DEVELOPMENT OF A NUMERICAL MODEL CONCERNING ELECTROMAGNETIC WAVE PROPAGATION IN TURBULENT FLOWS

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Abstract

A numerical model concerning electromagnetic wave propagation in turbulent flows such as in liquids, gases and plasma is presented. Propagation of waves, falling under an arbitrary corner on the turbulent flow with an inhomogeneous structure of velocity and concentration of turbulences is considered. Multiple scattering of waves on an internal surface of turbulent bodies of rotation: a cone and paraboloid is investigated . Comparison of results of accounts to experimental data on ultrasonic and electromagnetic sounding the turbulent flow of water and plasma is spent.

1. INTRODUCTION

Until now mostly in studying propagation and scattering phenomena the cases of isotropic casual-inhomogeneous media has been considered [1,2].In case of random media such as clouds discrete scatterers are used as a first approximation to the theory of multiple scattering and in case of dense clouds - diffusion approximation [1] are applied. For the intermediate cases there has been only limited analytical methods in the literature.

The necessity of analysis of real world problems of signal propagation in non-stationary anisotropic casual media such as: turbulent flows of liquids, gases and plasma requires the development of new methods of analysis [2-7]. The purpose of this work is the development of a numerical model of electromagnetic wave propagation in non-stationary anisotropic casual media.

2. STATEMENT OF A PROBLEM AND METHOD OF ITS DECISION

Propagation of a wave through axisymmetrical flow with an inhomogeneous profile of velocity and concentration of turbulence is considered here and which is described by function

$$\varphi(\rho) = \varphi_0 \exp(-\mu_1\rho^2 - \mu_2(\rho - \rho_0)^2), \qquad (1)$$

where φ_0 - is the average velocity or turbulence ccncentration on an axis of the flow, μ_1, μ_2 - parameters, describing a degree of a inhomogeneous of the flow, ρ_0 - fixed

meaning of undimensional coordinate ρ, calculated from an axis of a flow. The scattering geometry of electromagnetic wave on the turbulent flow is presented on figure 1.

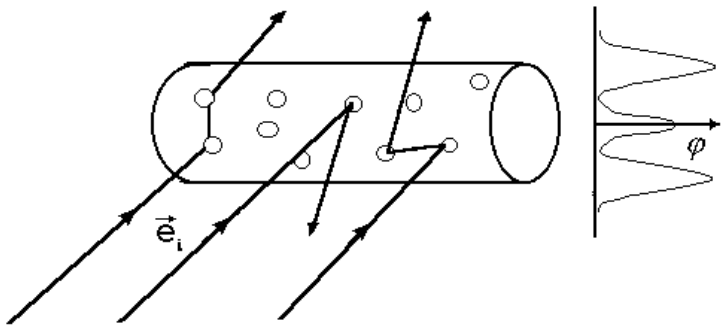

Figure 1. The scattering geometry of electromagnetic wave on the turbulent flow.

It is assumed, that the wavelength of the wave is less than sizes of the flow and scattering occurs incoherently by an image on statistically independent turbulences. To the analyse the problem a method of stochastic modeling is applied [3,4].

The wave falling on a flow is simulated in phase coherent beams, uniform as planes wave fronts and oriented along a direction of propagation of the wave. The initial coordinates of beams get out on a surface of a flow according to a specified law. In determining the length of free propagation of the beam in a inhomogeneous flow the method of the maximum section is used [3,4].

The type of interaction of a wave with turbulences is determined according to the cross-sections of absorption σ_p, scattering σ_r and fictitious scattering σ_f, known that $\sigma_p + \sigma_r + \sigma_f = 1$.

In case of fulfilment of a condition scattering of a wave the direction of propagation of the beam changes according to set indicatrix over-radiation turbulences.

It would be interesting to consider the diagram of over-radiation turbulences of quasi-mirror type [5-7], which allows to capture a wide range of parities between the characteristic size of turbulences inhomogeneous l and wavelength λ at $l >> \lambda$ the narrow diagram of over-radiation turbulences up to $l << \lambda$ at the wide diagram, when it aspires to isotropic.

The individual vector in the direction of propagation of the scattering wave is defined by expressio

$$\vec{e}_s = \vec{e}_i - 2\vec{e}_q(\vec{e}_i\,\vec{e}_q), \qquad (2)$$

where

$$\vec{e}_q = (\vec{n} + \vec{p}) / \left|(\vec{n} + \vec{p})\right|.$$

Here $\vec{n}$ - normal to the surface of scatterer, $\vec{p}$ - the casual vector, tangent to the surface in the point of reflection ($\vec{p} \perp \vec{n}$).

