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Collective mode dynamics of the vortex lattice in a high T_c superconductor

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Abstract. Dispersion relations have been obtained numerically for the collective modes of the flux line lattice of a high T_c superconductor in the London limit and the effect of pinning forces is included. It is found that the waves propagating along the magnetic field the dispersion consists of two branches and that the low frequency branch may interact with other low-frequency excitations in the lattice.

Keywords. Collective modes; flux line lattice.

1. Introduction

It is obvious that for many applications of the high T_c superconductors the dissipation of energy must be kept to a minimum. Thermally-activated processes which contribute to energy dissipation are closely linked with the motion of flux lines. In this context it is interesting to study the collective mode dynamics of the flux line lattice (FLL) and the role, if any, of the collective modes in the depinning of flux lines.

Collective modes of the FLL in a conventional type-II superconductor were first studied by De Gennes and Matricon (1964), who obtained the dispersion relation $\omega = \Omega_0 k^2 \lambda^2$ for the circularly-polarized modes with the wave vector $k \parallel B$, and $\omega = \Omega_0 k^2 \lambda d$ for the elliptically-polarized modes with $k \perp B$. Here $\Omega_0 = eB/m^*$ is the cyclotron frequency, B the applied magnetic field, λ the London penetration depth and d the inner-vortex separation. De Gennes and Matricon had neglected the current oscillations. Abrikosov *et al* (1965) showed that when current oscillations were taken into account the undamped elliptically polarized modes with $k \perp B$ were not possible. A quantized version of the theory of the collective mode was developed by Fetter *et al* (1966) and by Fetter (1967). However, the role of the pinning forces in the collective mode dynamics of the FLL has not been studied in detail even for conventional type-II superconductors.

In the case of the high T_c superconductors, the structure of the FLL has been studied both experimentally (Gammel *et al* 1988) and theoretically (Campbell *et al* 1988), and the elastic properties by Kogan and Campbell (1989). However, the dynamics of the collective modes in the high T_c superconductors has not yet been addressed.

It is the purpose of this paper to study the collective modes in the FLL of a high T_c superconductor based on the macroscopic approach of Abrikosov *et al* (1965) and in addition, to include the effect of the pinning forces. An outline of the theory is given in the next section. The numerical results for the dispersion of collective modes with the wave vector parallel to the magnetic field are discussed in the following section.

2. Theory of the collective modes in a FLL

Since for the high T_c superconductors the coherence length is short and the Ginzburg-Landau parameter κ is very large, the mixed state can be described in the London limit. Accordingly, the London equation in the presence of vortices located at sites ρ_i in a two-dimensional space ρ can be written as

$$\mu_0\lambda^2\nabla \times j_s + B = \phi_0\sum_i Q\delta(\rho - \rho_i)/|Q|. \tag{1}$$

Following Abrikosov *et al* (1965) and including the forces due to friction and pinning one can write for the time dependence of the supercurrent the following equation:

$$\frac{\partial j_s}{\partial t} - \frac{(j_s \times Q)}{Ne^*} = \frac{Ne^{*2}}{m^*}E + F_{\text{friction}} + F_{\text{pinning}}. \tag{2}$$

where the fluxoid $Q = \nabla \times j_s + (B/\mu_0\lambda^2)$ and the supercurrent $j_s = Ne^*V_s$. N, e^*, m^* and V_s refer to the effective number, charge, mass and velocity of the superconducting electron respectively. In addition, δ is the Dirac delta function, ϕ_0, the flux quantum, and E, the electric field.

For modes with the wave vector parallel to the magnetic field, the term representing the friction force can be written as $F_{\text{friction}} = \alpha|Q|\dot{s}/m^*e^*$ and $F_{\text{pinning}} = -Ks/m^*e^*$ where s is the displacement of the FLL, and α and K are constants. Assuming that all quantities representing the displacement, the current and the fields, vary as $\exp[i(k \bullet r - \omega t)]$ the dispersion relations can be written in the polarization representation (i.e. $s_{\pm} = s_x \pm is_y$) as:

$$(1 + \beta^{-1})\omega_{\pm} = \Omega_0(\pm 1 - i\alpha) + \omega_0^2. \tag{3}$$

Here $\beta = k^2\lambda^2$ and $\omega_0^2 = K/Nm^*$.

3. Results and discussion

The numerical results are displayed as three dimensional graphs in figures 1a and 1b for the "+" and the "−" branches respectively. For zero-pinning, the two solutions are degenerate in agreement with Abrikosov *et al* (1965). For extremely strong pinning, the two solutions again coalesce into one, the frequency being determined mainly by the pinning potential. In the intermediate region, the "−" branch spans a range of low frequencies and hence may interact with other low frequency excitations of the crystal under suitable conditions. It would also be interesting to see if the mean square displacement of this mode contributes to the suggested melting of the FLL.

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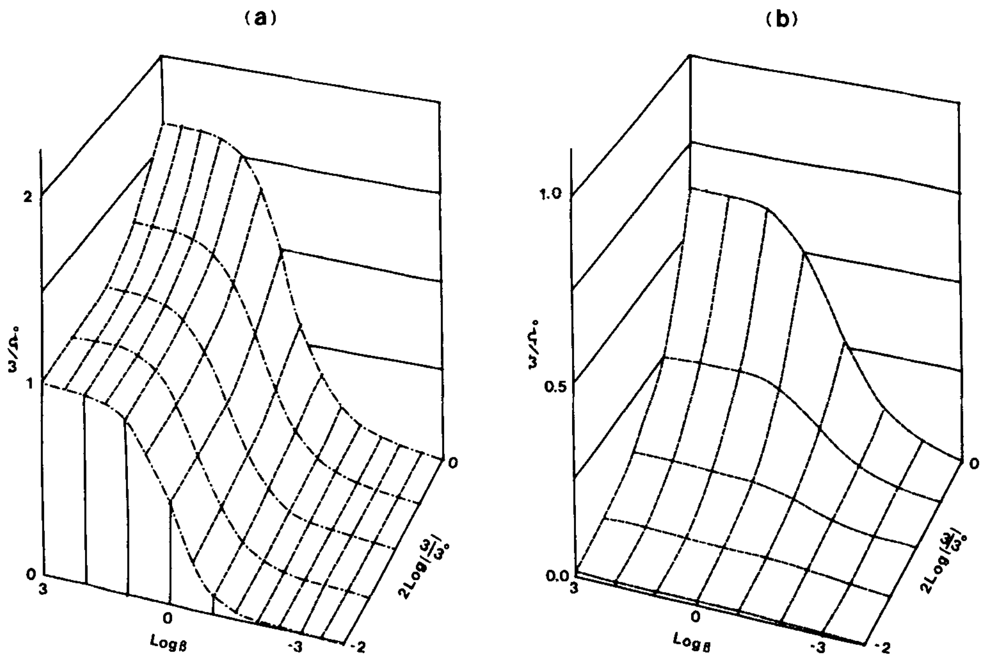

Figure 1. Dispersion of the collective modes of the FLL in the polarization representation. **a.** "+" branch. **b.** "−" branch.

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