Possibility of application of the dynamo effect to generation of superhigh magnetic fields.

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Introduction

In MGD - installations [1-4], intended to generate high magnetic fields using compression of magnetic flux by a conducting material which is preliminary accelerated by explosion, electromagnetic or the other forces, the magnetic field increases until the magnetic pressure becomes equal to the hydrodynamic pressure H from $\mathrm{H}^2/4\pi = \upsilon^2\rho$, where ρ is the density, H is the magnetic field intensity, υ is the velocity of a conducting material. In the generation of the greatest pulsed magnetic fields the main limitations are the dissipative processes and the material compressibility which are very quickly increase during the final stage of compression of magnetic flux.

The compressibility of a conducting material reduces the effect of energy cumulation to a great extent [1]. Dissipative processes such as the turbulent diffusion and ohmic one, the turbulent mixing of a conducting material as a result of magnitohydrodynamic and convective unstabilities, divide the main scale of compression L into large number of small parts, in which dissipation prevails over generation, and mix a magnetic field with a material. The material expands on heating, pressure of magnetic field on conduction falls sharply. In these cases arising turbulence is isotropic, and isotropic turbulence has not the properties of generations [5].

This report deals with the case, when unfavourable for superhigh magnetic fields generation agents like magnitohydrodynamic and convective instabilities, compressibility and turbulence, become necessary conditions for the $\alpha\omega$ -dynamo-effect, which can help to generate high magnetic fields efficiently.

From the dynamo theory it is well known that the $\alpha\omega$ -dynamo-effect is generated in the convective zone of astrophysical objects with the availability of gyrotropic turbulence, differential rotating and seeding large-skale magnetic field of azimuthal or meridianal configuration [5-8]. Gyrotropic turbulence results from the Coriolis forces acting on rising (or lowering) convective cell in the medium stratified by density. For initiation of the dynamo effect, a high magnetic Reynolds number $R_m = L\upsilon/\eta >> 1$ [8], here L is the scale of motion of an electrically conducting material, υ is its velocity, η is the ohmic damping coefficient is required. In operation the characteristic spatial scale of the electrically conducting, moving continuum is reduced (divided) and in response to changing scale the magnetic Reynolds number $R_m = \ell\upsilon/\eta$, (here ℓ is the small scale of motion) is reduced. A necessary condition for dynamo to operate properly is that $\ell\upsilon/\eta \approx 1$ [7].

Conditions required for initiation of the $\alpha\omega$ -dynamo-effect may be obtained under compression of quickly rotating and conducting, follow spherical shell by high magnetic field. During the process of collapse and compression of the rotating shell differential rotating and gyrotropic turbulence one occur, and gyrotropic turbulence already has generating properties.

Statement of the problem.

We deal with the compression of quickly rotating and conducting shell, placed in the centre of a solenoid, generating the high pulsed magnetic field. As a source of the high pulsed magnetic field, we select the MK-1 [1] explosive cascade magnetocumulative generator, which consists of a solenoid-shell, surrounded by a ring-shaped charge externally, and wire cascades. The initial magnetic field with duration as high as 100 μs and amplitude 0.2 MGs is created in the generator under discharge of the capacitor blocks into the solenoid-shell. At the instant the initial field is at a maximum, the charge is detonated. The arising convergent cylindrical blast wave accelerates the solenoid-shell to the centre, and it compresses the initial magnetic flux. The duration of compression pulse is equal to 10 μs. The magnetic field intensity at a maximum of a compression pulse is equal to 10 MGs. The region of a uniform magnetic field at a maximum occupies the area of several cubic centimetres, and the finite diameter is about one centimetre.

To suppers a moment proportional to $\Omega \times \mathrm{H}$ disturbing stable rotation of a body, it is necessary that the dynamically axis of rotation should be the same in direction with the magnetic field in the solenoid. For symmetric collapse of the rotating shell it is necessary that the area of uniform magnetic field in the solenoid-should be much greater than the geometrical dimensions of the shell and that the shell be in the centre of this uniform area at the compression beginning instant.

We set the parameters of the shell in accordance with the generator parameters. The initial diameter of the shell is equal to 1 cm, its thickness is equal to 0.1 cm, the shell is manufactured from copper and air is evacuated from its cavity. The shell spins up to 10^4 revolutions per second in a gyroscope with a free suspension. The depth of penetration (skin) of the initial magnetic field is approximately equal to the shell thickness, and the depth of penetration of quickly increasing magnetic field is much len than the shell thickness.

