Mathematical Simulation of Infrasonic Waves Propagation Through Vegetation into Ground

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Abstract – **In this paper, the processes of propagation the infrasonic acoustic waves in the lower atmosphere are investigated if a vegetable layer is presence. Analysis can carry out using 2D-simulation (instead 3D-simulation) due to enough large distance of from a source to forest massif. A three-layer model "Air-vegetation layer-ground" is considered. Authors study the problem of an interaction the acoustic waves falling at a given angle on the ground with vegetable layer and seismic waves arising in the ground. A question about the vegetation influence to amplitudes of the acoustic and seismic waves excited in the ground is investigated. The influence of a friction coefficient to the attenuation velocity of the acoustic oscillations in the vegetation is also estimated. An algorithm and a program for calculation the acoustic pressure levels in different media using wave equations for air, Euler's gas dynamics equations for vegetable layer and elasticity equation for the ground have been implemented and realized.**

Index Term – **Acoustic waves, infrasound, vegetable layer.**

I. Introduction

THE solution of the problem of prediction of destructive geoecological risks is associated with the solution of a multifactor problem. Natural and technogenic explosions include power polygon and quarry explosions, earthquakes, volcanic eruptions etc. The greatest interest is to study of the acoustic impact from mass explosions that influence to industry and residential buildings. Some authors have shown that under certain conditions the influence of some meteorological factors can lead to the multiply increase geoecological risks [1-4]. In particular the numerical simulation of seismic and acousto-gravity waves propagation in atmosphere was carried out in [5] if wind was present.

At the same time, there are factors that lead to effect of the weakening risks in presence of a snow cover, a vegetation massif, a geological heterogeneity of the relief. Earlier authors considered the partial statements of problems of the acoustic waves propagation associated with influence estimation of the separate factors

Problems related to the impact of snow cover on the propagation of elastic waves, have been solved in [6-9]. Using numerical modeling, the authors found that the acoustic wave is strongly absorbed in the snow even by a small thickness. Some problems of the influence estimation of a different altitude surface relief on the acoustic oscillations were considered in [10-13]. These papers also study a technique to obtain the quantitative estimations of the influence urban relief on the acoustic situation, a development the protection technology from the infrasonic source such as transport noise.

The papers [14-16] describe theoretical and experimental investigations of the acoustic waves propagation in the vegetable massif to study their ecological protective features from adverse technogenic acoustic oscillations, like for example protective tree band along large highways and railways from transport noise. These investigations are actual but poorly studied.

In the present paper, the attenuation characteristics caused by the influence of the vegetation layer on the surface propagation of acoustic oscillations from the distant infralow frequency vibrational sources are evaluated. A three-layer model "Air-vegetation layer-ground" is considered. The problem of interaction of the acoustic waves falling at a certain angle on the ground covered with the vegetation and seismic waves arising in the ground is studied. The question about influence of the vegetation on amplitudes of seismic waves excited in the ground is investigated. A system of differential equations of Euler's gas dynamics, wave and elastic equations with boundary conditions is constructed. It describes the propagation of incident and reflected acoustic waves in air and the propagation of acoustic refracted and reflected waves in vegetation and seismic waves in elastic ground. Amplitudes and pressures of reflected and refracted acoustic and seismic waves were calculated and analyzed depending on various characteristics of the vegetable layer.

II. Problem Statement

Consider a 3-layer model consisting of air, vegetation and ground. Suppose that an acoustic wave propagates in the lower atmosphere from the distant infralow frequency source and falls onto the ground with the vegetation layer on the surface at a certain 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 medium vegetable layer is characterized by the friction coefficient α. Its physical meaning is associated with the absorption effect creating by the vegetation. The friction coefficient α depends on coefficient of aerodynamic resistance c_d and specific density of the vegetation surface (leaves and branches) *S*. 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 investigated: How does the vegetation layer influence on amplitudes of the acoustic waves decreases depending on the properties of this layer. Assume

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that the infralow frequency source is located at a distance much greater than the acoustic wavelength. Therefore, its wave front is assumed to be locally flat and the analysis is carried out in the framework of 2D modeling.

