Mathematical Simulation of Acoustic Waves Propagation through Forest Layer onto Ground

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Abstract. In this paper, aspects of the numerical modeling of acoustic waves propagation in 2D inhomogeneous model "atmosphere-forest layer -ground" are considered. The linear damping function was introduced into the main acoustic equations. This function characterizes the energy dissipation of the acoustic waves propagating in the forest layer. The problem of the interaction of acoustic waves falling onto the ground covered by the forest layer and seismic waves arising in the ground are considered. The influence of the forest layer on the amplitudes of acoustic waves and seismic waves excited in the ground was investigated. An influence of damping coefficient on the rate of acoustic oscillations attenuation in the forest was estimated. The algorithm and the program for calculation the acoustic pressure levels in different media using the wave equation for the atmosphere, Euler's gas dynamics equations for forest, and the elasticity equation for the ground have been developed and implemented. The results of numerical experiments as instantaneous snapshots of the wave field were presented.

INTRODUCTION

Among modern geoecological problems, there is an important problem of estimation the geoecological risks for the social and natural environment from impact of the acoustic waves generated by natural and technogenic events of increased danger. Such events include powerful test site and career explosions [1-3], technogenic noise of highways [4], airport noises [5], rockets launch sites [6, 7]. Theoretical and experimental investigations in this field are related to the study of the acoustic impact from natural and technogenic explosions to the integrity of industrial and residential objects. Some authors considered earlier the meteofactors increasing the environmental risks from explosions. The negative impact of acoustic oscillations can be repeatedly amplified under the influence of meteorological factors. In particular, it causes the formation of the spatial focusing phenomenon of acoustic oscillations in a certain azimuthal direction with respect to the source [8, 9, 10]. At the same time, there are factors that lead to weakening of acoustic oscillations from explosions. These factors are the presence of snow [11, 12], forests and relief along the propagation path of acoustic waves [13-15].

One of the measures to absorb the acoustic oscillations is protective afforestation, seated along major highways and railways, wind turbines and near other noise sources. When solving many practical problems the special interest for researchers is to study the acoustic wave fronts interaction with permeable obstacles, which include the forest [16-18]. Recently, ammunition with expired shelf life has been disposed. There were cases when glass were knocked out in the houses, masonry of furnaces and facades of houses were damaged by the acoustic wave from explosions. An effective way to reduce the influence of the ammunition disposal processes on residential buildings is to place the test sites in forests or the arrangement of existing test sites by special systems of forest shelterbelts [19]. Problem of protection against technogenic noise through the tree belts planting become increasingly important.

In the present paper, authors estimate the attenuation characteristics in the forest layer on the propagation of acoustic oscillations generated by infralow-frequency vibrational sources. The problem of interaction between the acoustic wave, falling at a given angle onto the ground, acoustic waves passing in the forest and seismic waves arising in the ground in the "air-forest-ground" model is considered. Moreover, influence of the forest on the amplitude of seismic waves excited in the ground is investigated. A system of differential equations of gas dynamics, wave and elastic equations with boundary conditions is constructed. It describes the propagation of reflected acoustic waves in the air, as well as the propagation of refracted and reflected waves in the forest and seismic waves in the elastic ground. Pressures amplitudes of the reflected and refracted acoustic waves and seismic waves are calculated and analyzed depending on various characteristics of the forest massif. The results of numerical experiments are presented as the wave field snapshots.

PROBLEM STATEMENT AND ANALYTICAL SOLUTION

Consider the problem of an acoustic wave incidence under a given angle on the ground with the forest layer on the surface. It is case of long-range propagation of acoustic waves from an infra-low-frequency source. To solve this problem, we consider a 3-layer model consisting of air, forest and ground (Fig. 1). The acoustic wave falls in the air onto the forest at a given angle θ ($0 \le \theta \le 90^o$) to the vertical. In this model, air occupies the upper half-space with the sound speed c and density ρ. The forest is medium layer with damping function related to the absorbing effect of the acoustic oscillations energy. In this case the damping function depends on the coefficient of aerodynamic resistance c_d and the specific density of the forest surface (leaves and branches) S [18]. The ground occupying the lower half-space is characterized by density ρ_g, longitudinal and transverse wave velocities V_p and V_s. The question is how much the amplitude of the acoustic wave decreases depending on the properties of forest. In this case, assume that the source is at a distance much longer than the acoustic wavelength, so the wave front is locally flat and it is possible a 2D model for given model.

