INTENSIFICATION OF THE LF IG WAVE STRUCTURES IN THE IONOSPHERIC PLASMA AT INTERACTION WITH NONUNIFORM WINDS

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Abstract - Theoretical explanation of the generation and intensification of low frequency (LF) internal gravity waves (IGW) is presented. The method used is based on generalizing results on shear flow phenomena from the hydrodynamicscommunity. In the 1990s, it was realized that fluctuation modes of spectrally stable nonuniform shearedflows are non-normal. That is, the linear operators of the flows modal analysis are non-normal and the corresponding eigenmodes are not orthogonal. The non-normality results in linear transient growth with bursts of the perturbations and the mode coupling, which causes the amplification of LF IG waves shear flow driven ionospheric plasma. Transient growth substantially exceeds the growth of the classical dissipative trapped-particle instability of the system. It is shown that at initial linear stage of evolution IGW effectively temporarily draws energy from the shear flow significantly increasing (by order of magnitude) own amplitude and energy. With amplitude growth the nonlinear mechanism turns on and the process ends with self-organization of nonlinear solitary, strongly localized IGW vortex structures. Accumulation of these vortices in the ionosphere medium can create the strongly turbulent state.

I. INTRODUCTION

Internal gravity waves (IGWs) play an important role in the formation of the general circulation, thermal regime, and composition of the middle and upper atmosphere. According to present knowledge, the main portion of IGW energy reaches the middle and upper atmosphere from tropospheric sources. In the middle and upper atmosphere the amplitudes of waves increase, they break and produce substantial amounts of heat and momentum (Holton, 1983).

One of the important properties of IGW is their significant influence on the distribution of the electromagnetic waves in atmospheric-ionosphere layers (Gershman, 1974). Consequently, ionosphere electric currents and electromagnetic fields may re-influence the wave properties of IGW at ionosphere altitudes. In the ionosphere, in contrary to the lower layers of the atmosphere, investigating the dynamics of wave processes non-uniform and non-stationary properties of the wind process, the turbulent state of the lower ionosphere and the influence of non-uniform electromagnetic forces should be taken into account. These factors, which are due to the low density medium in the ionosphere and the relatively high conductivity of the ionosphere gas, are strongly pronounced and they can sufficiently affect the propagation characteristics of wave patterns. Consequently, the general circulation in the ionosphere must have specific features that are absent in the troposphere.

The stationary problem of the existence of ionosphere wave disturbances in case of rectilinear uniform medium flow (for large-scale Rossby type waves) has been discussed for the first time in the work of Dokuchaev (1959). It has been revealed that in the theoretical study and interpretation of the dynamics of the winds above 100 km it is necessary to consider the possible deviations from the geostrophic winds associated with the action of electromagnetic forces. Further, a number of other works have appeared (Hines and Reddy, 1967; Aburjania et al., 2013 and others), which studied the non-stationary evolution of wind structure in the conducting ionosphere medium under the influence of the spatially non-uniform geomagnetic field.

The action of the geomagnetic field, on the one hand, leads to the inductive damping of the waves associated with Pedersen or transverse (with respect to the geomagnetic field) conductivity, on the other one - to the gyroscopic effect due to the Hall conductivity of the ionosphere acting on the perturbation like the Coriolis force. As a result of the joint action of spatially non-uniform Coriolis and electrodynamic (related to the geomagnetic field) forces the new type waves with different characteristics from the usual waves in the neutral medium may exist in the ionosphere. These waves can be called as magnetized waves.

II. GENERATION AND INTENSIFICATION OF IGW AT LINEAR STAGE OF EVOLUTION

To study the linear stage of interaction of internal gravity waves with the local non-uniform zonal wind and geomagnetic field, the model of the medium and basic hydrodynamic equations for the lower ionosphere, is given in Aburjania at all 2013.
On the basis non-modal approximation, shear flows can become unstable transiently till the condition of the strong relationship between the shear flows and

wave perturbations is satisfied (Chagelishvili et al., 1996), e. i. the perturbation falls into amplification region in the wave number space. Leaving this region, e. i. when the perturbation passes to the damping region in the wave vector space, it returns an energy to the shear flow (Aburjania et al., 2010). The experimental and observation data shows the same (Gossard and Hooke, 1975).