The expression, used for modeling of the vector $\vec{p}$, is written down as

$$\vec{p} = (\vec{e}_u \cos\varphi + \sin\varphi[\vec{n}\,\vec{e}_u] / \left|[\vec{n}\,\vec{e}_u]\right|)\beta\sqrt{x_1}, \qquad (3)$$

where $\vec{e}_u$ - the individual vector, directed along formating bodies of rotation, which approximated scatterer;

$\varphi = 2\pi x_2$ - azimuth corner in the plane, tangent to the surface in the point reflection, x_1, x_2 - random number, in uniform distributed in the interval from 0 up to 1; β - factor, describing width of the indicatrix over-radiation of turbulence inhomogeneous. In case $\beta >> 1$ of turbulence inhomogeneous disseminates isotropic.

Owing to moving scatterers occurs Doppler shift of frequency of the wave [4]:

$$f_* = (\Delta f c) / (f_0 V_0) = (\vec{e}_{i+1} - \vec{e}_i)(\vec{e}_v + \delta\,\vec{e}_\delta)\varphi(\rho),$$

where Δf - shift of frequency, c - velocity of propagation of the wave in media ; f_0 -frequence of the falling wave; V_0 - velocity of moving turbulences inhomogeneous on the axis of the flow, $\vec{e}_i, \vec{e}_{i+1}, \vec{e}_v$ - individual vectors, appropriate to directions of propagation of beams before and after scattering, and direction of the axis of the flow, $\delta = \Delta V / V_0$ - the relation of velocity of casual moving turbulences inhomogeneous to velocity of their directed movement on the axis of the flow; $\vec{e}_\delta$ - the individual vector in the direction of casual moving turbulences inhomogeneous .

During modeling casual trajectories of beams in the flow calculation and accumulation in a computer memory dopler of shift of frequency, aquired by the wave in result of multiple interaction with moving turbulences inhomogeneous will be carried out. At an exit of the beam for the limits of the flow the computer remembers

shift saved by it of frequency and direction of its propagation. After multiple recurrence of process of tracking for beams and normalize of results we receive the spectral characteristics of the signal, scattering by the flow.

3. PROPAGATION OF THE WAVE UNDER THE CORNER TO THE FLOW

Below results of research of dependence of parameters of the scattering signal from the direction of propagation of the falling wave and factors of the inhomogeneous of the profile of the flow μ_1 and μ_2 are stated. The accounts were carried out for isotropic of the indicatrix over-radiation turbulences at fall collimation of the bunch of beams on the axis of the flow under various corners. Radius of the flow at accounts relied to equal two average lengths of free distribution of the beam in the flow with evenly distributed turbulences inhomogeneous. The size ρ_0 at accounts relied equal 1.

On figure 2 dependence on the corner of sounding of the flow θ of energy past through the flow coherent of the signal P_c (curves a) and energy unitary, doubly and three-fold of scattering signals P_1, P_2, P_3 (curves b,c,d) is submitted. The sizes P_c, P_1, P_2, P_3 are normalized on energy of the falling bunch of beams P_0. The continuous curves on fig. 1 correspond to factors of the inhomogeneous of the profile of the flow μ_1=1; μ_2=0; and shaped - μ_1= 0; μ_2= 1. The relative error of calculations made size <1 %.

To growth of the corner of sounding of the flow there is the increase coherent component in the spectrum and reduction incoherent unitary, doubly and three-fold the scattering components. It is explained by that the probability of passage of beams through the flow without interaction in case of large corners of fall θ grows, and scattering beams -decrease.

The energy of coherent and incoherent components of the signal appear above for the case, when scatterers are concentrated in the vicinity of the axis of the flow (μ_1 = 1, μ_2 = 0, the continuous curves on figure 2) and occupy minimum volume. Probability of passage of the flow the beam without scattering, and also exit them from the flow in result only one, two and three acts scattering in this case grows.