Harmonic Acoustic Waves

The wave equations with constant density and sound speed are solved for air. Consider the following wave equations:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = 0; \quad \rho\frac{\partial u}{\partial t} + \nabla p = 0, \tag{1}$$

where p, $\vec{u}=(u_x, u_z)$ and c are pressure, two-dimensional vector of air particles displacement and the sound velocity. The solution of the equation (1) can be represented as superposition of the plane harmonic waves. Then the resulting air pressure will be written as the sum of the pressures of the incident and reflected waves.

$$P = P_0 e^{i\omega t - ik_x x - ik_z z} + P_1 e^{i\omega t - ik_x x - ik_z z} \tag{2}$$

Here k_x, k_z are wave vectors projections along x and z axes.

The forest model is based on the Euler equations system and can be written in coordinate form:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \rho\left(\dfrac{\partial u_x}{\partial x} + \dfrac{\partial u_z}{\partial z}\right) = 0 \\ \dfrac{\partial u_x}{\partial t} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} - \dfrac{\alpha}{\rho}u_x \\ \dfrac{\partial u_z}{\partial t} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial z} - \dfrac{\alpha}{\rho}u_z, \end{cases} \tag{3}$$

where u_x, u_z are components of the velocity vector of the air particles, ρ is air density, c is sound speed, $\alpha = f(x, z)$ is linear damping function for the forest. The presence of the inhomogeneous component in equations (3) is represented by the additional term with the friction coefficient α. As a result, we obtain the following equation for the pressure $p(x, z, t, \alpha)$:

$$\frac{\partial^2 p}{\partial t^2} - \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial z^2}\right) + \frac{\alpha}{\rho}\frac{\partial p}{\partial t} = 0. \tag{4}$$

The solution of equation (4) can be written as the sum of the pressures of the refracted and reflected waves:

$$P = P_2 e^{i\omega t - ik_x x - ik_z z} + P_3 e^{i\omega t - ik_x x - ik_z z} \tag{5}$$

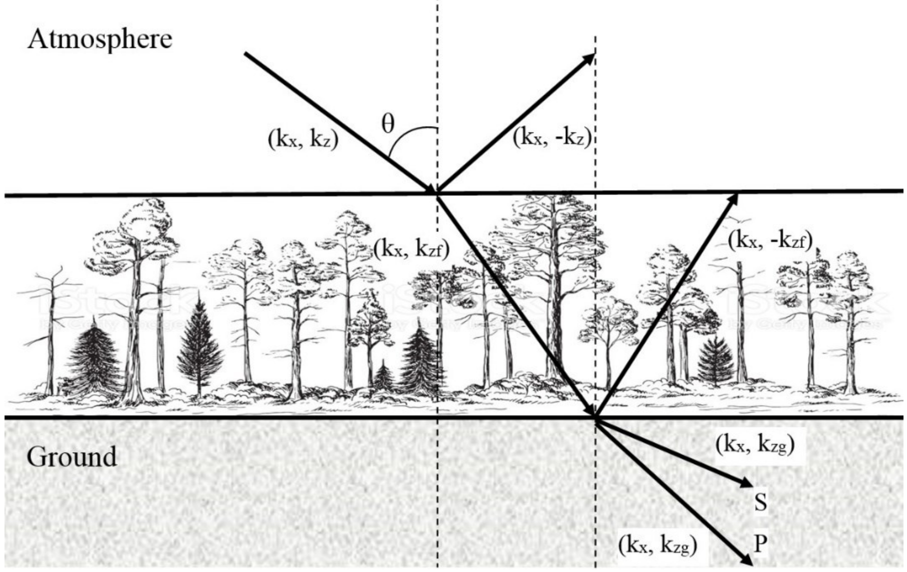


Fig. 1. Incident acoustic wave at a given angle in the three-layer model "air-forest-ground"

