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VIBRATIONS OF ABRIKOSOV VORTICES IN SUPERCONDUCTORS

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Abstract.*In this work, the phenomenon of oscillation of the vortex matter as a result of thermomagnetic instability in a superconductor is theoretically investigated. The spatial and temporal distributions of small thermal and electromagnetic perturbations in a plane semi-infinite superconducting sample are studied. Based on the system of equations for temperature, magnetic induction, and vortex motion, a dispersion relation was obtained that determines the growth (or decay) increment of small perturbations. It was shown that, under certain conditions, depending on the values of the parameters of the system, jumps - oscillations of the magnetic flux is observed.*

Key words: *superconductors, small perturbations, flow jumps, vortex oscillations, critical state.*

INTRODUCTION

Recently, great attention has been paid to the phenomenon of magnetic flux oscillations arising as a result of thermomagnetic instability in superconductors [1]. In the process of studying the dynamics of thermomagnetic instabilities, vibrational modes in the mixed state of a superconducting Nb-Ti sample were detected as a result of a catastrophic avalanche [2]. To explain the observed oscillation processes, a theoretical model was proposed that takes into account the inertial properties of vortex matter. These oscillation phenomena were interpreted as the result of the existence of a finite value of the effective mass of the vortex, i.e. oscillations can be considered as a manifestation of the inertial properties of vortex matter [3].

In this work, the phenomenon of magnetic flux oscillations - the oscillation of vortex matter as a result of thermomagnetic instability of the critical state in a superconductor is theoretically investigated. The spatial and temporal distributions of small thermal and electromagnetic perturbations in a plane semi-infinite superconducting sample are studied. Based on the system of equations for temperature, magnetic induction, and vortex motion, a dispersion relation was obtained that determines the growth (or decay) increment of small perturbations. It was shown that, under certain conditions, depending on the values of the parameters of the system, jumps - oscillations of the magnetic flux can be observed.

BASIC EQUATIONS

The system of equations of macroscopic electrodynamics is used to simulate the evolution of temperature and electromagnetic field perturbations. The distribution of magnetic induction $\vec{B}(r, t)$ and transport current $\vec{j}(r, t)$ in a superconductor is given by the equation

$$\text{rot}\,\vec{B}=\frac{4\pi}{c}\vec{j}\ . \quad (1)$$

The relationship between the magnetic induction $\vec{B}(r, t)$ and electric field $\vec{E}(r, t)$ is described by Maxwell's equations

$$\text{rot}\,\vec{E}=-\frac{1}{c}\frac{d\vec{B}}{dt}\ , \quad (2)$$

$$\vec{E}=\frac{v}{c}\vec{B}\ . \quad (3)$$

The equation of motion of the vortices can be written in the form

$$m\frac{dV}{dt}+\eta V+F_L+F_P=0\,, \quad (4)$$

where m is the mass of the vortex of unit length, $F_L=\frac{1}{c}\vec{j}\,\vec{\Phi}_0$ is the Lorentz force, $F_L=\frac{1}{c}\vec{j}_c\,\vec{\Phi}_0$ is the pinning force, $\eta=\frac{\vec{\Phi}_0 H_{C2}}{c^2\rho_n}$ is the viscosity coefficient, ρ_n is the resistance in the normal state, $\vec{\Phi}_0=\frac{\pi hc}{2e}$ is the magnetic flux quantum, is the upper critical field [4]. In combining the relation (4) with Maxwell's equations (1, 2), we obtain a nonlinear diffusion equation for the magnetic flux induction $\vec{B}(r, t)$ in the following form

$$\frac{d\vec{B}}{dt}=\nabla\left(\vec{v}\cdot\vec{B}\right) \quad (5)$$

$$m\frac{dv}{dt}+\eta v=-\frac{1}{c}\Phi_0(j-j_c). \quad (6)$$

The temperature distribution in superconductor is governed by the heat conduction diffusion equation

$$\nu\frac{dT}{dt}=\Delta\left[\kappa(T)\Delta T\right]+\vec{j}\vec{E}, \quad (7)$$

where $\nu=\nu(T)$ and $\kappa=\kappa(T)$ are the heat capacity and thermal conductivity coefficients of the sample, respectively. We use the Bean model for the current density $\vec{j}(T,E,B)$ and assume that it does not depend on the magnetic field induction, $j=j_C(B_e,T)$, i.e., $j_C=j_0-a(T-T_0)$ [5], where B_e is the value of the external magnetic induction; $a=j_0/(T_C-T_0)$; j_0 is the equilibrium current density, T_0 and T_C are the initial and critical temperature of the sample, respectively [6]. We assume that the external magnetic field $\vec{B}=(0,\ 0,\ B_e)$ is directed along the z axis and the magnetic field sweep rate $\dot{B}_e=\text{const}$ is constant.