Non-uniform zonal wind or shear flow can generate and/or intensify the internal gravity waves in the ionosphere and provoke transient growth of amplitude, i.e. transient transport the medium into an unstable state. In the next subsection we confirm this view by using a different, more self-consistent method for the shear flow.

Acoording to above discussions, further analysis of the features of magnetized IGW wave at the linear stage in the ionosphere should be conducted in accordance with a non-modal approach. Considering the initial model equations into moving coordinate system, where the coordinates become time dependent, the coefficients of the initial system of linear equations will obtain temporal dependence. Such mathematical transformations replace this spatial non-uniform property into temporal one. Thus, the initial-boundary problem is reduced to the initial problem of Cauchy type. Hence, the coefficients of are independent of spatial variables, the Fourier transformation of these equations with respect to spatial variables x_1, z_1 is already possible without any local approximation, the temporal evolution of these spatial Fourier harmonics (SFH) are considered independently:

$$\frac{\partial V_x}{\partial \tau} = -SV_z + k_x P - [b_0 + \nu k^2(\tau)]V_x, \quad (1)$$

$$\frac{\partial V_z}{\partial \tau} = k_z(\tau)P - \rho - [b_y + \nu k^2(\tau)]V_z, \quad (2)$$

$$\frac{\partial \rho}{\partial \tau} = V_z, \quad (3)$$

$$k_x V_x + k_z(\tau)V_z = 0.$$

Here, $\mathbf{V}_0(z) = v_0(z)\ \mathbf{e_x} = A \cdot z \cdot \mathbf{e_x}$ is a background of a plane zonal shear flow (wind) velocity, which is non-uniform along the vertical,

$\mathbf{V} = \mathbf{V_0}(z) + \mathbf{V}(x,z,t)$, $\rho = \rho_0(z) + \rho(x,z,t)$,

$P = P_0(z) + P(x,z,t)$, $v_0'(z) = dv_0(z)/dz$

$\omega_g = (g/H)^{1/2} > 0$ — frequency of Brunt-Vaisala for stably stratified incompressible isothermal atmosphere; $K^2 = k_x^2 + k_z^2 + 1/(4H^2)$,

$K_1^2 = K_2^2 - ik_z/H$, $K_2^2 = k_x^2 + k_z^2 - 1/(4H^2)$,

$(x,z) \Rightarrow (x_1, z_1)/H$, $S \Rightarrow A/\omega_g$,

$k_{x,z} \Rightarrow k_{x_1,z_1} H$; $k_z = k_z(0) - k_x S\tau$,

$k^2(\tau) = (k_x^2 + k_z^2(\tau))$, $\nu \Rightarrow \nu/\omega_g H^2$,

$b_0 \Rightarrow (\sigma_P B_0^2)/(\rho_0 \omega_g)$, $b_y \Rightarrow (\sigma_P B_y^2)/(\rho_0 \omega_g)$.

Closed system of equations (1) - (4) describes the linear interaction of IGW with a shear flow and the evolution of the generated disturbances in the dissipative ionosphere medium. We note once again that after these transformations the wave vector k $(k_x, k_z(\tau))$ of the perturbation became dependent on time: $k_z(\tau) = k_z(0) - k_x S \cdot \tau$; $k^2(\tau) = (k_x^2 + k_z^2(\tau))$. Variation of the wave vector according to time (i.e. splitting of the disturbances' scales in the linear stage) leads to significant interaction in the medium even of such perturbations, the characteristic scale of which are very different from each other at the initial time (Aburjania et al., 2006).