Table 1 shows the characteristics of forest massifs for calculation of the friction coefficient α = -ρ*c_d *S. Table 1 contains values of aerodynamic resistance coefficients c_d and specific densities of the forest surface (leaves and branches) *S.* For real massifs, there is an empirical dependence of the aerodynamic resistance coefficient c_d and the density of the forest surface *S* on the type of forest massif and of the trees height [18].

Table 1. Characteristics of forest massifs

Tree type	Height H, m	S	c_d
Small-leaved forest	7-30	1.2	0.02
Pine	10-50	1.2	0.03
Bush	1-5	7	0.05

The "air- forest edge" boundary conditions are equality of the pressures and velocities by component z in the both media

$$u_{z1}\big|_{z=0} = u_{z2}\big|_{z=0}, \; P_1\big|_{z=0} = P_2\big|_{z=0};$$

Acoustic refracted wave with the sound velocity c and frequency ω falling on the boundary "forest-ground". The boundary conditions have the form:

$$\begin{aligned} &\sigma_{xz}^{\mathrm{gr}}\big|_{z=h} = 0, \; \sigma_{zz}^{gr}\big|_{z=h} = p\,\mathrm{e}^{i(\omega t - kx)} \\ &u_z^{air}\big|_{z=h} = u_z^{gr}\big|_{z=h} \end{aligned} \tag{6}$$

As follows from (6) the acoustic wave pressure p is equal to the normal ground stress $\sigma_{xz}^{\mathrm{gr}}$, $\sigma_{zz}^{\mathrm{gr}}$ the velocities for the component z u_z^{air}, u_z^{gr} are equal in both media.

For the ground elastic equations with constant characteristics λ_{gr}, μ_{gr}, ρ_{gr} are solved:

$$(\lambda_{\mathrm{gr}} + \mu_{\mathrm{gr}})\mathrm{grad}\cdot\mathrm{div}u_{\mathrm{gr}} + \mu_{\mathrm{gr}}\Delta u_{\mathrm{gr}} - \rho_{\mathrm{gr}}\cdot\frac{\partial^2 u_{\mathrm{gr}}}{\partial t^2} = 0. \tag{7}$$

The solution of equation (7) can be sought as potentials [20, 21].

$$\begin{aligned} &\varphi = \varphi(\mathrm{x,z,t}) = P_4\,\mathrm{e}^{i(\omega t - kx - k_{\varphi z} z)}, \\ &\psi = \psi(\mathrm{x,z,t}) = P_5^{\exp i(\omega t - kx - k_{\psi z} z)}. \end{aligned} \tag{8}$$

The potentials φ and ψ are related to the displacement field by following formulas in the general forms:

$$u_x = \frac{\partial\varphi}{\partial x} - \frac{\partial\psi}{\partial z}, \quad u_z = \frac{\partial\varphi}{\partial z} + \frac{\partial\psi}{\partial x}.$$

Substituting the potentials φ and ψ from (8) into the boundary conditions (6), we will obtain a system of equations for P_4 and P_5 coefficients:

$$\begin{aligned} \sigma_{xz}\big|_{z=0} &= \mu\left[2\frac{\partial^2\varphi}{\partial x\partial z} + \frac{\partial^2\psi}{\partial x^2} - \frac{\partial^2\psi}{\partial z^2}\right]_{z=0} = 0, \\ \sigma_{zz}\big|_{z=0} &= \left[\lambda\frac{\partial^2\varphi}{\partial x^2} + (\lambda+2\mu)\frac{\partial^2\varphi}{\partial z^2} + 2\mu\frac{\partial^2\psi}{\partial x\partial z}\right]_{z=0} = \rho\exp^{i(\omega t - kx)}; \end{aligned} \tag{9}$$

Let the value of the pressure amplitude of the incident wave is equal P_0. It is necessary:

- To calculate the coefficients of P_1, P_2, P_3 corresponding to the pressures amplitudes of the reflected and refracted waves in the forest;
- To calculate the coefficients of P_4, P_5 corresponding to the pressures amplitudes of the longitudinal and transverse waves arising in the ground;
- To construct a 2D model of the inhomogeneous medium "air-forest" and to obtain the numerical solution of the Euler equations of gas dynamics.

