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Original Article

Wave Propagation in a Well Located in an Isotropic Viscoelastic Medium

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Abstract *- Studies of propagation and diffraction of waves in the medium with wells are an urgent task in geophysics and geology. The present work is devoted to studying a cylindrical reinforced well with a liquid located in a viscoelastic medium. It is shown that the wave field observed in the well can be represented by a combination of different waves (hydro waves, water), differing in characteristic dispersion, spectrum behavior, and field distribution along the radius of the well. Dispersion curves of phase and group velocities are calculated for media with different viscoelastic parameters. It is found that at cutoff frequencies, transverse waves have abnormally low attenuation. It is revealed that at low phase velocities (hydro waves), with increasing wavelength, the real and imaginary parts of the phase velocity monotonically increase.*

Keywords *- Attenuation, Viscoelastic medium, Well, Hydro wave, Water waves, Liquid.*

1. Introduction

In recent years, during geophysical studies of wells and near the borehole space, much attention has been paid to the propagation of low-frequency and high-frequency limit waves. Real media have absorption for shear and volumetric deformations, which should be taken for attention in field geophysics when isolating oil and gas reservoirs by acoustic method [1,2]. Several works are devoted to studying the propagation of elastic vibrations in wells filled with liquid [3,4]. Meanwhile, as several data show, the attenuation of the transverse wave turns out to be the most sensitive to the parameters of collectors [5]. In [6], the dispersion equation for normal waves in the axisymmetric case is obtained, and the dispersion of hydro waves is studied. Also, in [7], a solution is constructed for the case of a source arbitrarily located in a well. In the article [8], a formal solution to the well-point source field problem is constructed. In [9, 10], attention is paid to the propagation of Stoneley waves and their low-frequency limit – hydro waves. In recent times, the theory of propagation of Stoneley and hydro waves has been built quite fully, which takes into account various details of the structure of the well [11,12].

[13] considered the acoustic characteristics in the metaverse environment with these evolving virtual spaces.

The article [14] analyses the prospects for applied mathematical and algorithmic support usage to study the sealing capability of contact shut-off valve sealing joints.

In work [15], the performance of two methods is compared for identifying dominant low-frequency vibrations.

The article [16] analyzes the reflection coefficient and high wave transmission coefficient on change in the coefficient of pipe wall roughness.

The article [17] for approximating and solving two-point boundary value problems deals with applying two Finite Difference discretization (Redlich-Kister) schemes.

In the article [18], several denoising methods are proposed to improve image quality.

In the present work, the propagation of natural waves of low-frequency and the high-frequency limit is investigated.

2. Methods

2.1. Problem statement and solution methods

In an infinite viscoelastic medium ($r > r_N$), a multilayer well ($1(r_0 < r < r_1)$, $2(r_1 \le r \le r_2)$, N ($r_{N-1} < r \le r_N$)) with a liquid ($0 \le r \le r_0$) is located. At a point with coordinates $r = 0, z = 0$, there is a point source of the delta function type $\delta(t)$. The wave propagation velocity and density in the corresponding media are denoted by $c_{pk}, c_{sk}, \rho_k (k = 1, \dots N)$ Equations of motion of the medium and the well, for longitudinal φ_k and transverse ψ_k potentials, are represented as

$$\frac{\partial^2\varphi_k}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi_k}{\partial r}+\frac{\partial^2\varphi_k}{\partial z^2}-\int_0^t R_{pk}(t-\tau)\nabla^2\varphi_{rk}(r,\tau)d\tau =$$
$$=\frac{1}{c_{pk}^2}\frac{\partial^2\varphi_k}{\partial t^2}\quad (k=1,2,3....N),$$
$$\frac{\partial^2\psi_{k-1}}{\partial r^2}+\frac{1}{r}\frac{\partial\psi_{k-1}}{\partial r}+\frac{\partial^2\psi_{k-1}}{\partial z^2}-$$
$$-\int_0^t R_{s(k-1)}(t-\tau)\nabla^2\psi_{k-1}(r,\tau)d\tau=\frac{1}{c_{s(k-1)}^2}\frac{\partial^2\psi_{k-1}}{\partial t^2}\quad ,$$
$$\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}. \tag{1}$$

Here $R_{pj}(t-\tau), R_{sj}(t-\tau)$ - are the relaxation cores.