III. THEORY

The wave equations for air pressure and relation between velocities and pressures have the form:

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

where p, $\vec{u}=(u_x, u_z)$ и c are the pressure, the velocity vector of the air particles and sound speed. The solution of equation (1) can be represented as harmonic waves. Than the resulting air pressure will be written as the sum of the pressures of the incident and reflected waves:

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

where P_0, P_1 are the amplitudes of the falling and reflected waves, $\omega=2\pi f$ is the angle frequency, k_x , k_z are wave vector projections along x and z axes.

Consider the 2D problem statement of the interaction the acoustic waves with vegetable massif. This problem is based on a system of differential equations of Euler's gas dynamics and can be written as:

$$\begin{cases} \frac{\partial \rho}{\partial t} + \rho c^2\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z}\right) = 0 \\ \frac{\partial u_x}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{\alpha}{\rho}u_x \\ \frac{\partial u_z}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{\alpha}{\rho}u_z, \end{cases}$$

where $\vec{u}=(u_x, u_z)$ are the velocity vector of the air particles, ρ is air density, c is sound speed, α is the friction coefficient in the vegetation. As a result, we obtain the expression depending on only the pressure p:

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

The solution of equation (2) can be written also as the sum of the pressures of the refracted and reflected waves:

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

where P_2, P_3 are the refracted and reflected waves amplitudes.

The friction coefficient α depends on the aerodynamic resistance coefficient c_d and the specific density of the vegetation surface (leaves and branches) S. Table 1 shows the characteristics of vegetation massifs. For real massifs, the nonuniform distribution of the vegetation surface density S in height is characteristically.

TABLE I
CHARACTERISTICS OF VEGETATION 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- vegetation edge" boundary conditions are equality of the pressures and velocities by component z in the both media.

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

The acoustic refracted wave falling on the "vegetable layer-ground" boundary is taken into account in the boundary conditions as follow: the acoustic wave pressure with constant speed c and frequency ω is equal to the normal ground stress. As a result we have the following equalities:

$$\begin{gathered} \sigma_{xz\text{упр}}\big|_{z=h} = 0, \sigma_{zz\text{упр}}\big|_{z=h} = p\,\mathrm{e}^{i(\omega t - kx)} \\ u_{z\text{воздух}}\big|_{z=h} = u_{z\text{упр}}\big|_{z=h} \end{gathered} \qquad (3)$$

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

$$(\lambda_{\text{gr}} + \mu_{\text{gr}})\text{grad}\cdot\text{div}u_{\text{gr}} + \mu_{\text{gr}}\Delta u_{\text{gr}} - \rho_{\text{gr}}\cdot\frac{\partial^2 u_{\text{gr}}}{\partial t^2} = 0. \quad (4)$$

The solution of equation (4) can be sought in the form of potentials.

$$\varphi = P_4\,\mathrm{e}^{i(\omega t - kx - k_{\varphi z} z)}, \; \psi = P_5\,\mathrm{e}^{i(\omega t - kx - k_{\psi z} z)}. \qquad (5)$$

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 (5) into the boundary conditions (3), we will obtain a system of equations for A and B coefficients:

$$\begin{gathered} \sigma_{xz}\big|_{z=0} = \mu\left[2\frac{\partial^2\varphi}{\partial x\partial z} + \frac{\partial^2\psi}{\partial x^2} - \frac{\partial^2\psi}{\partial z^2}\right] = 0, \\ \sigma_{zz}\big|_{z=0} = \left[\lambda\frac{\partial^2\varphi}{\partial x^2} + (\lambda + 2\mu)\frac{\partial^2\varphi}{\partial z^2} + 2\mu\frac{\partial^2\psi}{\partial x\partial z}\right] = \rho\exp^{i(\omega t - kx)} \end{gathered} \qquad (6)$$

Let $P_0=1$ be the incident wave amplitude. It is necessary: to calculate the coefficients P_1, P_2, P_3, P_4, P_5, which correspond to the pressures amplitudes of the reflected and refracted waves.

IV. SIMULATION RESULTS

Programs of the mathematical simulation for calculating the acoustic waves pressure levels were developed and implemented using the equations (2)–(6). The simulation numerical results of the acoustic wave fields within the three-layer model "air-vegetation-ground" are presented. Test calculations to debug the developed programs were performed. The acoustic pressure values for the refracted and reflected waves in the case of the harmonic acoustic wave passing through the vegetation onto ground considering the friction coefficient are computed.