Calculation of Acoustic Pressures Levels

To calculate the acoustic pressure levels, the program based on equations (2) - (9) has been developed. The acoustic pressures values for the refracted and reflected waves are computed when the harmonic acoustic wave passes through the forest with the friction coefficient α. It is noted that the absorption effect of the acoustic wave energy is observed. As an example, Fig. 2 shows the acoustic pressures graphs for the refracted and reflected waves in the forest, respectively, depending on the incident angle θ at different heights of 0, 5, 10, 50 meters, and frequency of 10 Hz. As follows from Figure 2 that the absorption effect noted above. At the height of 50 m and θ of 90°, the amplitude of the acoustic pressure can decrease by more than an order of magnitude.

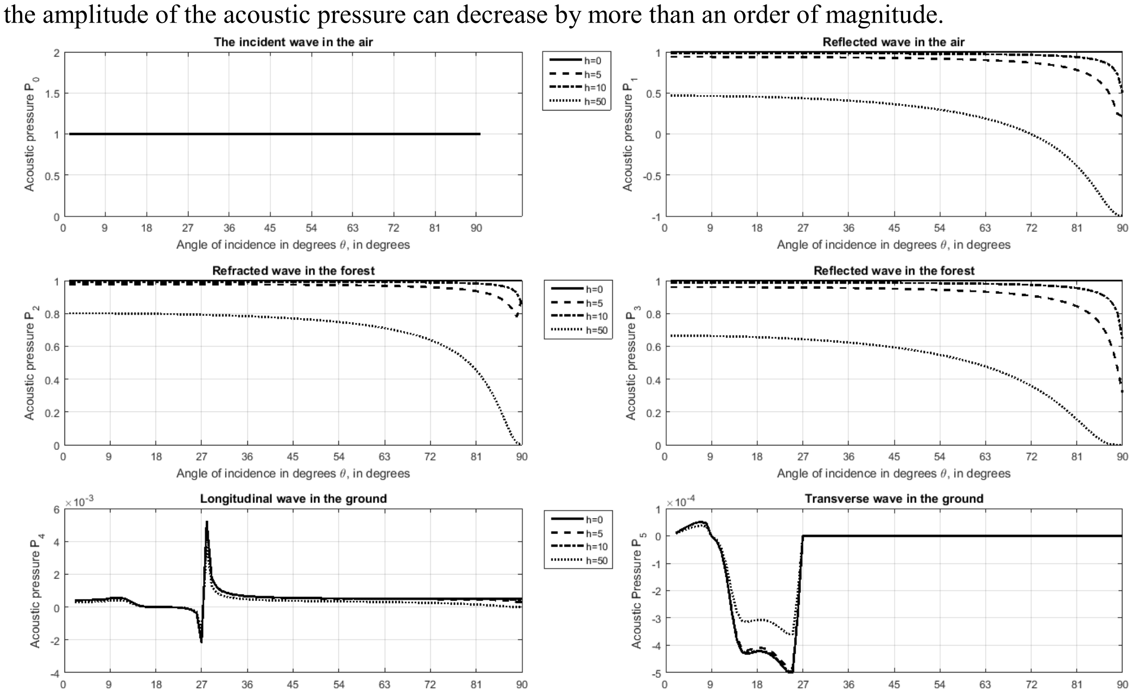


Fig.2. Graphs of the acoustic pressure for refracted and reflected waves depending on the incidence angle θ for the acoustic wave propagation through the forest at various heights of 0, 5, 10, 50 meters, frequency of 10 Hz.