In equations (1), put $\psi_0 = 0$ if there is a liquid in the pipe space. As is known, the voltages τ_{rrk}, τ_{rzk} and mixing u_{rk}, u_{zk} are determined through the potentials φ_k, ψ_k by the equalities

$$\tau_{rzj}=2\tilde{\mu}_j\left(\frac{\partial^2\varphi_j}{\partial r\partial z}-\frac{\partial^2\psi_j}{\partial z^2}\right)+\frac{\mu_j}{c_{sj}^2}\frac{\partial^2\psi_j}{\partial t^2};$$
$$\tau_{rrj}=\frac{\tilde{\lambda}_j}{c_{pj}^2}\frac{\partial^2\psi_j}{\partial t^2}+2\tilde{\mu}_j\frac{\partial^2\varphi_j}{\partial r^2}-2\tilde{\mu}_j\frac{\partial^2\psi_j}{\partial z\partial r}; \tag{2}$$
$$u_{rj}=\frac{\partial\varphi_j}{\partial r}-\frac{\partial\psi_j}{\partial z},$$
$$u_{zj}=\frac{\partial\varphi_j}{\partial z}+\frac{\partial\psi_j}{\partial r}+\frac{\psi_j}{r}.$$

Here $\tilde{\mu}_j, \tilde{\lambda}_j$ is the operator modulus of elasticity of the form:

$$\tilde{\lambda}_\kappa f(t)=\lambda_{0\kappa}\left[f(t)-\int_0^t R_{\lambda\kappa}(t-\tau)f(\tau)d\tau\right]; \tag{3}$$
$$\tilde{\mu}_\kappa f(t)=\mu_{0\kappa}\left[f(t)-\int_0^t R_{\mu\kappa}(t-\tau)f(\tau)d\tau\right],$$

$f(t)$– arbitrary function, $\lambda_{0\kappa}, \mu_{0\kappa}$– instantaneous elastic modulus.

For example, let us consider a plate $(r_0 < r < r_1)$ located in a viscoelastic medium $(r > r_1)$. At the interface of a viscoelastic medium with a liquid, the boundary conditions of the non-existence of normal components of mixing and stresses and the equality of tangential stresses in a solid to zero are met:

$$u_{r1}\Big|_{r=r_1}=u_{r2}\Big|_{r=r_1},\ u_{z1}\Big|_{r=r_1}=u_{z2}\Big|_{r=r_1},$$
$$\tau_{rz2}\Big|_{r=r_1}=\tau_{rz3}\Big|_{r=r_1},\ \sigma_{rr2}\Big|_{r=r_1}=\sigma_{rr3}\Big|_{r=r_1},$$
$$u_{r1}\Big|_{r=r_0}=\frac{\partial u_{r2}}{\partial t}\Big|_{r=r_0},\ u_{z1}\Big|_{r=r_0}=\frac{\partial u_{z2}}{\partial t}\Big|_{r=r_0}, \tag{4}$$
$$\tau_{rz1}\Big|_{r=r_0}=0.$$

To solve the system of integro-differential equations (1)-(4), take the Laplace and Fourier-Bessel transformations

$$\varphi_0=c_{s2}\int_0^\infty k\cos kzdk\int_{\sigma-i\infty}^{\sigma+i\infty}AJ_0(-ik\alpha_0)e^{k\eta c_{s2}t}d\eta;$$
$$\varphi_1=c_{s2}\int_0^\infty k\cos kzdk\int_{\sigma-i\infty}^{\sigma+i\infty}(BH_0^{(1)}(-ik\alpha_1)+CH_0^{(2)}(-ik\alpha_1))e^{k\eta c_{s2}t}d\eta;$$
$$\varphi_2=c_{s2}\int_0^\infty k\cos kzdk\int_{\sigma-i\infty}^{\sigma+i\infty}DH_0^{(2)}(-ik\alpha_2)e^{k\eta c_{s2}t}d\eta;$$
$$\psi_1=c_{s2}\int_0^\infty k\sin kzdk\int_{\sigma-i\infty}^{\sigma+i\infty}(LH_1^{(1)}(-ik\beta_1)+MH_1^{(2)}(-ik\beta_1))e^{k\eta c_{s2}t}d\eta;$$
$$\psi_2=c_{s2}\int_0^\infty k\sin kzdk\int_{\sigma-i\infty}^{\sigma+i\infty}EH_1^{(2)}(-ik\beta_2)e^{k\eta c_{s2}t}d\eta. \tag{5}$$

where $J_0, H_0^{(2)}, H_1^{(2)}$ – are, respectively, the Bessel, Hankel functions of the zero and first order of the second kind, k- is the wave number,

$$\alpha_j=\sqrt{1-\gamma_j^2m^2}, \gamma_j=c_{s01}/c_{p0j}, \beta_j=\sqrt{1-\delta_j^2m^2},$$
$$\delta_j=c_{s01}/c_{s0j}, m=c_\phi/\Gamma_s c_{s01}, j=0,1,2.$$

