliptical cross-sectional cylindrical cavity located in an elastic medium, the condition can be expressed as follows:

$$\sigma_{\xi z} \Big|_{\Sigma_1} = 0,\ \Sigma_1 = \Sigma_1 (\xi = \xi_0, 0 \le \eta \le 2\pi) \qquad (5)$$

The utilization condition of Somerfield's invariance in an elliptic vacuum is carried out infinitely. The shape of the SH *XOY* - surface that comes to the elliptical void from infinity due to the infinity is as follows:

$$w_0 = Ae^{i(k_1(x\cos\theta + y\sin\theta) - \omega t)}, \qquad (6)$$

Here A- descending wave amplitude, in the case of the set, this magnitude will be given by; $k_1 = \dfrac{\omega}{c_{s1}}$ wavenumber, θ – the angle at which the falling wave is aligned with the axis of the Ox. The solution of the equation (3) presented above is sought as follows

$$w^{\square} = W(\xi,\eta)e^{i\omega t}, \qquad (7)$$

Here $W(\xi,\eta)$ - is the displacement amplitude and satisfies the following complex parametric differential equation $\left[\frac{1}{c^2H^2}\left(\frac{\partial^2}{\partial\xi^2}+\frac{\partial^2}{\partial\eta^2}\right)+(\alpha_1\Gamma_1)^2\right]W(\xi,\eta)=0$, (8)

Here $\Gamma_1(\omega)=1-\Gamma_1^c(\omega)+i\Gamma_1^s(\omega), k_1^2=\omega^2\rho/\mu_{01}, \alpha_1^2=k_1^2/c_{s1}^2$

Under the influence of the SH wave, the expression for the displacement in the elliptic coordinate system, which can occur in a cavity-elastic medium, is given as follows [15]:

$$w_0 = A\sum_{n=0}^{\infty} i^n \begin{bmatrix} Ce_n(\xi,q)ce_n(\eta,q)Ce_n(\theta,q)+ \\ +iSe_{n+1}(\xi,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} e^{i\omega t}. \qquad (9)$$

Here ce_n and se_n - Periodic (trigonometric) functions of Mate, Ce_n, Se_n - Radial or modulated functions of the Mate. The general solution of the equation (8) presented above is expressed through the Mate function and appears as follows

$$w^{\square} = \sum_{n=0}^{\infty} \begin{bmatrix} C_n Me_n^{(1)}(\xi,q)ce_n(\eta,q)ce_n(\theta,q)+ \\ +S_{n+1}Ne_{n+1}^{(1)}(\xi,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} e^{i\omega t}, q=\frac{1}{4}(\alpha_1\Gamma_1 c)^2 \qquad (10)$$

Here $Me_n^{(1)}(\xi,q)$ and $Ne_{n+1}^{(1)}(\xi,q)$ - Mathieu - Hankel functions, C_n and S_{n+1} integral constants or arbitrary constants.

The general solution (10) mentioned above expresses the reflection or diffraction of incident waves on an elastic medium-medium interface [16,17]. By the reflected wave that returns from the surroundings of the elliptic cavity, the increase in displacement amplitude is obtained by the addition of the incident and reflected waves: $w = w_0 + w^{\square}$.

These waves are quantified by the Sommerfeld's radiation condition, which is established by defining the Mathieu function. The arbitrary constant amplitudes in the last solution (5) are determined by the boundary condition. To find these arbitrary constants, we use the following relation.

$$\sum_{n=0}^{\infty} \begin{bmatrix} C_n Me_n^{(1)\prime}(\xi_0,q)ce_n(\eta,q)ce_n(\theta,q)+ \\ +S_{n+1}Ne_{n+1}^{(1)\prime}(\xi_0,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} +$$

$$+A\sum_{n=0}^{\infty} i^n \begin{bmatrix} Ce_n^{(1)\prime}(\xi_0,q)ce_n(\eta,q)ce_n(\theta,q)+ \\ +iSe_{n+1}^{(1)\prime}(\xi_0,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} = 0 \qquad (11).$$