Figure 3 shows the acoustic pressure graphs for the refracted and reflected waves, respectively, depending on the angle of incidence θ at frequencies f = 8, 15, 80 Hz. As follows from Fig. 3, when the frequency is increased by an order of magnitude, the attenuation rate of the acoustic pressure is almost 10 times higher.

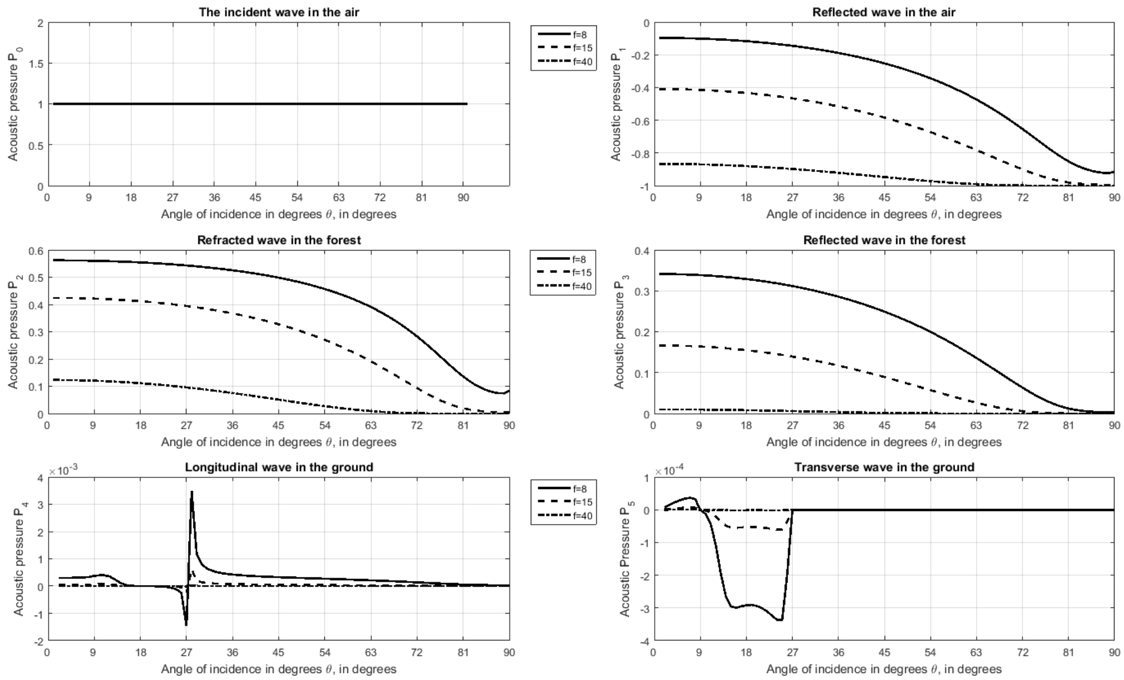


Fig.3. Graphs of acoustic pressure for refracted and reflected waves depending on incidence angle θ at different frequencies of 8, 15 and 40 Hz.

II. NUMERICAL MODELING OF THE INHOMOGENEOUS MEDIUM

Finite-Difference Methods

The problem of the acoustic wave propagation from a point source located outside the forest near the boundary with the ground is considered. The forest has a finite size. The acoustic wave propagation in this case was carried out using numerical simulation. The numerical modeling is related to the solution of the gas dynamics equations system (3) in the two-dimensional case, in the presence of an inhomogeneous component characterizing the forest. The simulation area is a rectangle in the two-dimensional coordinate system Oxz (Figure 4.). The system of equations (3) is solved for the corresponding zero boundary and initial conditions.

