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FREQUENCY LIMITATIONS FOR THE APPLICABILITY OF THE CRITICAL STATE MODEL

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Abstract—The frequency dependence of the surface impedance Z of superconductors has been studied in the frequency range 10 Hz–100 kHz. An essential deviation of $Z(\omega)$ from the linear law predicted by the usual critical state model is found. The character of this deviation depends qualitatively on the amplitude of the magnetic field. Results obtained are interpreted in the framework of the modified model where we take into account the contribution of a dissipative term to the screening current. The value of this term is connected with the V–I characteristics of the superconductor, so it is possible to obtain some information about these characteristics by the contactless method.

The critical state model is commonly used to explain the magnetic properties of hard superconductors. The distribution of the magnetic induction B inside a superconductor is described by the equation

$$\text{curl}\,\mathbf{B} = (4\pi/c)J_c(B) \cdot \mathbf{E}/E, \tag{1}$$

where J_c is the critical current density and E is the electric field. This model was proposed by Bean to describe static magnetization curves of homogeneous superconductors. The background of its application to granular systems [1] concerns static conditions too. However, it is well known that many observations of electromagnetic properties of hard superconductors are interpreted in the framework of the model (1). For example, the magnetic field dependence of the critical current density $J_c(B)$ calculated in the framework of the critical state model using results of measurements of the surface impedance $\mathscr{Z} = \mathscr{R} - i\mathscr{X}$ is in a good agreement with direct measurements of the critical current for ceramic as well for melt-textured samples [2]. In spite of the popularity of the critical state model a question was raised as to whether this model can be used to describe the electromagnetic properties of superconductors. It is known that electric fields exist in the volume of a sample owing to the magnetic flux varying with time. In other words, a superconductor in the dynamic regime is always in the resistive state. This means that the superconducting critical current is accompanied by an existing dissipative component of current in the bulk of the sample. Under such conditions the model (1) must be modified to take into account this component [3, 4]. A corresponding equation describing the distribution of the magnetic injunction may be written as follows

$$\text{curl}\,\mathbf{B} = [J_c(B) + \sigma(E) \cdot E] \cdot \mathbf{E}/E, \tag{2}$$

where σ is the dissipative conductivity of the medium which rapidly increases with the electric field E.

This item is discounted in the usual critical state model (1). So, the special analysis of the response of a superconductor to the external electromagnetic signal in the framework of material equation (2) is needed. Recently [4], we have carried out the study of the dependence of the surface impedance $\mathscr{Z} = (4\omega d/c^2)z = (4\omega d/c^2)[r(\omega) + ix(\omega)]$ of granular high-T_c superconductors on frequency. We found that this dependence contains significant information about the V–I plot of a sample in the resistive state. Here, we present new experimental data for YBCO melt-textured samples.

The real and imaginary parts of the surface impedance z of samples have been measured in the frequency range 10 Hz–100 kHz using a standard inductive method. The pick-up coil was wound closely on the sample. Pick-up signals proportional to r and x were extracted by a phase sensitive

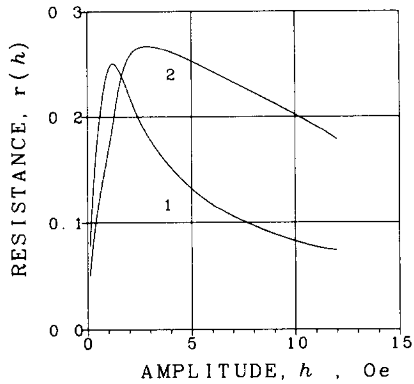

Fig. 1. The dependence of r on the a.c. magnetic field amplitude h for the ceramic sample at 77 K. Curves 1 and 3 correspond to the frequencies $\omega/2\pi = 30$ Hz and 100 kHz respectively.

amplifier PAR-124A. The measurements were carried out at liquid nitrogen temperature.

We have studied granular Y–Ba–Cu–O system samples prepared by a solid state reaction and melt-textured samples of the same system. They were plates with thickness in the range 0.1–5 mm.

Dependencies of the surface resistance r on the external a.c. magnetic field amplitude h for the superconducting ceramic plate with thickness $d = 0.8$ mm are presented in Fig. 1. The curve 1 was obtained at $\omega/2 = 1$ kHz and the curve 2 at the frequency 100 kHz. Analogous results were obtained for the melt-textured sample with thickness 0.1 mm having a critical current density about 10^4 A/cm^2 at $H \sim 10$ kOe (Fig. 2). Curve 1 was obtained at $\omega/2\pi = 175$ Hz and curve 2 at a frequency of 44 kHz at a d.c. magnetic field of 10 kOe oriented parallel to ab plane. The difference between the curves in these figures shows a noticeable frequency dependence of the surface resistance r which cannot be explained in the simple critical state model (1).

We have developed a modified critical state model. In accordance with a number of papers, the dissipative component of the current density in (2) is assumed to be a power function of the electric field E with the exponent γ. According to our calculations the behavior of $r(\omega)$ has a natural explanation in the framework of the modified model (2). The difference between curves 1 and 2 in Figs 1 and 2 is connected with the contribution of the dissipative term in (2) to the screening current density. Our experimental data are in qualitative agreement with calculated results.

In principle, it is possible to obtain the parameters of a V–I plot of a superconductor by measuring the frequency dependence of its surface impedance. According to [4], the frequency

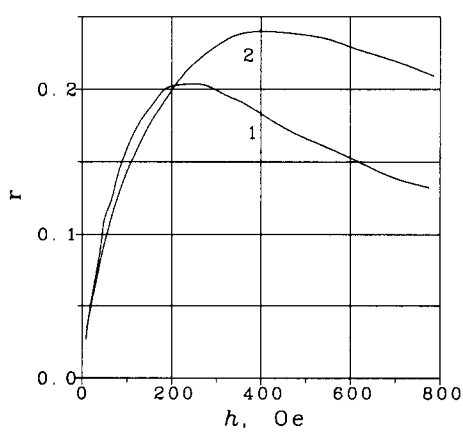

Fig. 2. The dependence of r on the a.c. magnetic field amplitude h for the melt-textured sample, at the d.c. magnetic field $H = 10$ kOe and $T = 77$ K. Curves 1 and 2 correspond to the frequencies $\omega/2\pi 175$ Hz and 44 kHz respectively.

correction to the impedance is proportional to ω^{γ}. This means that at moderate frequencies the value $\rho = | r(\omega)/r(0) - 1 |$ must change with frequency by a power law. This deduction is confirmed by the results of calculations. Results for ceramic samples obtained from the experimental dependence $\rho(\omega)$ are in accordance with the direct measurements of V–I plots. Analogous data handling of the measured dependence for melt-textured samples gives a value of γ of order of unity which is much lower than the value $\gamma = 22$ obtained from the usual measurement. However, the magnetic field dependence of $J_c(B)$ measured by the contactless method [2] is in accordance with the direct measurements. We consider that these results may be connected with a nonuniform current density distribution in melt-textured samples.

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