Multiplying the two sides of the last (11) equation in accordance with the mat'e function $ce_0(\eta,q), ce_1(\eta,q),.....$ and $se_{n+1}(\eta,q)$ if we integral the ham over the length of the Ellipse, and using the orthogonality property of the mat'e function, then arbitrary invariant magnitudes can be found:

$$C_n = -i^n ACe_n'(\xi_0,q)/Me_n(\xi_0,q),$$
$$S_{n+1} = -i^{n+1}ASe_{n+1}'(\xi_0,q)/Ne_{n+1}(\xi_0,q). \qquad (12)$$

Putting the arbitrary constants found from (12) in (10), then we find the complete representation or expression of the displacement. This gives a private solution to the last expression (8) and takes the following view

$$w = A\sum_{n=0}^{\infty} i^n \begin{bmatrix} Ce_n(\xi,q)ce_n(\eta,q)Ce_n(\theta,q)+ \\ +iSe_{n+1}(\xi,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} e^{i\omega t} +$$

$$+\sum_{n=0}^{\infty} \begin{bmatrix} (-i^n ACe_n'(\xi_0,q)/Me_n(\xi_0,q))Me_n^{(1)}(\xi,q)ce_n(\eta,q)ce_n(\theta,q)+ \\ +(-i^{n+1}ASe_{n+1}'(\xi_0,q)/Ne_{n+1}(\xi_0,q))Ne_{n+1}^{(1)}(\xi,q)se_{n+1}(\eta,q)se_{n+1}(\theta,q) \end{bmatrix} e^{i\omega t},$$

From this displacement expression, it becomes possible to find the concentricity ($\sigma_{\eta z}^{\square} = \sigma_{\eta z}/2\mu_{0c}$) of the contour voltages produced in an ellipse transverse cross - sectional space in a Convex-elastic medium:

$$\sigma_{\eta z}^{\square} = \frac{A}{H}\sum_{n=0}^{\infty} i^n \begin{Bmatrix} \left[Ce_n(\xi,q)-Me_n(\xi,q)Ce_n'(\xi_0,q)/Me_n'(\xi_0,q)\right]Ce_n'(\eta,q)ce_n(\theta,q)+ \\ +i\left[Se_{n+1}(\xi,q)-Ne_{n+1}(\xi,q)Se_{n+1}'(\xi_0,q)/Ne_n'(\xi_0,q)\right]se_{n+1}'(\eta,q)se_{n+1}(\theta,q) \end{Bmatrix} e^{i\omega t}. \qquad (13)$$

When $\theta=0$ and $\xi=\xi_0=0$, the following condition on the displacement on the elliptic Σ_1 surface is satisfied:

$$w\big|_{\Sigma_1} = \sum_{n=0}^{\infty} i^n ce_n(\xi,\eta)ce_n(0,q)/ce_n(\pi/2,q)e^{i\omega t} \qquad (14)$$

Numerical results were obtained based on equations (13) and (14) when calculating expansion and contraction, resulting in finite results of complex numbers. The main goal is to find the $|\sigma_{max}| = |H\sigma_{\eta z\max}/2\mu_{01}A|$ constant that represents the concentration of maximum contraction related to b/a and θ. Due to the elongated environment of the elliptical conical cylindrical cube, the issue being studied can be approached using the theory of elasticity in the problem of single deformation. In this case, the differential equation of motion in elliptical coordinate systems (Figure1) leads to the Lame equation [19,20], and using the potentials of expansion and contraction along the elliptical boundary, it is expressed as follows:

$$u_{\xi\kappa} = \frac{1}{aJ}\left(\frac{\partial\phi_\kappa}{\partial\xi} + \frac{\partial\psi_\kappa}{\partial\eta} + e\frac{\partial^2\chi_\kappa}{\partial\xi\partial z}\right);$$
$$u_{\eta\kappa} = \frac{1}{aJ}\left(\frac{\partial\phi_\kappa}{\partial\eta} - \frac{\partial\psi_\kappa}{\partial\xi} + e\frac{\partial^2\chi_\kappa}{\partial\eta\partial z}\right); \qquad (15)$$
$$u_{z\kappa} = \frac{\partial\phi_\kappa}{\partial z} + e\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c_{sk}^2}\frac{\partial^2}{\partial t^2}\right)\chi.$$

Here, $k=1,2$ describes the equation of motion for the environment and elliptical body in the conventional way, c_{sk}^2 - the speed of the oscillations. The characteristics of an elliptical cavity located in a homogeneous and elastic environment are described by its equation of motion, using the Lame equation for a simple problem of elastic theory. The condition that the forces at the boundary are zero is imposed for the solution of the problem.