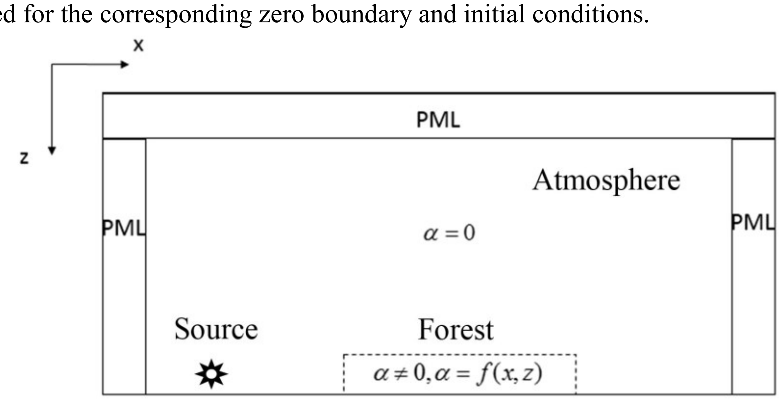


Fig. 4. Schematic representation of the two-dimensional modeling domain

To exclude unwanted reflected waves from the side and upper boundary of the computational domain, the PML (Perfectly Matched Layers) implementation methodology is applied [22, 23]. Thus, three subdomains of small size are allocated on the three boundaries, where the calculation formulas for PML are realized. A point source is used to generate the signal and simulate the acoustic waves propagation. The source can be located anywhere within the modeling area, excluding PML zones. In the equations system (3), the source is represented as the force component. Numerical modeling of the acoustic waves propagation in the inhomogeneous model "air-forest" uses the finite-difference methods. Finite-difference methods are widely used to solve many complex problems in various scientific fields of science. At the same time, they are enough flexible and convenient for parallel computations. Therefore, for the numerical solution of the system of the gas dynamics equations (3), a finite difference method on shifted grids is applied [24]. The method has a second order of accuracy in space and time. In the paper, the finite difference scheme is realized only for the same size of spatial steps Δx and Δz respectively and can be written for the equations (3) as:

$$p_{i,j}^{n+1} = p_{i,j}^{n} - \rho_{i,j}\frac{1}{2}\frac{\Delta t}{\Delta x}((u^{n}_{x,i+\frac{1}{2},j} - u^{n}_{x,i-\frac{1}{2},j}) + (u^{n}_{z,i,j+\frac{1}{2}} - u^{n}_{z,i,j-\frac{1}{2}})) \quad ,$$

$$u^{n+1}_{x,i+\frac{1}{2},j} = u^{n}_{x,i+\frac{1}{2},j} - \frac{1}{\rho_{x,i+\frac{1}{2},j}}\frac{1}{2}\frac{\Delta t}{\Delta x}(p^{n+1}_{i+1,j} - p^{n+1}_{i,j}) - \frac{1}{\rho_{x,i+\frac{1}{2},j}}\Delta t\alpha_{x,i+\frac{1}{2},j}u^{n}_{x,i+\frac{1}{2},j},$$

$$\rho_{x,i+\frac{1}{2},j} = \frac{1}{2}(\rho_{i+1,j} + \rho_{i,j}), \alpha_{x,i+\frac{1}{2},j} = \frac{1}{2}(\alpha_{i+1,j} + \alpha_{i,j})$$

$$p_{i,j}^{n+1} = p_{i,j}^{n} - \rho_{i,j}\frac{1}{2}\frac{\Delta t}{\Delta x}((u^{n}_{x,i+\frac{1}{2},j} - u^{n}_{x,i-\frac{1}{2},j}) + (u^{n}_{z,i,j+\frac{1}{2}} - u^{n}_{z,i,j-\frac{1}{2}})),$$

$$u^{n+1}_{x,i+\frac{1}{2},j} = u^{n}_{x,i+\frac{1}{2},j} - \frac{1}{\rho_{x,i+\frac{1}{2},j}}\frac{1}{2}\frac{\Delta t}{\Delta x}(p^{n+1}_{i+1,j} - p^{n+1}_{i,j}) - \frac{1}{\rho_{x,i+\frac{1}{2},j}}\Delta t\alpha_{x,i+\frac{1}{2},j}u^{n}_{x,i+\frac{1}{2},j},$$