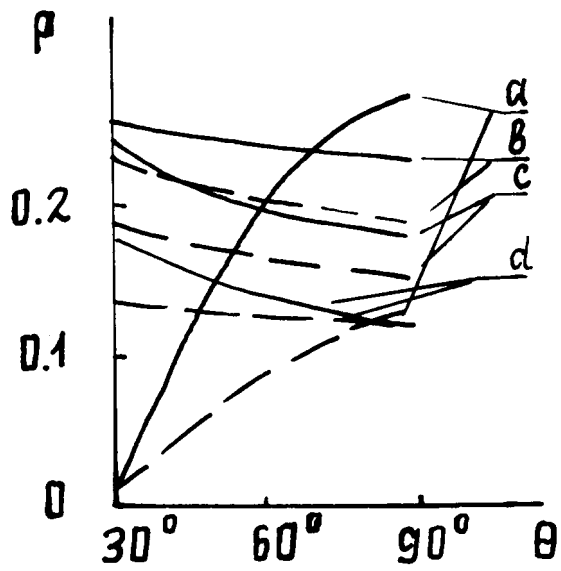

Figure 2. Dependence of energy of the signal on the corner of sounding of the flow. (Curve a- the coherent signal, b, c, d- unitary, doubly and three-fold scattering signals.)

4. PROPAGATION OF THE WAVE FOLLOWING TURBULENT FLOW

The considered above model of the turbulent flow allows essentially to simplify a problem for the case of propagation of the wave following to the turbulent flow. It is suggested, that the flat wave falls in the direction, opposite to the axis z of the body of rotation (of the cone or paraboloid). On its surface are chaotically located turbulences inhomogeneous. They have as directed velocity V_u, oriented along formative bodies of rotation thus and casual isotropic by velocity ΔV, distributed on the normal law. The sizes of the body of rotation much surpass length of the falling wave and characteristic sizes of turbulences inhomogeneous. The back scattering geometry in case propagation wave following turbulent flow is presented on figure 3.

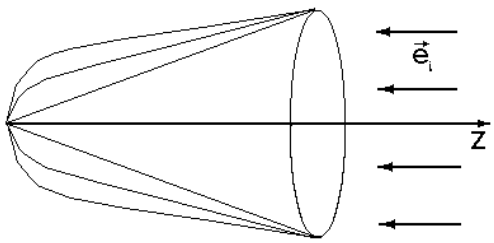

Figure 3. The back scattering geometry in case propagation wave following turbulent flow.

In this case the field of the scattering wave is formed in result multiple reflecters of the wave from the dynamically rough surface. Presence moving chaotically located on the surface turbulences brings in that the phases of beams after reflections from

the surface will be probably. The energy of the scattering signal is in this case proportional to number of beams, scattering in the given element of the corporal corner.

The initial coordinates of beams are evenly distributed on section of the body of rotation in the plane $z = z_m$. The beam proceeds before crossing with the surface of the body of rotation. The coordinates of crossing are determined from the joint decision of system of the equations

$$\vec{r} = \vec{r}_0 + |\vec{r} - \vec{r}_0| \vec{e}_i, \qquad (4)$$

$$Q(r_0) = 0. \qquad (5)$$

where the equation (5) is the equation of the surface, on which passes scattering. In the equation (4) known are $\vec{r}_0$ - of coordinate of the beginning of the beam and individual vector $\vec{e}_i$ in the direction of its propagation. At crossing the beam with a surface there is the change of the direction of its propagation according to set indicatrix over-radiation turbulences quasi-mirror type (1-3).

On figure 4 frequency spectrums of the signal, incoherent scattering on the dynamically rough surface of bodies of rotation are submitted. On the horizontal axis calculation size Doppler of shift of frequency $f_* = (\Delta f c) / (f_0 V_0)$, where Δf - shift of frequency, c - velocity of propagation of the wave, f_0 - frequency of the falling wave, V_u - velocity of moving turbulences inhomogeneous along formative bodies of rotation.

On the vertical axis of each spectral staff calculated energy of the signal, normalized on the maximum of energy in the spectrum. The spectral staff are brought for various meanings of the polar corner θ, calculated from the direction of the axis z of the body of rotation: a) $\theta = 14^0$, b) $\theta = 32^0$, c) $\theta = 50^0$, d) $\theta = 68^0$, e) $\theta = 86^0$.

Continuous, shaped and shaped-dotted the curves show frequency spectrum, received for the cone, paraboloid of the second and fourth orders accordingly. The accounts were carried out at the following meanings of parameters: the relation of the maximum longitudinal size of the body of rotation to cross $z_m / \rho_m = 2$, disperse of velocity of moving turbulences inhomogeneous $\Delta V / V_u = 0.2$, factor β, describing width of the indicatrix over-radiation of turbulences inhomogeneous, accepted

meaning, equal 1.5. Relative error of calculations in points of an arrangement of maximums of spectral pictures made size <4 %.