THE RESULTS AND DISCUSSIONS

Let us present a solution of equations (5)-(7) in the form

$$B=B_e+b(x,t),\quad v=v_0+v(x,t),\quad T=T_0+\Theta(x,t), \qquad (8)$$

where $T_0(x)$, $B_e(x)$ and $v_0(x)$ are the solutions to the unperturbed equations, which can be obtained within a quasi-stationary approximation. Substituting the above solution (8) into equations (5)-(7) we obtain the following system of differential equations

$$\frac{d\Theta}{dt}=2\upsilon-\beta\Theta, \qquad (9)$$

$$\mu\frac{d\upsilon}{dt}+\upsilon=-\frac{db}{dx}+\beta\Theta, \qquad (10)$$

$$\frac{db}{dt}=\left(\frac{db}{dx}+b\right)+\left(\frac{d\upsilon}{dx}+\upsilon\right). \qquad (11)$$

where dimensionless parameters $\mu=\frac{c\vec{\Phi}_0}{4\pi\eta^2}\frac{B_e}{2L^2}$ and variables $b=\frac{B}{B_e}=\frac{c}{4\pi}\frac{B}{j_C L}$, $\Theta=\frac{4\pi}{c}\frac{2\nu}{B_e^2}$, $v=V\frac{t_0}{L}$, $z=\frac{x}{L}$, $\tau=\frac{t}{t_0}=\frac{c\vec{\Phi}_0}{4\pi\eta}\frac{B_e}{2\mu_0 j_C L^2}$ were introduced. Here $L=\frac{c}{4\pi}\frac{B_e}{j_C}$ is the depth of penetration of the magnetic field into the superconductor [7].

We assume that the small thermal and magnetic perturbations has $\Theta(x,t),\ b(x,t),\ v(x,t)\cdot\exp(\gamma t)$, (where γ is the eigenvalue of the problem to be determined), we obtain from the system Eqs. (9)-(11) the following dispersion relations to determine the eigenvalue problem

$$\frac{d^2b}{dx^2}-\left[(\gamma+\beta)\mu-2\beta\right]\frac{db}{dx}+\left[(\mu+1)\gamma^2+(\mu-1)\beta-(\mu-1)\beta\right]b=0 \quad (12)$$

The instability of the magnetic front, as a rule [7-9], is determined by the positive values of the increment $\mathrm{Re}\,\gamma\geq 0$. Then we can assume that the instability arises under the condition $\mathrm{Re}\,\gamma=0$. Analysis of the dispersion relation shows that the growth increment is positive $\mathrm{Re}\,\gamma\geq 0$ if the condition $\mu\geq\mu_C=2$ is met. In this case $\mu\geq\mu_C$, the small perturbations increase with time and the magnetic flux front is unstable. In the case when the increment is negative $\mu\geq\mu_C$ and any small perturbation will decay. At a critical value, the increment is zero $\gamma=0$ [8].

In the particular case when $\mu = 1$, the increment γ is determined by the stability parameter β. Then, the stability criterion can be represented as $\beta>1$. In another particular case, when the thermal effects are insignificant ($\beta=1$), the following dispersion relation can be obtained

$$\frac{d^2b}{dx^2}-\mu\frac{db}{dx}+\left[(\gamma-1)(\mu+1)\right]b=0 \quad (13)$$

Representing the solution of the dispersion equation (13) in the form

$$b \sim e^{-ikx}$$

we can obtain the dependence of the increment γ on the wave vector k. An analysis shows [7] that when $k<kc=\mu$, the increment is positive and a small perturbation increases with time. For the values of the wave vector $k>k_c$, the quantity γ is negative and the small perturbation decays exponentially. It can be shown [9], that for $k = k_c$ the increment is $\gamma = 0$. If the wave vector tends to zero $k \to 0$ or infinity $k \to \infty$, the quantity $\gamma = 1$ and a small perturbation increases. In this case, the quantity γ is determined by the relation

$$\gamma=\frac{2\mu}{\mu+1}.$$

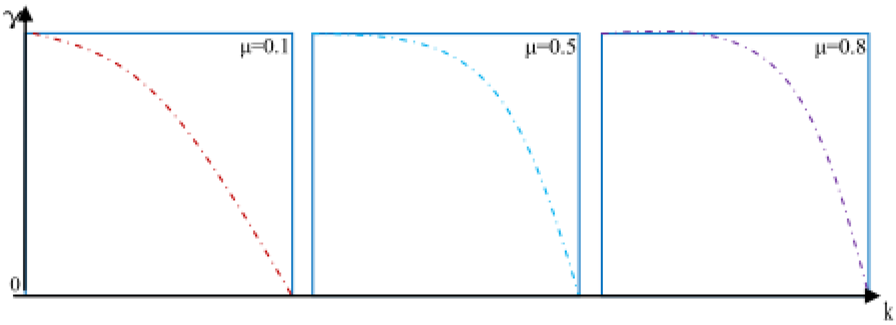

Fig 1. The dependence of the growth rate of γ on the wave vector k for μ=0.1, 0.5, 0.8.

For $\mu = 0$, the value of the increment is $\gamma = 0$. For $\mu = 1$, the value of $\gamma = 1$. The dependence of the growth rate of γ on the wave vector is shown in Fig. 1. for various values of the parameter μ. As μ increases, the parameter γ increases. At certain values of the parameter μ, magnetic flux jumps are observed, which take into account the inertial properties of the vortices.

CONCLUSION

In this work, the phenomenon of oscillation of the vortex matter as a result of thermomagnetic instability in a superconductor is theoretically investigated. The spatial and temporal distributions of small thermal and electromagnetic perturbations in a plane semi-infinite superconducting sample are studied. Based on the system of equations for temperature, magnetic induction, and vortex motion, a dispersion relation was obtained that determines the growth (or decay) increment of small perturbations. It was shown that, under certain conditions, depending on the values of the parameters of the system, jumps - oscillations of the magnetic flux is observed.

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