We conventionally break compression of the hollow shell by a high magnetic field down to several stages:

1) diffusion of the initial magnetic field into the rotating hollow shell,
2) collapse of the rotating shell under quickly increasing magnetic field with occurrence of differential rotation,
3) generation of the azimuthal magnetic field by the differential rotation,
4) compression of the rotating shell, its heating and occurrence of gyrotropic turbulence,
5) generation of magnetic field by the $\alpha\omega$ -dynamo-effect.

Diffusion of magnetic field into conducting rotating shell is explained in the papers [10,11]. The distribution of force lines of magnetic field in spherical shell in maximum of the initial field is shown in Fig.1.

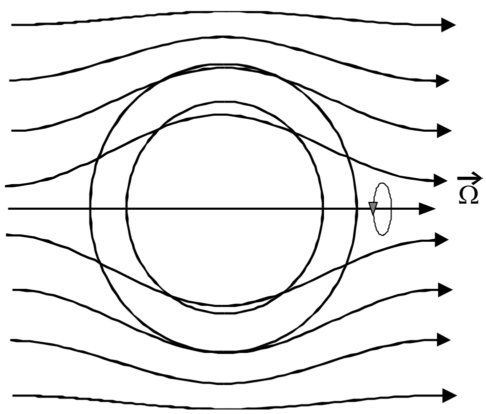

Fig. 1. Diffusion of pulsed magnetic field into rotating shell..

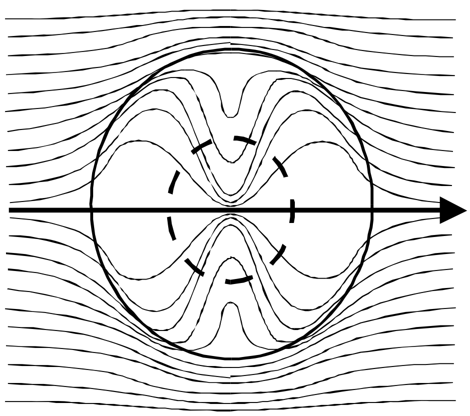

Fig.2. Distribution of magnetic field within the collapsing shell at R_m>>1.

If the pressure of magnetic field is much greater than the strength limit of the shell material, then the shell is recognised as fluid and its motion under electromagnetic forces is described in the context of magnetic hydrodynamics. At high rate of the shell collapse the magnetic Reynolds number is much greater than one

(R_m>>1), so the field is "frozen" into the shell material and it is transported with this material. Radial collapse of the shell and compression of magnetic flux by the shell are shown in Fig.2. The region of effective generation of azimuthal magnetic field is dotted.

This pattern is heavily distorted by the differential rotation, which occurs as a result of the Coriolis forces acting on the collapsing shell.

Without considering friction between layers differential rotation is appropriate to the conservation of angular momentum.

If for differential rotation $R_m >> 1$, then the field is "frozen"into particles of medium. Interior parts move in a circle farther than exterior ones, and the azimuthal field B_φ is extracted from the seeding meridianal field B_p therewith, during one revolution of the outer boundary of the generation region, two closed magnetic force lines of the field are formed and they have distinct direction above and below the plane of equator (see Fig.3).

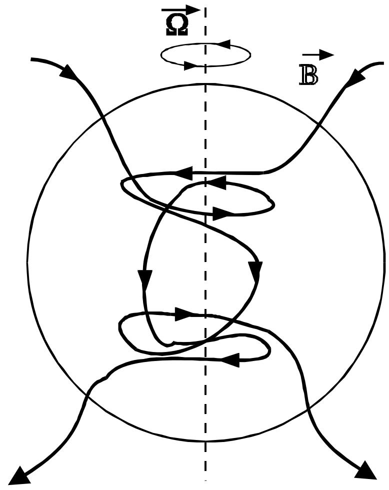

Fig.3. Generation of azimuthal magnetic field by differential rotation.

The azimuthal field increases until the magnetic pressure will be equal to the hydrodynamic pressure

$$\frac{B_\varphi B_p}{4\pi} = \rho\upsilon\Omega r, \quad (1)$$

here υ is the rate of the shell collapse. When the azimuthal field peaks, then smoothing out imhomogeneity of differential rotation and damping of the field effectively operate. From the formula (1) one can see that, the greater are the rotation velocity and the collapse rate, the greater the value of azimuthal field which can result from this.

