Comparison of two methods for analysis of vortex motion: Flux creep versus Nonlinear current-voltage curve approach

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We compare two commonly accepted approaches for simulations of thermally-activated vortex motion in superconductors. The flux creep approach is based on the expression \( E = vB \) for the electric field via the local flux density and the velocity of the thermally-activated flux motion. The other approach employs a phenomenological nonlinear current-voltage curve, \( E(j) \). Our numerical simulations show that the two approaches give similar but clearly different results, the difference being most pronounced in the areas of low \( B \). We find that the flux creep approach provides a better description of the experimental current distributions in a YBaCuO current-carrying strip determined by magneto-optical imaging.

Flux creep analysis has for many years been widely used to reproduce evolution of flux and current density distributions, current-voltage curves, magnetisation and susceptibility for superconductors of various shapes [1,2]. Such an analysis is always based on the Maxwell equation, \( \frac{\partial B}{\partial t} = -\frac{\partial E}{\partial x} \), where \( E \) is the electric field, \( B \) is the flux density. However, there exist two commonly accepted ways to define the electric field. The flux creep approach [1] uses the expression \( E = vB \), where \( v \) is the velocity of thermally-activated vortex motion. Then

\[
E = v_c B e^{-\frac{E(j)}{kT}},
\]

where \( U \) is the pinning energy depending on the local value of the current density, \( j \). Another approach to the problem consists in using a phenomenological \( E(j) \) relation [2]. It is usually chosen in the power law form:

\[
E = E_c \left( \frac{j}{j_c} \right)^n, \quad n \gg 1.
\]

The two approaches becomes similar if one chooses the logarithmic current dependence of the pinning energy, \( U(j) = U_c \ln(j/j_c) \), and if \( U_c/kT \equiv n \). However, an important difference remains. In the flux creep model one always has \( E \propto B \), i.e. the electric field induced by the vortex motion is proportional to the number of moving vortices. In the \( E(j) \) approach with \( B \)-independent \( j_c \) and \( E_c \), this proportionality is absent.

In order to carry out simulations one also needs a relation between the flux and current density distributions. Let us consider here a thin strip with thickness \( d \) and width \( 2w \). Then, in zero applied field the Biot-Savart law gives \( B(x) = d \mu_0/(2\pi) \int_{-w}^{w} j(u)/(u-\gamma) du \).

Figure 1(a,b) presents evolution of current density distribution in a strip with transport current obtained by numerical simulations within the two approaches. It is assumed that the transport current \( I_t \) through initially zero-field-cooled strip linearly increases in time. The parameters were \( U_c/kT = 5, \frac{dI_t}{dt} = 10^{-3} I_v/2w \), and \( E_c = 0.2 \varepsilon_0 \mu_0 j_c d/\pi \).

The distributions are qualitatively similar to each other and to that expected in the Bean model [4]. Namely, the current density is found maximal in the flux penetrated regions near the strip edges. As current increases, the flux penetrates deeper. Finally, the central not penetrated region shrinks, and the current becomes distributed more or less uniformly.

Meanwhile, one can see two clear differences between \( j \)-distributions obtained within different approaches: (i) in the penetrated regions \( j(x) \) increases in (a) but decreases in (b) when \( x \) changes from the edge towards the center; (ii) there is a peak in \( j(x) \) at high currents in (a) at the center where \( B = 0 \). These differences can be briefly ex-
plained as follows. In the $E(j)$ approach, $j(x)$ follows $E(x)$ and, thus, monotonously decreases from edges towards center. In the flux creep approach, however, one has $v(j) = E/B$, which means that $j$ tends to be larger where $|B|$ is smaller. In particular, $j(x)$ is relatively small at the edges where $|B|$ is maximal, but divergent in the annihilation zone where $B = 0$.

Our additional simulations show that as $n \equiv U_c/kT$ becomes larger, the two approaches give closer results and for $n \to \infty$ both coincide with the Bean model prediction [4]. One should also note that although the two approaches predict quite different spatial distributions, the integral characteristics such as current-voltage curves remain almost identical.

Figure 1(a,b) shows the current distribution in YBaCuO strip obtained from the flux density distribution measured by magneto-optical imaging at 20 K [3]. The transport current up to 4.5 A was applied to the strip with pulses of 100 ms duration. One can see that the experimental data better fit the results of simulations by the flux creep model, Fig. 1(a). Nevertheless, the sharp peak of $j$ in the strip center predicted by simulations at large currents is not observed. More experimental studies are needed to finally discriminate between two approaches.

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REFERENCES