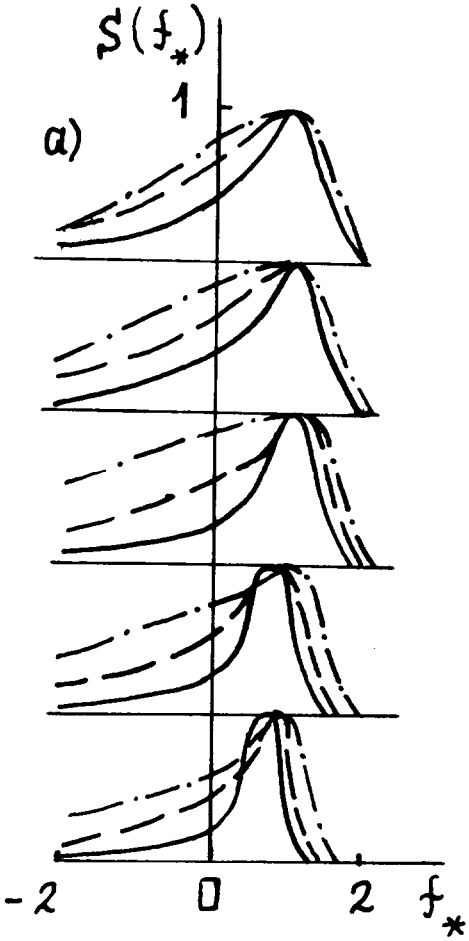

Figure 4. Frequency spectrum of the signal, scattering on the cone, paraboloid of the second and fourth orders, which correspond continuous, shaped and shaped-dotted curves.

The form of the frequency spectrum is characterized by smooth increase of energy with growth of frequency up to achievement of the maximum meaning. Then there is the sharp reduction of energy of the signal up to zero. It is explained by that while the positive shift of frequency is limited from above, negative shift grows with increase of number of reflections. With growth of the corner of the exit of beams θ there is the shift of the maximum of the frequency spectrum to the axis of ordinates. It takes place because the size of the greatest possible positive displacement of frequency thus decreases.

As follows from figure 4, occurrence of second final radius of curvature in the disseminating surface brings to increase of energy of the signal, scattering with

negative shift of frequency. This fact takes place because the number of the acts of scattering much grows.

In result of spent accounts is established, that to increase order the equation, describing the disseminating surface, there is the narrowing to the axis z of the diagram over-radiation of the body of rotation. This fact is explained by that to growth of curvature of the surface (for fixed meaning z) there is the reduction of the greatest possible corner of the exit of the beam θ. It brings to focusing of energy of the scattering signal.

5. APPROBATION OF RESULTS

It would be interesting to carry out comparison of results of numerical modeling of wave propagation in turbulent flows with experimental data on ultrasound and electromagnetic sounding turbulent of the flow of water and plasma.

On figure 5 shaped curve presents a received experimentally frequency spectrum of ultrasound signal, scattering under angle 20^0 to axis of turbulent flow of water [8].

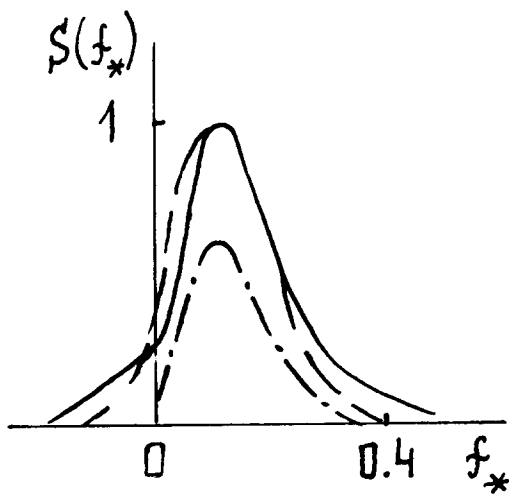

Figure 5. Frequency spectrum of the ultrasound, scattering on the turbulent flow of water. The continuous curve - account, shaped - experiment [8], shaped-dotted - contribution unitary scattering.

Continuous curve on figure 5 presents the results of numerical modeling multiple scattering of wave on turbulences of flow from factor of inhomogeneous profile

velocity of flow μ_1=1, μ_2=0 and inhomogeneous profile of concentration of flow μ_1=0, μ_2=5.

The comparison calculation and experimental curves [8] of frequency spectrums was carried out. It permits to make the conclusion about that in experiment the maximum of profile velocity turbulences is disposed on the axis of the flow and the maximum of profile concentration -on the surface of the flow.

Shaped-dotted curve on figure 5 presents the contribution in frequency spectrum of energy of unitary scattering signal, which dos not containe of spectral component with negative meaning dopler shift of frequency. Therefore, presence in frequency spectrum energy scattering signal with negative shift of frequency is accounted by multiple scattering of ultrasound wave on moving turbulences.