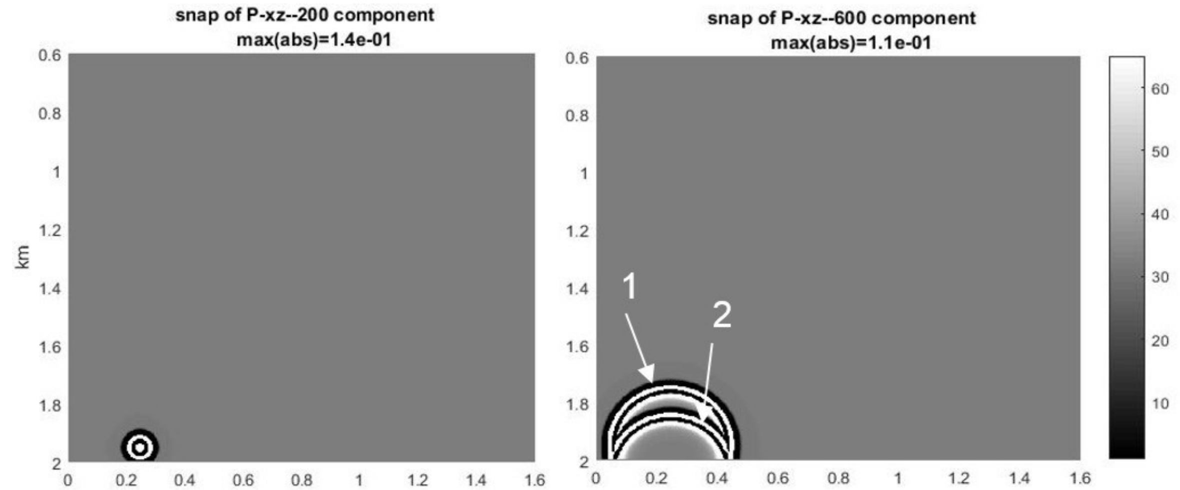
$$\rho_{x,i+\frac{1}{2},j} = \frac{1}{2}(\rho_{i+1,j} + \rho_{i,j}), \alpha_{x,i+\frac{1}{2},j} = \frac{1}{2}(\alpha_{i+1,j} + \alpha_{i,j})$$

To exclude waves reflection from the boundaries of the computational domain, the realization methodology PML in the form of C-PML (Convolution-PML) is used. So, the equations in the PML zones are solved for approximation with additional factor and damping coefficients [23]. This approach has been successfully applied to solve the dynamic problem of elasticity theory from the numerical modeling of seismic fields [25, 26].