The following phase of the process includes compression of central region of the shell and its heating. As a result of spherical cumulation, inner layers of the shell gain the high radial rate of collapse. The inner layers converge to the centre forming the blast wave, so on impact a large part of the progressive kinetic energy of the shell transforms into the elastic energy of compression and heating of the material. The shell is in the compressed condition for as long as increasing forces of magnetic pressure act on its conducting outside. Cylindrical cumulation and spherical one are accompanied by quick growth of magnetohydrodynamic and convective instabilities at the interfaces "fluid-field", "fluid-gas". This brings into mixing of the material with the field and into forming of turbulent motions. With the availability of rotation, density gradient and temperature gradient turbulence become gyrotropic [7,8].

Gyrotropic turbulence occur when the correlation $< \upsilon rot \upsilon_2 > \neq 0$, here υ is the velocity of rising (lowering) convective cells, υ_2 is the velocity of expanding (contracting) of cells]. Existence of such correlation points to the fact that the right spiral and the left one are not on equal terms. A measure of spiral is recorded as $< \upsilon rot \upsilon_2 >= \ell' \upsilon \Omega (\rho)^{-1} \nabla\rho < \upsilon rot \upsilon_2 >= \ell' \upsilon \Omega (\rho)^{-1} \nabla\rho$, here ℓ' is the correlation length, Ω is the angular velocity of macro-object rotation, ρ and $\nabla\rho$ are respectively the density and the density gradient of the medium, in which the cell rises (lowers).

In the compressed shell the Coriolis force $F = 2\rho[\upsilon\Omega]$, acting on radially rising (lowering) convective cells, is a source of differential rotation. Differential rotation is generated, if the radial component υ_r is greater than the others υ_θ and υ_φ. In other words, the generator of angular velocity operates only in the absence of equivalence of radial direction and angular one for the momentum flow of random velocities [12,13].

A convective element, rising or lowering along the radius, expands or it is contracted because of density gradient, that is , it gains the additional components of velocity - υ_θ and υ_φ. Therewith arising the momentum of Coriolis forces gives the element additional rotation. The convective cell acts on the azumuthal (meridianal) magnetic field and forms small-scale loops from it (see Fig.4). Then, because of ohmic dissipation the loops close in another way and form the large-scale magnetic field. Generation of magnetic field by the $\alpha\omega$ -dynamo-effect is covered by the equation

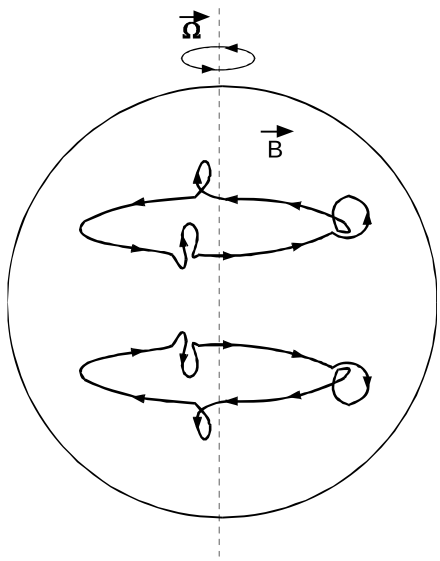

Fig.4. Generation of meridianal magnetic field by convective cells.

$$\frac{\partial \mathrm{B}}{\partial t} = \mathrm{rot}\, \alpha\, \mathrm{B} + \mathrm{rot}[\mathrm{vB}] - (\eta + \eta_T)\Delta\, \mathrm{B}, \tag{2}$$

here $\alpha = -(1/3) < \upsilon rot \upsilon_2 > \tau = -(2/3)\ell'^2\Omega\nabla\rho/\rho$, τ is the correlation time, η_T - the coefficient of turbulent diffusion.

The joint action of the α -effect and the differential rotation leads to generation of dynamo waves. The direction of propagation of the waves depends on the sigh of product $\alpha(r,\theta)\nabla\Omega(r,\theta)$ [5,7,8].

Generation of azimuthal magnetic field during the collapse of rotating shell.