On the basis of (1) - (4) an equation of energy transfer of the considered wave structures can be obtained, which gives possibility to identify the pattern of energy density variation with time:

$$\frac{dE(\tau)}{d\tau} = -\frac{S}{2}\left(V_x^*(\tau)\cdot V_z(\tau) + V_x(\tau)\cdot V_z^*(\tau)\right) - b_1(\tau)|V_x|^2 - b_2(\tau)|V_z|^2, \quad (5)$$

Here the asterisk denotes the complex conjugate values of the indignations, $b_1(\tau) = b_0 + \nu k^2(\tau)$, $b_2(\tau) = b_y + \nu k^2(\tau)$ and the density of the total dimensionless energy of the wave perturbations $E(\tau)$ in the wave number space is given by:

$$E[k(\tau)] = \frac{1}{2}\left(|V_x|^2 + |V_z|^2 + |\rho|^2\right) \quad (6)$$

It's obvious that the transient evolution of wave energy structures in the ionosphere is due to the shear flow $(S \neq 0,\ A \neq 0)$, dissipative processes - induction decay ($b_0 \neq 0,\ b_y \neq 0$) and viscosity ($\nu \neq 0$). In the absence of shear flow $(S = 0,\ A = 0)$, and dissipative processes $(\nu = 0,\ \sigma_P = 0)$, the energy of the considered wave disturbances in the ionosphere conserves $dE(\tau)/d\tau = 0$. The total energy density of the perturbations (6) consists of two parts: $E[k] = E_k + E_t$, where the first term is the kinetic energy of perturbation $E_k = \left(|V_x|^2 + |V_z|^2\right)/2$, and the second - thermobaric energy $E_t = |\rho|^2/2$, stipulated due to the elasticity of perturbations.

To emphasize the pure effect of shear flow on the evolution of IGW, for simplicity, we consider non-dissipative ionosphere, i.e. we suppose that

$(\nu = 0, \sigma_P = 0)$. Further, on the basis of equation (5) the reason, what actually leads to the evolution of the energy of the wave disturbance – to their growth or decrease - will be. In this purpose the right-hand side part of equation (5) have to be calculated.

From the initial equations an expression for the normalized energy density of the Fourier harmonics is obtained:

$$\bar{E}(\tau) = \frac{E(\tau)}{E(0)} = \frac{\left(1+k_0^2\right)^2}{\left[1+(k_0 - S\tau)^2\right]^{1/2}} \quad (7)$$

and for the IGW energy transport equation (at $b_1 = b_2 = 0$)

$$\frac{d\bar{E}(\tau)}{d\tau} = \frac{\left(1+k_0^2\right)^2 \cdot (k_0 - S\tau)}{\left[1+(k_0 - S\tau)^2\right]^{3/2}} \quad (8)$$

Here for the convenience of numerical analysis a new parameter $k_0 = k_z(0)/k_x$ is introduced.

An expression for the increment (decrement) of the shear instability $\Gamma(\tau) = (1/\bar{E}(\tau)) \cdot d\bar{E}(\tau)/d\tau$ in the non-dissipative ionosphere is also determined:

$$\Gamma(\tau) = \frac{k_0 - S\tau}{1 + (k_0 - S\tau)^2} \quad (9)$$

In the initial stage of evolution when $k_0 = k_z(0)/k_x > 0$ (when $k_z(\tau) > 0$) over time τ, $0 < \tau < \tau^* = k_z(0)/(Sk_x)$, the energy density of IGW increases monotonically and reaches its maximum value (exceeding its initial value by an order) at the time $\tau = \tau^*$. Further, at $\tau^* < \tau < \infty$ the energy density begins to decrease (when $k_z(\tau) < 0$), and monotonically returns to its initial approximately constant value. In other words, in the early stages of evolution, temporarily, when $k_z(\tau) > 0$ and IGW perturbations are in the intensification region in wave-number space, the disturbances draw energy from the shear flow and increase own amplitude and energy by an order during the period of time $0 < \tau < \tau^* = k_z(0)/(Sk_x) = 100$. Then (if the nonlinear processes and the self-organization of the wave structures are not turned on), when $k_z(\tau) < 0$, IGW perturbation enters the damping region in wave number space and the perturbation returns energy back to the shear flow over time $\tau^* < \tau < \infty$ and so on. Such transient redistribution of energy in the medium with the shear flow is due to the fact that the wave vector of the perturbation becomes a function of time $k = k(\tau)$, i.e. disturbances' scale splitting takes place. The structures of comparable scales effectively interact and redistribute free energy between them. Taking into account the induction and viscous damping the perturbation's energy reduction in the time interval $\tau^* < \tau < \infty$ is more intensive than that shown on fig. 1, the decay curve in the region $\tau^* < \tau < \infty$ becomes more asymmetric (right-hand side curve becomes steeper), and part of the energy of the shear flow passes to the medium in the form of heat.