It is notes that the effect of absorbing the acoustic waves energy is observed. As an example, Figure 1 demonstrates the acoustic pressure graphs for the refracted and reflected waves respectively depending on the incidence angle θ in case the acoustic wave passes through the vegetation at the different heights of 0, 5, 10, 50 meter and by frequency of 10

Hz. The Figure 1 demonstrates the absorption effect noted above. The acoustic waves amplitudes can decrease more an order at the angle of 90° and the height of 50 m.

Figure 2 shows the acoustic pressure graphs for the refracted and reflected waves respectively depending on the incidence angle θ at the various frequencies of 8, 15, 40 Hz. We can see in the Fig. 2 that with increasing the frequency by an order, the acoustic pressure attenuation rate is almost 10 times higher. The dissipation rate is influenced by the presence of wind. Figure 3 presents attenuation curves of the acoustic pressure within vegetation at the frequency of 10 Hz. It follows from Fig. 3 that the acoustic pressure is greater when the wind blows from source to the vegetation than when the wind blows in the opposite direction.

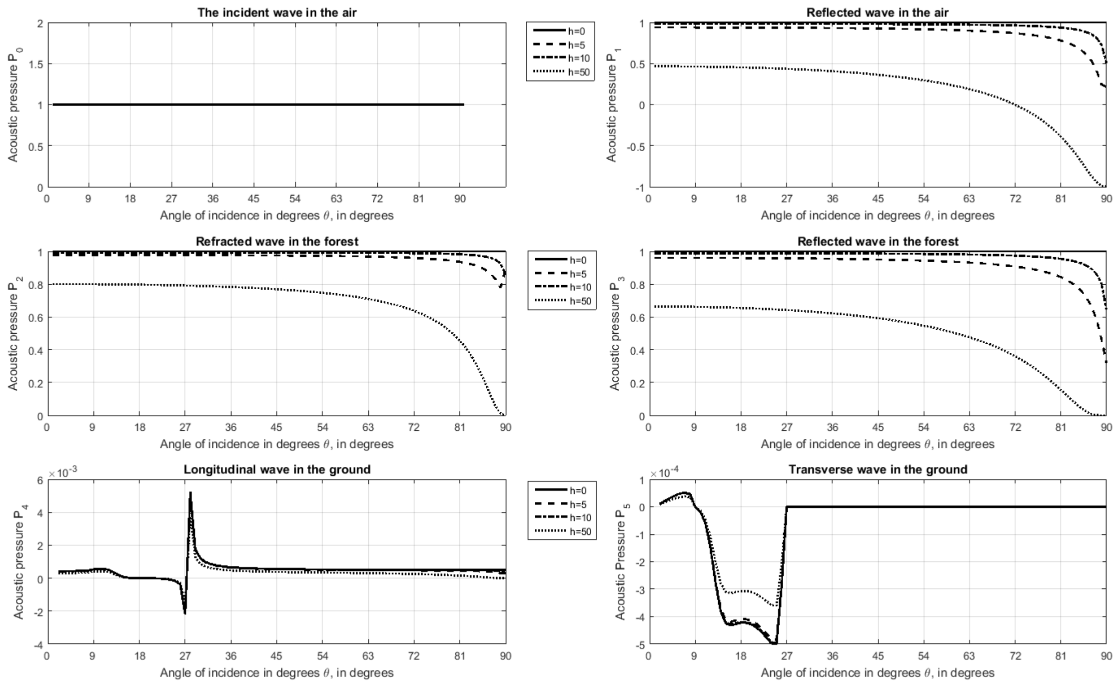

Fig. 1. Graphs of the acoustic pressure for refracted and reflected waves depending on the incidence angle θ for the acoustic wave propagation through the vegetation at various heights of 0, 5, 10, 50 meters, frequency of 10 Hz.