$$\left[\frac{(\lambda+2\mu)}{aJ}\frac{\partial u_\xi}{\partial\xi} + \frac{\lambda}{aJ}\frac{\partial u_\eta}{\partial\eta} + \frac{\lambda sh2\xi}{2aJ^3}u_\xi + \frac{(\lambda+2\mu)}{2aJ^3}\sin 2\eta u_\eta\right]_\Gamma = 0,$$
$$\left[\frac{\lambda}{aJ}\frac{\partial u_\xi}{\partial\xi} + \frac{\lambda}{aJ}\frac{\partial u_\eta}{\partial\eta} + \frac{\lambda sh2\xi}{2aJ^3}u_\xi + \frac{\lambda}{2aJ^3}\sin 2\eta u_\eta\right]_\Gamma = 0. \qquad (16)$$

Moving potentials amplitudes $\phi_n(r), \psi_n(r)$ satisfies Gel'mgol's equations:

№	n=0	n=I	n=2	n=3
1	0,31529D+00 -i0,24476D+00	0,07927D+01 -i0,27538D+00	0,11075D+01 -i0,49782D+00	0,12755D+01 -i0,39915D+00
2			0,128621D+00 -i0,07852D+00	0,47232D+01 -i0,13223D+01
3			0,404607D+00 -i0,078552D+00	0,08123D+00 -i0,13228D+00

$$\nabla^2\phi_n + \alpha^2\phi_n = 0 \quad , \quad \nabla^2\psi_n + \beta^2\psi_n = 0 \quad .$$

The solutions of Gelmgolds equations are expressed through the Mate function. If we use (16) linear conditions, we can obtain a system of algebraic equations with complex coefficients. In order for this system to have a solution, the main determinant composed of coefficients with unknown values must be equal to zero [18]. The elements of the main determinant are calculated as a function of the complex parameter ω . To determine the complex parameter ω, we obtain the frequency equation as follows:

$$(n^2-1)F_n(x)F_n(y) - (y^2/2)F_n(x) + F_n(y) + n^2 - (n^2 - y^2/2)^2 = 0 \qquad (17)$$

Here $F_n(x) = xce_n(x)/se_n(x), \quad n = 1,2,3...$.

3. Results and their analysis

The complex parametric frequency equation (17) is solved using the Müller method. This transcendental equation has two parts of roots: the real (Re Ω) and the imaginary (Im Ω) parts. The real part of the complex frequency expresses the oscillation frequency of the mechanical system, while the imaginary part expresses the damping coefficient (attenuation coefficient). The results of the calculations $n \geq 0$ $(v_1 = 0{,}25)$ are presented in Table 1. Analysis of the results from the table shows that the real and imaginary parts of the complex frequency increase with the increase of the order (n). The frequency equation (17) is dependent only on the Poisson coefficient (ν) .

It was found that when the value of the Puasson coefficient $0 \leq \nu \leq 0{,}4$ changes in the range, the actual and abstract parts of the frequency change to 27%. Table 1. Change of complex frequency with respect to n.

4. Conclusions

The results obtained for a cylindrical cavity when a=b were compared with the results obtained for an elliptical cavity located in an elastic environment (by Prof. Safarov I.I.). The results were found to have a difference of up to 3%. The frequency of oscillations of the elliptical cavity located in an elastic environment was found to be dependent not only on the Poisson coefficient (ν), but also on the a/b parameter. When the value of the Poisson coefficient $0 \leq \nu \leq 0{,}4$ changed within a certain range, the real and imaginary parts of the frequency varied by up to 25%, and the dependence on a/b changed by up to 20%.

$$\frac{\partial^4 V}{\partial\eta^4} - 2\bar{r}^2\frac{\partial^2 V}{\partial\eta^2} - +\bar{S}^4 V = \frac{L^4}{D}q(x). \qquad (18)$$

Here $\bar{r}$, $\bar{S}$, L, D - constant parameters.

The problem was solved by the method of initial parameters. Taking into account the fact that the depth of the foundation changes when a concentrated load is applied to the elastic beam, a bending moment plot is constructed, as a result of which a decrease in the bending moment will occur.

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