Thus, even in a stable stratified ionosphere ($\omega_g^2 > 0$), temporarily, during the time interval $0 < t^* \approx 100/(\omega_g) \sim 5 \cdot 10^3 s \approx 1.5$ hour IGW-intensively draws energy from the shear flow and increases own energy and amplitude by an order. Accordingly, the wave activity will intensify in the given region of the ionosphere due to the shear flow (inhomogeneous wind) energy.

CONCLUSIONS

Linear amplification of IGW perturbation is not exponential as in the case of the AGW in the inverse-unstably stratified ($\omega_g < 0$, when IGW cannot be generated) atmosphere (Aburjania, 2010)), but in algebraic-power law manner. Intensification of IGW is possible temporarily, for certain values of environmental parameters, shear and waves, which form an unusual way of heating of the shear flow in the ionosphere: the waves draw their energy from the shear flow through a linear drift of SFH in the wave number space (fragmentation of disturbances due to scale) and pump energy into the region of small-scale perturbations, i.e. in the damping region. Finally, the dissipative processes convert this energy into heat. The process is permanent and can lead to strong heating of the medium. Intensity of heating depends on the level of the initial disturbance and the parameters of the shear flow.

A remarkable feature of the shear flow is the dependence of the frequency and wave number of perturbations on time $k_z = k_z(0) - k_x S\tau$, $k(\tau) = (k_x^2 + k_z^2(\tau))^{1/2}$. In particular, frequency and wave number transient growth leads to a reduction of scales of the wave disturbances due to time in the linear regime and, accordingly, to energy transfer into a short scale region - the dissipation region. On the other hand a significant change in the frequency range of the generated disturbances stipulates in the environment the formation of a broad range of spectral lines of the perturbations, which is linked to the linear interactions and not to the strong turbulent effects. Moreover, amplification of the SFH perturbation and broadening of wave modes' spectra occur in a limited period of time (transient interval), yet satisfied the relevant conditions of amplification and a strong enough interaction between the modes.

It should be emphasized that the detection of the mechanism of the intensification and broadening of

the spectrum of perturbations became possible within the non-modal mathematical analysis (these processes are overlooked by more traditional modal approach). Thus, non-modal approach, taking into account the nonorthogonality of the eigenfunctions of the linear wave dynamics, proved to be more appropriate mathematical language to study the linear stage of the wave processes in shear flows.

IGW is characterized by an exponential growth of the amplitude of the perturbed velocity at the vertical propagation in an environment with exponentially decaying vertical equilibrium density and pressure (Hines, Gossard, Hook, 1975). According to observational data, IGW disturbances manifest themselves in a wide range of heights - from the troposphere to the upper ionosphere heights $z \leq 600$ km (Gossard and Hook, 1975). At ionospheric altitudes (above 90 km) the conductive medium strongly impacts on the IGW, causing its remarkable damping due to local Pedersen currents.

IGW structures are eigen degrees of freedom of the ionospheric resonator. Therefore, influence of external sources on the ionosphere above or below (magnetic storms, earthquakes, artificial explosions, etc.) will excite these modes (or intensified) in the first. For a certain type of pulsed energy source the nonlinear solitary vortical structures will be generated (Aburdjania, 2006), which is confirmed by experimental observations (Sundkvist et al., 2005). Thus, these wave structures can also be the ionospheric response to natural and artificial activity.

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