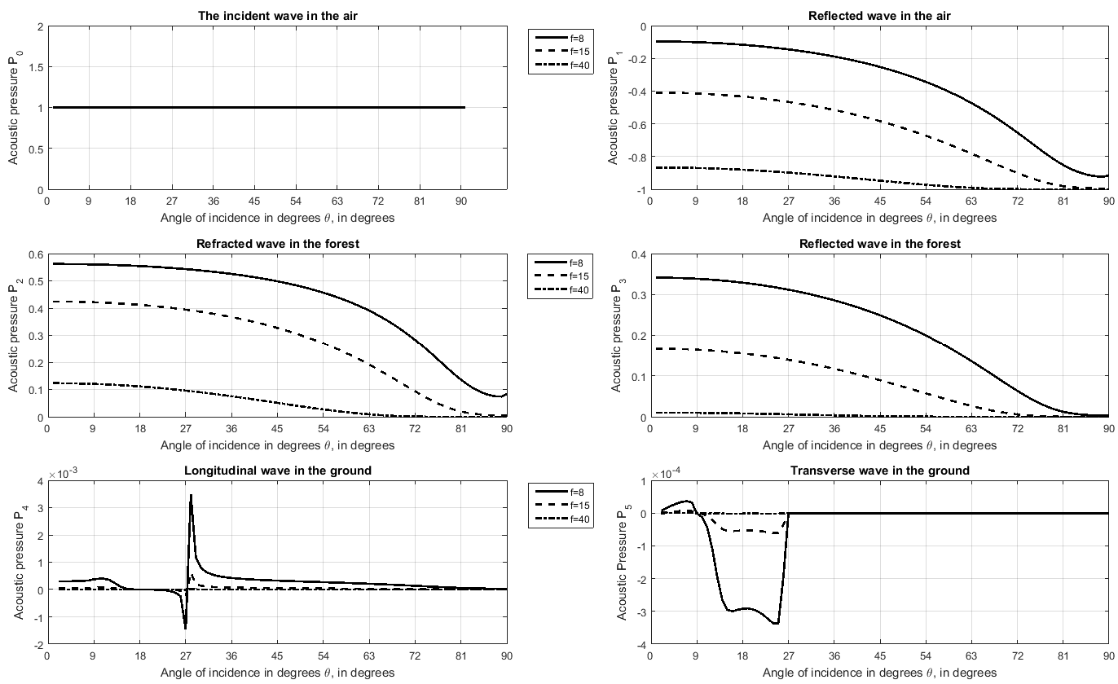

Fig. 2. Graphs of the acoustic pressure for refracted and reflected waves depending on the incidence angle θ at different frequencies of 8, 15 and 40 Hz.