The pulsed magnetic field acts on the rotating conducting shell by forces of magnetic pressure in accordance with the distribution of magnetic field intensity on the surface of conducting shell. For a well-conducting hollow shell placed in the centre of a long solenoid shell, in the case when the skin is much less than the shell thickness, this distribution in spherical coordinates has the tangential component [4].

$$H_\theta = H_0\left(\frac{R^2}{R^2 - r^2 \sin^2\theta}\right)\sin\theta, \tag{3}$$

here H_0 is the magnetic field intensity in the solenoid without shell, R is the inside radius of the solenoid shell, r is the outside radius of the shell. On the other hand, on the rotating shell the centrifugal force acts, which is recorded as

$$\mathrm{F} = m_i\Omega^2 r_i \sin\theta, \tag{4}$$

here, i is the serial number of a "fluid" particle of the shell, m_i is the mass of a particle, Ω is its angular velocity, r_i is the distance from the shell centre to a particle, θ is the angular counted from the rotational axis, therewith the rotational axis is coincident with the axis of solenoid-shell.

Radial collapse of the rotating spherical shell occurs with formation of the compound differential rotation $\Omega(r,\theta)$ in accordance with the conservation of angular momentum. To find $\Omega(r,\theta,t)$, it is necessary to solve the sophisticated two-dimensional equation of motion of rotation spherical shell under the influence of high pulsed magnetic field in the MK-1 generator, but for estimate of the differential rotation and for estimate of azimuthal magnetic field value it is sufficiently to solve the one-dimensional equation of the shell motion, in which Ω depends only on r, numerically. In this case the equation of motion is significantly simplified, and without considering viscosity it can be recorded as

$$\frac{\partial \upsilon}{\partial t} + \left(\upsilon\nabla\right)\upsilon = -\frac{1}{\rho}\nabla P + \frac{1}{2}\nabla\left[\Omega r\right]^2, \qquad (5)$$

here P is the pressure of magnetic field on the shell surface. Such simple simulation always describes the phase of acceleration adequately. It can not be used for prediction of the maximum velocity of the inner surface at once, because the velocity will be limited essentially by the compressibility of shell material [2], but it is unable as the upper estimate of velocity of the inner surface. The lower estimate can be obtained simply, based on the results of the paper [14] and on the computations for the collapse of rotating shell. From them the instantaneous distribution of pressure over the shell radius can be obtained for any instant and for any region. Thereafter, for estimate of the elastic compression the well-known equation of state should be used [15]. Substituting the maximum density found from the equation of state and the thickness of compressed shell into equation (5), we begin a calculation from the initial radius of inner surface identical to that for incompressible shell, and we continue the calculation to the radius, for which the distribution of pressure over instants was defined. These calculations give us the lower estimate for the rate of collapse of inner surface of rotating shell.

The results of computational solution of one-dimensional equation of motion of rotating "instantly compressed" conducting shell under high pulsed magnetic field in the MK-1 generator in the fast rotation approximation are shown in Fig. 5, Fig.6.

Differential rotation curve dipole lines of force extending them in azimuthal direction (see Fig.3), and ohmic dissipation recloses them forming the azimuthal magnetic field B_φ. Generation of the azimuthal magnetic field by differential rotation is described by the azimuthal component of the equation

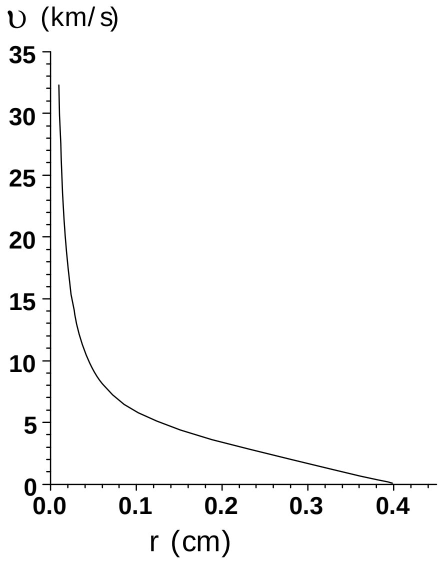

Fig.5 Lower estimate for the velocity of inner surface of " instantaneously compressed" shell, rotating with the initial angular velocity $\Omega=2\pi\ 10^4\ c^{-1}$, as function of radius.