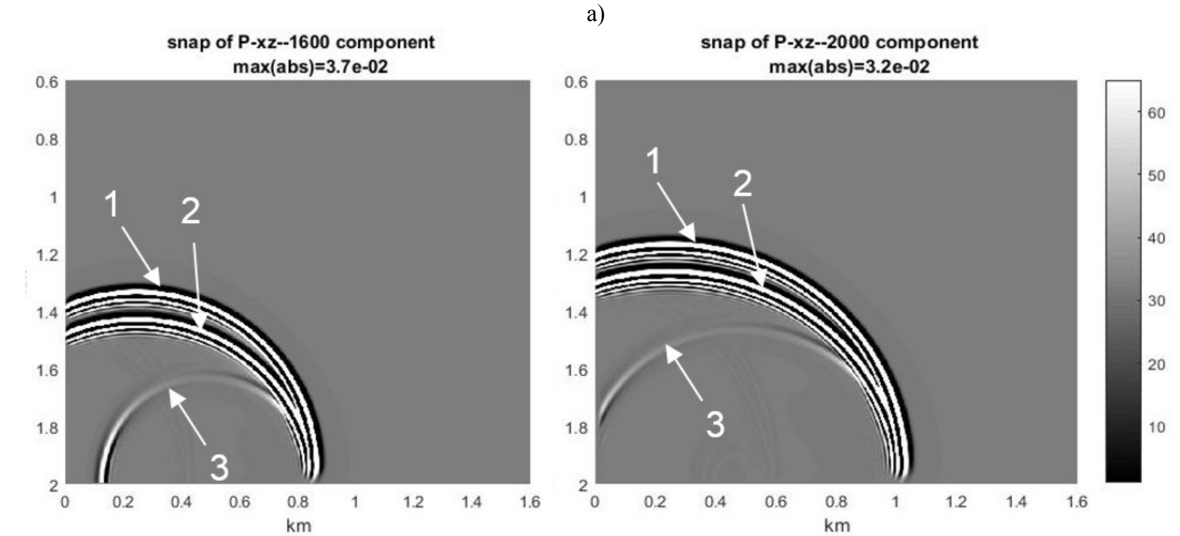
Results of Numerical Modeling

To carry out theoretical experiments on modeling of the acoustic waves propagation from the point source in inhomogeneous media, a computational program has been developed. The program implements the proposed finite difference scheme. At the same time, multi-core processors use parallelization technology with OpenMP (Open Multi-Processing). To study the interaction of the acoustic wave with the forest massif the numerical simulation was carried out based on the created program for the inhomogeneous “air-forest massif” model. A two-dimensional modeling area with linear dimensions of 2.04 km x 2.04 km was chosen (Fig. 4.). The inhomogeneous medium includes two objects: containing air medium (1), forest (2). Parameters for the atmosphere were chosen as sound velocity of 340 m/s and density of 1.2 g/m^3. The grid model for calculations was 1200x1200 nodes. The point source of acoustic waves with the frequency of 5 Hz was located in the air medium with coordinates of 0.25 km along the Ox axis and 1.95 km along the Oz axis. As the forest, a subdomain was created in the general medium with the length from 0.5 km to 1.5 km along the Ox axis and the height of 0.05 km along the Oz axis.

As a result of this program for calculating of the acoustic waves levels in a two-dimensional model “air-forest” in the presence of the forest, a set of snapshots of the wave field was obtained (Fig. 5). The snapshots demonstrate different types of acoustic waves: 1 is falling wave, 2 are reflected waves from the lower rigid boundary (Fig.5a, 5b), 3 are refracted waves due to the presence of a forest massif (Fig. 5b). The results were obtained using the Matlab package. As follows from presented snapshots, we can trace the evolution of changes in the pressure field due to the presence of forest. In particular, it is easy to see the formation of the reflected wave after acoustic wave arrival on the front boundary of the forest massif (Fig. 5b).



a)



b)

Fig. 6 Snapshots of the wave field for acoustic pressure at different times for the case where forest is present.

CONCLUSION

In this paper, the problem of interaction between the acoustic wave falling onto ground with forest layer in the three-layer model "air-forest layer-ground" was considered for the case of long-range propagation from the infra-low-frequency source. The mathematical modeling of the processes of the infrasonic waves propagation in the atmosphere through the forest with the introduced friction force is performed. It was assumed that at large distance from the source the spherical wave field is locally flat allowing 2D modeling. The impact of the friction coefficient on the attenuation rate of acoustic oscillations in the forest was estimated. The algorithm and the program for calculating the acoustic pressure levels in different media using the wave equation for the atmosphere, Euler's gas dynamics equations for forest have been implemented. The initial parameters and boundary conditions was defined and as well test calculations were performed using the developed programs within the created mathematical model.

The system of acoustic equations in the two-dimensional case is presented to study the interaction of acoustic waves with the forest massif. A method for solving the system of equations describing the acoustic waves propagation from the point source in the inhomogeneous model "air-forest" is proposed. The linear damping function characterizing the energy dissipation of the acoustic wave in the forest was introduced. For numerical implementation, the finite difference scheme has been designed.

The software implementation using the OpenMP parallel programming technology has been worked on the base of the algorithm described above. This approach allows to calculate on several processors and cores of multi-core computing systems with shared memory, even on a PC. Using this program, a non-uniform model "air-forest massif" was generated and numerical experiments were performed to simulate the acoustic waves propagation from the point source. Theoretical results of model calculations in the form of two-dimensional snapshots of the acoustic wave field are obtained and presented. The program can be used for calculations on SMP systems, as well as on computing devices such as Xeon Phi.

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