In work [9] the frequency spectrum of the radiosignal, reflected from turbulent flow of the plasma, received for the case of sounding following to the flow along its axis, is brought.

On figure 6 the received experimentally continuous curve [9], and also shaped and shaped-dotted curves of the frequency spectrum of the radiosignal, received in result of numerical modeling in the present work are brought. On the horizontal axis on figure 6 meaning undimensional Doppler of shift of frequency, and on vertical - energy of the signal, normalized on the maximum of energy in the spectrum are calculated.

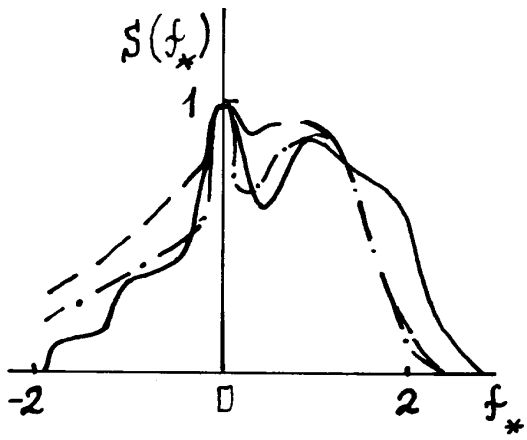

Figure 6. Frequency spectrum of electromagnetic waves, scattering on the turbulent flow of plasma. A continuous curve - experiment [9]. Shaped and shaped-dotted curves - accounts scattering of waves on the paraboloid of the second and fourth orders.

Shaped and shaped-dotted curves on figure 6 are received at scattering of radiowaves on paraboloid second (factor mirror, describing probability mirror of

reflection of beams from the surface, α =0.035) and fourth (α =0.005) orders. Thus the relation of the maximum longitudinal size of plasma formation to maximum cross is equally $z_m / \rho_m = 2$; factor β, describing width of the indicatrix over-radiation scatterers accepted meaning β=1,5; the relative size dispers of velocity scatterers is equal $\Delta V / V_0$= 0,2. The polar corner of the exit of beams from plasma formation is made in limits from 0 up to 9^0.

Experimentally observed frequency spectrum is characterised by set overlapped discrete (at f_*=0) and continuous spectral components. Accounts show, that the size of factor β, describing width of the diagram over-radiation scatterers, much influences the situation of the maximum continuous component in the spectrum. To growth β there is the shift of the maximum of the spectrum in the party of large meanings of shift of frequency, as thus the vector scattering, determined by expression (2), ever more misses the direction normal to the surface. At β=1,5 situation of the specified maximum on settlement shaped and shaped-dotted of curves is close the situation of the maximum on the experimental continuous curve.

Factor of specular α influences on distribution of energy between discretic and continuous components in the spectrum. To various types of surfaces there in this case correspond such meanings of factor α, at which ratio between sizes discrete and maximum continuous component is close to the appropriate ratio on the experimental curve.

Similarity of the form of the experimental spectrum and curves, received in result of numerical modeling, allows to make the conclusion that such spectrum at the reflected signal occurs in result multiple scattering of electromagnetic waves on the internal surface turbulent plasma body of rotation.

6. CONCLUSIONS

In the given work the numerical model concerning electromagnetic wave propagation in turbulent flows such as in liquids, gases and plasma is offered and approbation. The problem about passage of the wave through the flow with the non-uniform profile of velocity and concentration of turbulences is solved. Dependence of parameters of scattering signal on the corner of sounding of the flow and factors,

describing the inhomogeneous of the structure of velocity and concentration of turbulences is investigated.

A case of sounding of the flow along its axis is considered, results of accounts repeated scattering of waves on the internal surface of turbulent bodies of rotation are received: the cone and paraboloid of the second and fourth orders. Dependence of angular and frequency spectrums of the scattering signal on the form of the disseminating surface and width of the diagram over-radiation is investigated.

Is established, that with growth order the equation, describing the surface, energy the spectral component with negative shift of frequency is increased and occurs focusing of energy of the scattering signal to the axis of the body of rotation. The increase of width of the diagram over-radiation scatterers of the quasi-mirror type is accompanied by displacement of the maximum incoherent component of the frequency spectrum in the party of large meanings of shift of frequency of the scattering signal. The spent comparison of results of accounts to experimental data on ultrasound and electromagnetic sounding of the turbulent flows of water and plasma has shown their satisfactory conformity and has allowed to receive the information about the parameters of the flows.

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