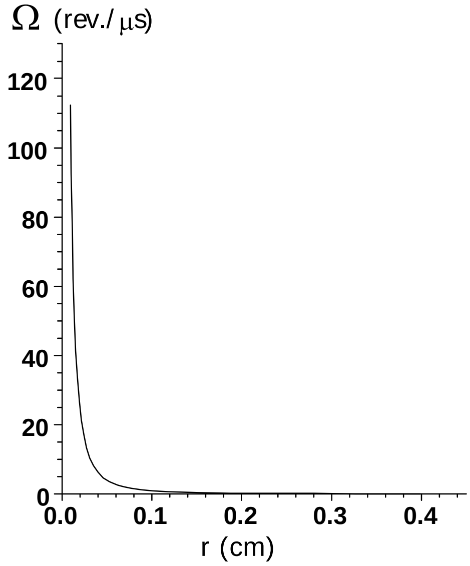

Fig.6 Lower estimate for the angular velocity of inner surface of "instantaneously compressed" shell, rotating with the initial angular velocity $\Omega=2\pi\ 10^4\ c^{-1}$, as function of radius.

$$\frac{\partial B_\varphi}{\partial t} = \mathrm{rot}\left(\upsilon_\varphi B_p\right) - \eta\Delta B_\varphi . \qquad (6)$$

We solve this equation in the kinematics approximation, that is, when $\rho\upsilon^2/2 >> B^2/8\pi$. In this case we neglect of reverse influence of the field on the large-scale velocity field υ_φ. The azimuthal field increases until arising magnetic stress cancels inhomogeneity of rotation.

The outer boundary of generation region is chosen from the condition of effectiveness of influence of differential rotation on generation of azimuthal magnetic field from the seeding meridianal magnetic field in the centre of collapsed shell (see Fig.2, where the outer boundary is dotted). We find the value of meridianal field

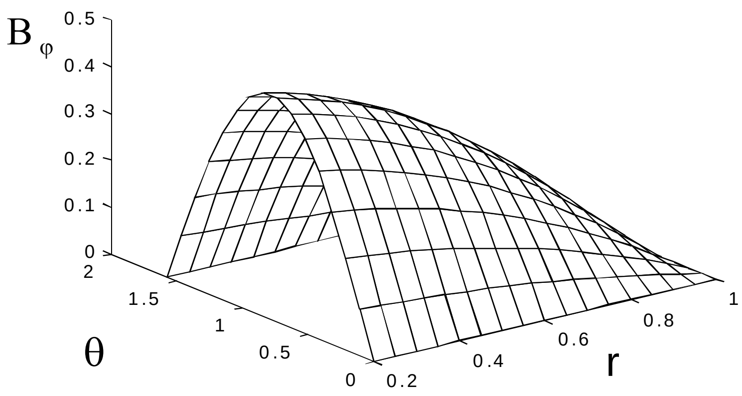

Fig. 7. (r,θ) - dependence of the value of azimuthal magnetic field B_φ in the core of shell of radius r.

from the equation of motion, and we consider its distribution in the region of generation as dipole distribution which may take the form of the azimuthal component of the vector potential. Then, in spherical coordinates the distribution of the field is recorded as

$$A_\varphi r \sin\theta = \frac{1}{2} B_p r^2 \sin^2\theta . \qquad (7)$$

For the case of permanent rotation the hydromagnetic equation (8) may be recorded as follows:

$$\left\{\frac{\partial}{\partial r} r^2 \frac{\partial}{\partial r} + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} - \frac{1}{\sin^2\theta}\right\} B_\varphi = \frac{2B_p d^2 \Omega_0}{\eta}\sin\theta\cos\theta, \qquad (8)$$

here d is the outer boundary of the generation region. Region, which is above this boundary, scarcely affects the generation of magnetic field, and in the vicinity of the centre the azimuthal component is equal to zero, thus the generation region has both upper boundary and lower one. The particular solution of this non-homogeneous equation takes the form:

$$B_\varphi = \frac{B_p \Omega_0 d^2}{3\eta}\left(r^2 - 1\right)\sin\theta\cos\theta . \qquad (9)$$

Adding the solution of the homogeneous equation, which follows from the condition B_φ=0 (at the boundary $r = d$), we obtain the general solution of equation (8)

$$B_\varphi = \frac{B_p \Omega_0}{3\eta}\left(r^2 - d^2\right)\cos\theta\sin\theta . \qquad (10)$$

The (r, θ)-dependence of the azimuthal magnetic field on the intervals $r \in [d/5, d]$, $\theta \in [0, \pi/2]$ is shown in Fig.7. Substituting values of parameters $B_p = 10^6$ Gs, $\Omega_0 = 10^6$ s^{-1}, $\eta = 1.6 \cdot 10^2$ cm^2/s (for example, for the copper shell), $d = 0.1$ cm, $r = 0{,}05$ cm, $\theta = \pi/4$, which are found from the equation of motion, into (12), we obtain the value of azimuthal magnetic field $B_\varphi = 7.5 \cdot 10^6$ Gs in one revolution of the outer boundary of the generation region.