For the integrand functions in solution (5) to be unambiguous, from points $\pm i\gamma^{-1}, \pm i$ of the plane of the complex variable η, draw sections into the left half-plane parallel to the real axis, and fix the branches of radicals c_{p1}, c_{s1} with the condition $arg\ c_{p1} = arg\ c_{s1} = 0$ at $\eta > 0$. It can be shown that there is no complete field at the point $i\delta^{-1}$of branching. In solution (5), the unknown constants are determined from the boundary conditions (4). Then get an inhomogeneous system consisting of seven algebraic (complex) equations. This system is solved by the Gauss method by allocating the main element. By equating the main determinant of the system to zero, get the dispersion equation. An elastic mechanical system is considered if the deformable element's rheological properties are not considered.

If the physical and mechanical parameters of the deformable medium of the well are the same, then it will be possible to determine unknown arbitrary constants in the form analytically

$$A=-\frac{1}{2\pi}\frac{\rho_{12}\frac{c_\phi^4}{c_{s1}^4}\alpha_1 H_0^{(2)}(\Omega_x)-\alpha_0 H_1^{(2)}(\Omega_x)\left[(2.0-\frac{c_\phi^2}{c_{s1}^2})^2\frac{H_0^{(2)}(\Omega_y)}{H_1^{(2)}(\Omega_y)}-4\alpha_1\beta_1\frac{H_0^{(2)}(\Omega_{z1})}{H_1^{(2)}(\Omega_{z1})}+\frac{2i\alpha_1 c_\phi^2}{kr_0 c_{s1}^2}\right]}{\rho_{12}\frac{c_\phi^4}{c_{s1}^4}\alpha_1 J_0(\Omega_x)-\alpha_0 J_1(\Omega_x)\left[(2.0-\frac{c_\phi^2}{c_{s1}^2})^2\frac{H_0^{(2)}(\Omega_y)}{H_1^{(2)}(\Omega_y)}-4\alpha_1\beta_1\frac{H_0^{(2)}(\Omega_{z1})}{H_1^{(2)}(\Omega_{z1})}+\frac{2i\alpha_1 c_\phi^2}{kr_0 c_{s1}^2}\right]},$$

$$B=-\frac{1}{2\pi}\frac{i(2.0-\frac{c_\phi^2}{c_{s1}^2})\rho_{12}\frac{c_\phi^2}{c_{s1}^2}\frac{2}{\pi\Omega_x}\alpha_0\frac{1}{H_1^{(2)}(\Omega_y)}}{\rho_{12}\frac{c_\phi^4}{c_{s1}^4}\alpha_1 J_0(\Omega_x)-\alpha_0 J_1(\Omega_x)\left[(2.0-\frac{c_\phi^2}{c_{s1}^2})^2\frac{H_0^{(2)}(\Omega_y)}{H_1^{(2)}(\Omega_y)}-4\alpha_1\beta_1\frac{H_0^{(2)}(\Omega_{z1})}{H_1^{(2)}(\Omega_{z1})}+\frac{2i\alpha_1 c_\phi^2}{kr_0 c_{s1}^2}\right]}, \tag{6}$$

$$C=-\frac{1}{2\pi}\frac{-2.0\alpha_0\alpha_1\rho_{12}\frac{c_\phi^2}{c_{s1}^2}\frac{2}{\pi\Omega_x}\frac{1}{H_1^{(2)}(\Omega_{z1})}}{\rho_{12}\frac{c_\phi^4}{c_{s1}^4}\alpha_1 J_0(\Omega_x)-\alpha_0 J_1(\Omega_x)\left[(2.0-\frac{c_\phi^2}{c_{s1}^2})^2\frac{H_0^{(2)}(\Omega_y)}{H_1^{(2)}(\Omega_y)}-4\alpha_1\beta_1\frac{H_0^{(2)}(\Omega_{z1})}{H_1^{(2)}(\Omega_{z1})}+\frac{2i\alpha_1 c_\phi^2}{kr_0 c_{s1}^2}\right]},$$

Expressions (5) and (6) are solutions to the problem for the potential of fields in the well and medium.