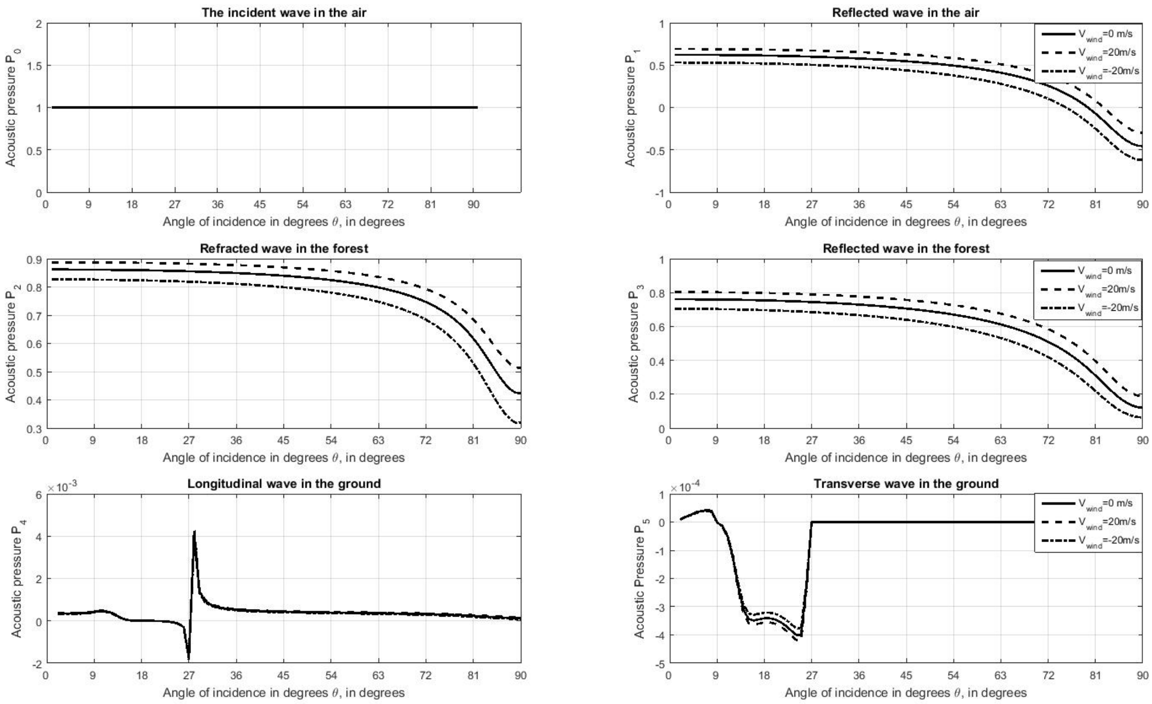

Fig. 3. Graphs of the acoustic pressure attenuation in the vegetation if the wind is present, frequency of 10 Hz. The solid line is the absence of wind; dashed-wind from the source to the vegetation (20 m/s); dot-dash-in the opposite direction (-20 m/s).

V. DISCUSSION OF THE RESULTS

Analysis of the simulation results showed that the pressures amplitude of the reflected wave in the air, and also the refracted and reflected waves in the forest, depend significantly on the incident wave angle in the air and on the frequency. Fig. 1 shows that as the angle of incidence increases, the pressure amplitudes decrease, and more sharply near 90^o. At the same time, the attenuation of the acoustic waves amplitudes in the forest increases with the vegetation height. The amplitudes of the longitudinal and transverse waves in the ground also depend on the vegetation height but to a lesser degree. Their dependence on the wave incident angle in the air has its feature. With increasing the incident angle, there is a limiting angle, after which the transverse wave is not excited in the ground. At this incident angle, the phase rotates 180 degrees along the longitudinal wave in the ground. Fig. 2 demonstrates that with increasing frequency the acoustic waves amplitudes decreases. The critical angle of the transverse wave disappearance is 27^o for 8 and 15 Hz. There is no critical angle for 40 Hz.

The presence of a wind also influences on the pressure amplitudes of the refracted and reflected waves in the vegetation. As follows from Fig. 3 the wind leads to increase of the pressure amplitudes in the direction from the source to the vegetable massif and decrease for the opposite direction. For the wind speed of 20 m/s, the variations magnitude is 10-15%. The presence of the wind does not influence to the critical angle for excitation of the transverse wave in the ground, and weakly affects to its amplitude, since this angle depends on the ratio of the elastic parameters of all three media and the frequency of the wave.

VI. CONCLUSION

The authors of this paper considered the problem of the acoustic wave falling at a given angle onto ground with the vegetation layer on the surface from distant infralow frequency source. The mathematical simulation of the propagation processes of the infrasonic acoustic waves in the atmosphere considering the friction forces within the vegetable layer is performed. It was assumed that at large distances form the source the spherical wave front is locally flat, which allowed 2D modeling. The friction coefficient influence on the attenuation rate of the acoustic oscillations in the vegetation is estimated.

The interaction problem of the acoustic waves falling at a given angle onto the ground with the vegetable layer and seismic waves arising in the ground in the “air-vegetation-ground” model was solved. For this problem boundary conditions and results of the problem solution of the acoustic waves propagation through permeable obstacle as vegetation were analyzed.

The algorithm and program for calculating of the acoustic pressure levels in various media using the wave equation for the atmosphere, Euler’s gas dynamics equations for vegetation and elastic equation for the ground have been developed and implemented. Within the created mathematical model, a choice of initial parameters and boundary conditions was justified and the test computations were performed.

Dependences of the acoustic pressure for refracted and reflected waves in the vegetation and longitudinal and transverse waves in the ground on the model parameters: the vegetation height, the acoustic wave frequency, and the influence of the wind are obtained.

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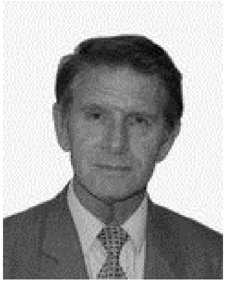

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