Differential rotation gaim the value of azimuthal magnetic field until the Loretz force balances Coriolis force (1), therefor, to generate high magnetic fields it is necessary that the shell should have the maximum initial angular speed, an effective conductivity, a high rate of collapse and a high value of the seeding meridional magnetic field.

The dynamo effect in a rotating shell

At the stage of compression a high part of both the progressive kinetic energy and the energy of increasing pulsed magnetic field transform to the elastic energy of shell material compression and the shell heating [16,17,18]. By the time of compression beginning in the central region of the shell the large-scale azimuthal magnetic field has been generated, and it is the seeding field for the $\alpha\omega$ - dynamo process (that is , it initiates the $\alpha\omega$ -dynamo process).

The joint action of the α effect and the differential rotation leads to the generation of the exponentially increasing or damped dynamo waves. It is necessary to solve this problem numerically because of its sophistication. Here there is only the qualitative representation of the initiation and the propagation of dynamo waves in the compressed shell, at the condition of homogeneity (in both space and time) of differential rotation, the α effect and coefficient of turbulent diffusion, to the kinematic approximation. Such representation is possible only in the case when the period of dynamo process is much less than the time of pulse increasing in the MK-1 generator.

This process is governed by equation (4). To show generation of dynamo waves, it is conveniently to transfer from the vector **B** to the two scalars - the azimuthal field B_φ and the φ -component of the vector potential A_φ of meridional field (it is always possible in the case when $\partial / \partial\varphi = 0$):

$$\begin{aligned} B_r &= \frac{1}{r \sin\theta} \frac{\partial}{\partial\theta}\left(A_\varphi \sin\theta\right), \\ B_\theta &= -\frac{1}{r}\frac{\partial}{\partial r}\left(rA_\varphi\right). \end{aligned} \tag{11}$$

Then in the spherical coordinates equation (4) takes the form:

$$\begin{cases} \dfrac{\partial A_\varphi}{\partial t} = \alpha B_\varphi - \left(\eta_T + \eta\right)\Delta A_\varphi, \\ \dfrac{\partial B_\varphi}{\partial t} = \dfrac{1}{r}\left\{\dfrac{\partial\Omega}{\partial r}\dfrac{\partial}{\partial\theta} - \dfrac{\partial\Omega}{\partial\theta}\dfrac{\partial}{\partial r}\right\}\left(rA_\varphi \sin\theta\right) - \left(\eta_T + \eta\right)\Delta B_\varphi. \end{cases} \tag{12}$$

Eliminating B_φ from the second equation, we obtain the equation for the vector potential:

$$\left\{\left(\frac{\partial}{\partial t} - \left(\eta_T + \eta\right)\Delta\right)^2 - \frac{\alpha}{r}\left(\frac{\partial\Omega}{\partial r}\frac{\partial}{\partial\theta} - \frac{\partial\Omega}{\partial\theta}\frac{\partial}{\partial r}\right)\left(r\sin\theta\right)\right\}A_\varphi = 0, \tag{13}$$

which has the wave solution of the tipe

$$A_\varphi = \exp i(\omega t - kr). \tag{14}$$

We substitute (14) into (13). Suggesting, that Ω is a function only of the r and that $\eta_T >> \eta$, we obtain the appropriate dispersion relation with the solution

$$\omega_{1,2} = -\frac{2k}{r}\eta_T \pm R\cdot\cos\mu + i\left(\eta_T k^2 \pm R\cdot\sin\mu\right), \tag{15}$$

where

$$\begin{aligned} R &= \left(\frac{\alpha\Omega_0 r_0^2\cos\theta - 4\eta_T^2 k^2 r}{r^3\cdot\cos(2\mu)}\right)^{1/2}, \\ \mathrm{tg}(2\mu) &= \frac{k\alpha\Omega_0 r_0^2 r\cos\theta}{4\eta_T^2 rk^2 + \alpha\Omega_0 r_0^2\cos\theta}. \end{aligned} \tag{16}$$