The study of wave propagation in liquids has practical applications in acoustic logging. When paying attention to the viscoelastic properties of the material, the arguments of cylindrical functions become complex, making it difficult to calculate kinematic parameters.

Using (2) and (5), it will be possible to obtain the corresponding displacements and stresses in the medium and well if the point source is zero. Then, using boundary conditions to determine arbitrary integral constants get the system of homogeneous algebraic equations. For a system of homogeneous algebraic equations to have nontrivial solutions, a sufficiently basic determinant of this system must be zero. From this consideration, get a transcendental equation in the form

$$\Delta(kr_0,\eta)=0. \tag{7}$$

It is known that the field of damped normal waves arising in a viscoelastic medium is described by deductions in the dispersion equation. Suppose in the equations of motion of the core, the relaxation of the medium and the well are equal to zero. In that case, the real roots correspond to undamped waves, which change their amplitude in the propagation process only due to geometric divergence and dispersion. Complex roots describe damped waves (or leaky waves), which have an additional exponential attenuation with distance due to energy radiation to infinity.

It can be shown that the transcendental equation (7) has complex roots in the left half-plane $Re\,\eta>0$ and purely imaginary roots on the axis $Re\,\eta=0$. To estimate the emerging waves, it is necessary to pay to attend the dispersion equation

$$\Delta(k,\eta)=\rho_{12}\frac{c_\phi^4}{c_{s1}^4}\alpha_1 J_0(\Omega_x)-\alpha_0 J_1(\Omega_x)\left[(2.0-\frac{c_\phi^2}{c_{s1}^2})^2\frac{H_0^{(2)}(\Omega_y)}{H_1^{(2)}(\Omega_y)}-4\alpha_1\beta_1\frac{H_0^{(2)}(\Omega_{z1})}{H_1^{(2)}(\Omega_{z1})}+\frac{2i\alpha_1 c_\phi^2}{kr_0 c_{s1}^2}\right]=0. \tag{8}$$

The number of roots and their position depends on the parameter kr_0. As the parameter kr_0. increases, the number of roots located on the imaginary axis increases. Complex roots correspond to damped oscillations. The real parts $c_{\phi R}$ correspond to the phase velocities of the propagating waves, and the imaginary parts mean the damping rate coefficient. Purely imaginary roots lying on the axis $Re\,\eta=0$ correspond to aperiodic oscillations.

The roots of equation (7) can be divided into two classes. The first class includes those of them that $kr_0=0$are at a finite distance from the origin. All other roots belong to the second class. The roots of the first-class describe vibrations whose spectrum begins with zero frequency.

In the well, the limiting cases of phase velocities when $\omega\to\infty$ and $\omega\to 0$ are of great practical importance. According to this classification, there are two types of normal waves in the well: hydro and water waves.

When the material's rheological properties are considered, all the dispersion equation's roots will become complex. The real part of the phase velocity varies up to 5%. Imaginary parts increase to 20%.

Hydro waves can be obtained if we go to the limit in equation (8) $ka\to 0$.

Then

$$c_{\phi l}^0=\frac{c_{s2}}{\sqrt{\rho_{12}+\Gamma_{s2}(\frac{c_{s2}}{c_{p1}})^2}}=c_{\phi lR}^0+ic_{\phi lI}^0\,. \tag{9}$$

It follows from formula (9) that $c_{\phi l}^{0}$ it is always less than the velocity c_{p1} of sound in water when the inequality $c_{s2} > c_{p1}\sqrt{1-\rho_{12}}$ is fulfilled. And also, $c_{\phi l}^{0}$ it is less than c_{s2}. If $ka \to \infty$then the velocity of the hydro wave $c_{\phi l}$ monotonically approaches the velocity c_e of the Stoneley surface wave at the flat boundary of a liquid and a solid

$$\left(2-\frac{c_{\phi}^{2}}{c_{s2}^{2}}\right)^{2}-4\alpha_2\beta_2+\frac{\alpha_2}{\alpha_1}\rho_{12}\frac{c_{\phi}^{4}}{c_{s2}^{4}}=0. \qquad (10)$$

It has a real root $c_e < min(c_{p1}, c_{s2})$.

Let's call water waves vibrations, the phase velocities of which, with increasing frequency, tends to the speed of sound c_{p1} in an infinite liquid.

3. Results and Analysis

The dispersion equation (8) is solved numerically by the Muller method. The dependences of phase velocities on the wavelength are investigated. It is revealed that at low phase velocities, the phase velocity monotonically increases with increasing wavelength. The equations are reduced to the Helmholtz equation, the solution of which is expressed in terms of the Bessel and Hankel functions.

An efficient algorithm and programs for calculating special Bessel and Hankel functions have been developed. Equation (8) is solved numerically by the Muller method.

Numerical results are obtained for the following parameter values:

for liquid: $c_{p1} = 1400m/c, \rho_1 = 1g/sm^3$;

for the good shell: $c_{p2} = 5000m/c, c_{s2} = 2800m/c, \rho_2 = 8g/sm^3$,*a*=20sm;

for surrounding viscoelastic medium: $c_{p2} = 2500m/c, c_{s2} = 1250m/c, \rho_2 = 4g/sm^3$;

And also, for the parameters of the relaxation kernel, $R(t) = Ae^{-\beta t}/t^{1-\alpha}$ let's take the following values: $A = 0{,}048; \beta = 0{,}05; \alpha = 0{,}1$. The calculation results are shown in Figures 1-2.

From the analysis of numerical results, it turns out that the dispersion of hydro waves can beat normal or abnormal, which is determined primarily by the relationship between the speed of sound in a liquid c_{p1} and the speed c_{s2} of transverse waves in a medium. The velocity of the longitudinal waves of the medium practically does not affect the kinematic characteristics (real and imaginary parts of the phase velocities) of hydro waves.

4. Conclusion

1. It is revealed that at low phase velocities (hydro wave) with increasing wavelength, the real and imaginary parts of the phase velocity monotonically increase.
2. It was found that $ka \to \infty$the velocity of the hydro wave $c_{\phi l}$ monotonically approaches the velocity c_e of the Stoneley surface wave at the flat boundary of the liquid and the viscoelastic body.
3. It is determined that the nature of the change in phase velocities (real and imaginary parts) are almost the same. In the region of long waves, the phase velocities monotonically increase, and in the region of short waves, they approach the asymptotic.

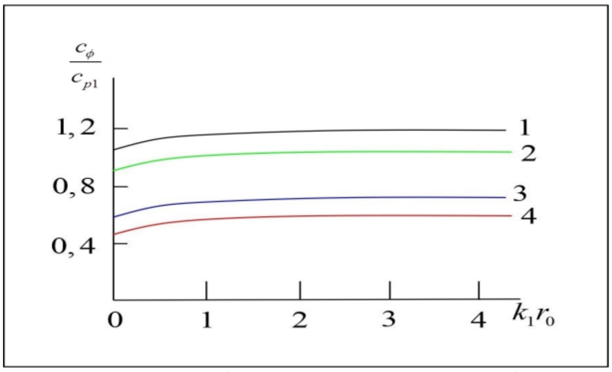

Fig. 1 Dependence of the real and imaginary parts of the phase velocity of the hydro wave on the wave number.

1. Re(c_ϕ/c_{p1}),$\gamma_2 = 0.25$; 2. Re(c_ϕ/c_{p1}),$\gamma_2 = 0.30$;

3.$10^{-2}\, Im(c_\phi/c_{p1})$,$\gamma_2 = 0.25$;

4. $10^{-2}\, Im(c_\phi/c_{p1})$,/$\gamma_2 = 0.30$.

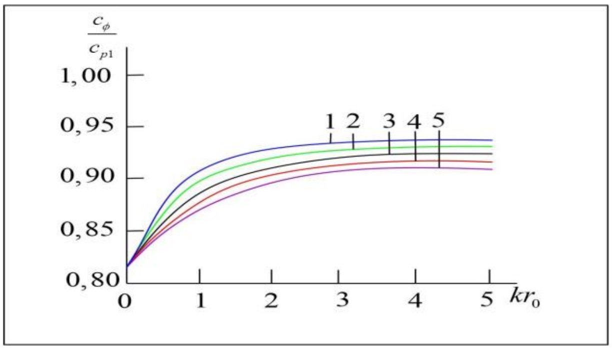

Fig. 2 Dependence of the real part of the phase velocity of the hydro wave on the wave number at different values $\gamma_2 = c_{s2}/c_{p2}$ (the ratio of the velocity of transverse waves to the longitudinal) of the environment c_{s2}: 1. $\gamma_2 = 0.35$; 2. $\gamma_2 = 0.40$; 3. $\gamma_2 = 0.45$; 4. $\gamma_2 = 0.5$; 5.

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