Then, for $\alpha > 0$ and $\nabla\Omega < 0$ in the bounded neighbourhood (r,θ) we obtain the real part of the solution of equation (13)

$$A_\varphi = e^{\gamma t}\cos(\omega^* t - k\theta),$$
$$B_\varphi = e^{\gamma t}\cos(\omega^* t - k\theta + \pi/4), \quad (17)$$

where $\omega^* = \mathrm{Im}(\omega)$ is the frequency and $\gamma = \mathrm{Re}(\omega)$ is the increment of dynamo waves. The waves propagate along the surface $\Omega(r) = const$ in the direction of increasing θ, therewith at $\nabla\Omega < 0$ the phase of the azimuthal field is $\pi/4$ ahead of A_φ. In the other important limiting case $\Omega = \Omega(\theta)$ they propagate with the frequency and the increment, which are identical to those in the above-mentioned case along radius. The dynamo waves occur, where the product $\alpha \cdot \nabla\Omega$, whose sign determined the propagation direction for thease waves, is different from zero. In the case, when Ω is a function of both r and θ and when $\nabla\Omega < 0$, the dynamo waves propagate in the direction of increasing r and θ. To gain the field it is necessary that $\mathrm{Re}(\omega) > 0$, then the condition of excitation of increasing mode takes the form

$$\alpha \frac{r_0^2}{r}\Omega_0 \cos\theta > 4\eta_T^2 k^2. \quad (18)$$

The key questions of the dynamo theory are both the value and the form of the tensor of turbulent diffusion in convective region [5,7,20]. This tensor is highly anisotropic, and its components may differ in value and in sign. The components of the tensor of turbulent diffusion are usually fitted to be in accordance with the observed parameters of dynamo model. To make rough estimate of η_T, one can use an approximation of mixing length, when $\eta_T = (1/3)\cdot \ell^* \upsilon$, (here ℓ^* is the mixing length, which is equal in orderto the density scale $\rho/\nabla\rho$, υ is the root-mean-square velocity [8], but parameters ℓ^* and υ are not exactly defined. Sometimes the total convective region or the size of large cells are chosen as ℓ^*.

In our case there are not some tentative parameters (for example, as for solar dynamo model),and furthermore η_T, α and Ω are time dependent. Then we can make only rough estimate of the value η_T, at which generation of dynamo waves is possible (at the condition, that both η_T and the other terms of (20) are constant and homogeneous).

For the generation region with the outer radius $r_0 = 0.1$ cm and the inner $r = 0.05$ cm the dynamo waves with the length $\lambda \approx 0.1$ cm will build up, beginning with $\Omega_0 = 2\pi 10^6$ s^{-1}, $\alpha = 4\cdot 10^5$ sm/s, $\eta_T = 5.5\cdot 10^3$ sm^2/s, $\cos\theta = 0.9$. Under thease conditions, $\mathrm{Re}(\omega) > 0$ is greater than zero and the $\alpha\omega$ dynamo effect can effectively generate dynamo waves with the period $T \approx 10^{-7}$ s.

The dynamo effect leads to increasing of the magnetic flux and to the field gain as a whole. During the process of the $\alpha\omega$ dynamo effect operating the wave with $\gamma > 0$ is quickly increasing and the wave with $\gamma < 0$ being quickly damped, therewith, over one period of the oscillatios the first harmonic will have increased by a factor of $\exp(2\pi) = 535$, and the second harmonic will have decreased by this factor. By this is meant that the feeble seeding field is necessary to generate magnetic field by $\alpha\omega$ dynamo effect. The field increases until the dynamic balance becomes between the Coriolis forces and the Lorentz forces.

Conclusion

This report considers the process of generation of azimuthal magnetic field by differential rotation, arising under the collapse of shell in high pulsed magnetic field, in a kinematic approximation.

The process of generation of high magnetic fields by $\alpha\omega$ -dynamo effect is discussed. The necessary conditions for increasing of dynamo waves in the compressed shell are presented.

It has been shown, that the $\alpha\omega$ -dynamo effect can effectively generate high magnetic fields from feeble seeding fields to allow increasing of the shell thickness the rotation velocity and the initial radius of shell. Increasing of thease parameters will lead to more effective energy extraction from the source of high pulsed magnetic field and to transformation of this energy into more power dynamo waves.

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