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ABSTRACT

1d and 2d simulations of the single vortex dynamics in the presence of random pinning potential and periodical one have been carried out. It is shown that the randomness of the pinning sites distribution has not considerable effect on the transport properties such as I-V characteristics of the high T_c superconductors, which has been widely discussed in the approximation of a periodical pinning potential using analytical method. The randomness effect is probably only reducing much the vortex diffusing mobility below the depinning current value, which is more obvious at lower temperature.

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There have been many efforts dedicated to the vortex dynamics in the high T_c superconductors in the last a few years due to its importance in trying to find materials with higher critical current density. Vortex dynamics in the superconductors tells us information about motion of the vortices influenced by various interactions,including the important pinning effects.Usually,the pinning is caused by inhomogeneities present in the superconductors,e.g.,impurities,defects,etc. However,in addition to the traditional pinning centers,the oxide superconductors with its characteristic layered structure have their own intrinsic pinning when the vortices move in a direction perpendicular to the layers[1]. In the conventional superconductors,vortex dynamics was usually studied in the two typical cases,which are the flux creep and flux flow. Correspondingly, there are successful classical Anderson-Kim's thermally activated flux creep model[2] and Bardeen-Stephen model[3] to describe them respectively. In high T_c superconductors,the thermal energy k_BT is rather higher and usually comparable with the pinning energy,so the simple flux creep description is only applicable in the low temperature region. When the thermal energy k_BT becomes comparable with the pinning energy both of the flux creep and flux flow will dominate the vortex dynamics and a correct description of the vortex motion in this regime is difficult. M.Inui et al used a single flux depinning model[4] to interpreter the resistive broadening in the high T_c superconductors in which they neglected the random distribution of the impurities and for simplicity took approximately a sinusoidal form to represent the position distribution of pinning sites. More recently,we, by taking the thermal fluctuating force into account explicitly,have successfully explained the widely observed power-law I-V characteristics in whole temperature region.[5] In our model a sinusoidal form of pinning potential was also assumed,which is more suitable to the intrinsic pinning with the magnetic field parallel to the planes.

More generally,however,the problem is complicated by the fact that due to inhomogeneities in the materials, the flux line always experiences a random potential background and the vortex mobility is thus determined by the combined effect of the random pinning potential and thermal fluctuations. Therefore,it is interesting and important to investigate effect on the flux motion due to the random distribution of pinning sites in materials. In this paper,we simulate the vortex diffusion in one and two dimensions in the presence of randomly distributed pinning sites and thermal noise. We find that the main I-V features in the mixed state of superconductor have not changed much due to the presence of randomness in the pinning sites distribution,which justifies many approximations used in the previous papers.

The dynamic equation of a single vortex is expressed as the following:

$$\eta\frac{d\vec{r}}{dt} = (\vec{F}_d + \vec{F}_p) + \dot{L}(t) \quad (1)$$

where η is the viscosity coefficient,$\vec{F}_d = (1/c)j\phi_0$ is the driving force with j being current density,and ϕ_0 as the superconducting flux quantum. $\vec{F}_p$ is the pinning force and $\dot{L}(t)$ is the fluctuating force which may be due to the random Lorentz force caused by thermal motion of the normal electrons in the vortex core. Here we consider $\vec{F}_p$ is caused by the interaction of the vortex with a number of pinning centers randomly positioned at $\vec{R}_i$ and as usual we choose a Gaussian form of the individual pinning wells

$$U_p = A_p\sum_i e^{\frac{-(x-x_i)^2}{\xi^2}} \quad (2)$$

where the amplitude A_p is the condensation energy stored in the vortex core,i.e.,$A_p = \frac{H_c^2}{8\pi}\xi_{ab}^2\xi_c^2$.The stochastic force $\dot{L}(t)$ is assumed to be a Gaussian white noise. In a Gauss-Markov process,the time t_i between two random-noise pulses are distributed as:$p(t_i) = 1/\tau\, exp(-t_i/\tau)$,where τ is the mean time between two pulses. In a system with a discrete grid of time steps Δ,the probability p that after Δ one random pulse acts on the vortex is given by $p = \int_0^\Delta p(t_i)\, dt = 1 - exp(-\Delta/\tau) \approx \Delta/\tau = p$. We find $\dot{L}(t)/\eta$ can be written as

$$(\frac{2\Delta k_B T}{\eta p})^{1/2}\sum_j \delta(t-t_j)\gamma(t_j)\Theta(p-q_j)$$

where j labels the jth time step.$\gamma(t_j)$ is a random number chosen from Gaussian distribution of mean 0 and width 1, and q_j is just a random number uniformly distributed between 0 and 1 . The $\Theta(x)$ is defined by

$$\Theta(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x < 0 \end{cases}$$

Combining the results described above,the one dimensional discretized equation can be written as

$$x^{n+1} = x^n + \frac{F_d^n + F_p^n}{\eta}\Delta + (\frac{2\Delta k_B T}{\eta p})^{1/2}\gamma_x\Theta(p-q_j) \quad (3)$$

We used the algorithm described above to simulate the vortex diffusion in a model superconductor for a system having 200 pinning sites and a length of 200 times coherence length ξ with periodical boundary condition . The parameters in our calculation is chosen as follows:

$\xi_{ab}(0) = 27$,$\xi_c(0) = 12$,$\rho_n(T_c) = 2\times 10^{-4}\Omega cm^{-1}$, $H_{c2}(0) = 127T$, $H_c(0) = 2.72$T

where η is determined from Bardeen-Stephen formula and it is easy to get

$$\eta = \frac{h\xi_c}{2c\rho_n}\frac{H_{c2}(0)}{H}\frac{(1-t)^{1/2}}{t} \quad ,$$

here we postulate that $\xi_{ab,c}(t) = \xi_{ab,c}(0)(1-t^2)^{-1/2}$, $H_c(t) = H_c(0)(1-t^2)$, $H_{c2}(t) = H_{c2}(0)(1-t)$, here $t = T/T_c$ is a reduced temperature. Now, we should choose also Δ and τ. To do so, we know that the first and second momentum can be obtained from Eq.(1),

$$M_1 \equiv \frac{1}{\tau} < \delta x > = \frac{1}{\eta} F, \qquad M_2 \equiv \frac{1}{\tau} < (\delta x)^2 > = \frac{2k_B T}{\eta} \qquad (4)$$

then, following the algorithm developed by A.Brass et al.[6] selection of the Δ and τ can be done by calculating the same moments and letting them to agree with those given in Eq.(3). They satisfy the following conditions.

$$\Delta \quad << \quad \frac{2k_B T \eta}{< F >^2} \quad << \quad \tau$$

where $< F >$ means the average net deterministic force on a flux.

We get the I-E characteristics in Fig.(1) for both situations of the random and periodical pinning potentials at temperature $t = 0.76$. The same features are shown in Fig.(2) for $t = 0.92$. Here $E = \frac{B}{C} < \frac{dx}{dt} >$, represents induction electric field. From them, we see that:

1) existing of a critical current j_{cr} below which the flux mobility almost suddenly falls to zero for both cases, no matter the pinning potential is a random or a periodical. Of course, the critical value of current for random pinning is higher than that for periodical situation ,which is more obvious at lower temperature, as seen in Fig.(1). This is because ,as shown in Fig.(3), amplitude of the random pinning potential has many peaks higher than the amplitude of the periodical one, and they prevent the vortex from diffusing. This phenomenon maybe have some relations with the so-called glass state[7] in which all of the

vortices can be pinned. If the interaction between the vortices is included, which is not considered in this short paper, perhaps the true glass state will be able to appear. This interesting problem will be discussed in a forthcoming paper.

2) above the j_{cr}, two curves completely coincide each other. That means the random distribution of the pinning sites in superconductor has no significant effect on the flux motion and so, the approximation, used in many analytical works, neglecting the randomness in the pinning site distribution and simply choosing a sinusoidal pinning potential is a reasonable, especially at higher temperature .

3) the power law I-E charactristics are seen in these figures for different temperatures, which is consistent with the analytical works[8] and the experiments.[9] That probably demonstrates that the dependence of of the pinning potential on current is a logrithmic in a rather wide temperature region.[10] However, we think, more preferably, that it is caused by the dynamical equation incorporating both of flux creep and flux flow naturally, as shown in our analytical work [5], and numerical simulation done in this paper. This is because we never include a dependence of the pinning potential (random or periodical) on the current density j . We think, most probably, this power law behavior has some deeper intrinsic relation with the so-called self-organized criticality [11,12], shown in a Langevin equation followed by the vortex moving in a periodical potential or more generally, in a dynamical equation with a random potential.

In addition to the 1d simulation, we have also made similar calculation for two dimensional case. From Eq.(1), it is easy to get a discretized equation for the 2d situation. The equation is

$$x^{n+1} = x^n + \frac{F_{dx}^n + F_{px}^n}{\eta}\Delta + (\frac{2\Delta k_B T}{\eta p})^{1/2}\gamma_x\Theta(p - q_j)$$

$$y^{n+1} = y^n + \frac{F_{py}^n}{\eta}\Delta + (\frac{2\Delta k_B T}{\eta p})^{1/2}\gamma_y\Theta(p - q_j) \qquad (5)$$

In this paper,we only include the Lorentz force as the driving force $\vec{F}_d$,and consider that the current flows along y direction. therefore,in Eq.(5),y component,$F_{d_y}^n$,of the driving force should be zero. The calculation result is shown in Fig.(4) for two different temperatures,from which no significant differences with the 1d case are found. The I-E behaviour is very similar to that in 1d case. However,in this work,we do not include the Magnus force in our equation of motion. So, the driving force in the y direction is very weak,and is given by only the thermal noise. Therefore,including the Magnus force will make the motion of flux become more like a two dimensional. Whether or not the situation becomes different after the Magnus force is taken into account is not known now,and will be left for future study.

In conclusion,we have simulated the vortex diffusion in the presence of random pinning potentials for 1d and 2d cases and particularly discussed the I-E characteristics . We find that the obtained results are similar to those got before using the periodical potentials. At last,we would like to strengthen that our simulation is just in the context of single vortex dynamics and we just include the combined effects from randomness in pinning sites distribution and thermal fluctuation. But,in some cases,single vortex dynamics will not be enough, the collective effect should be important.What effects on the flux motion the collective behaviors have,we think,is also a very interesting and important work. In that case,will the superconducting glass state really exist? Is there any "truly" superconducting state? All of them are still open for future work.

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Figure Captions

Fig. 1. Calculated electric field vs current-density curves in 1d case for both random and periodical pinning situation at t=0.76. Here, ◂ —-periodical pinning; □ —-random pinning.

Fig. 2. Same as Fig.1,but at t=0.92.

Fig. 3. Random pinning potential U vs x position in one dimension.

Fig. 4. Calculated electric field vs current-density curves in 2d case for random and periodical pinning potentials at t=0.96 (◂ —-periodical; • —-random),and for only random pinning at t=0.76 (□ —-random).

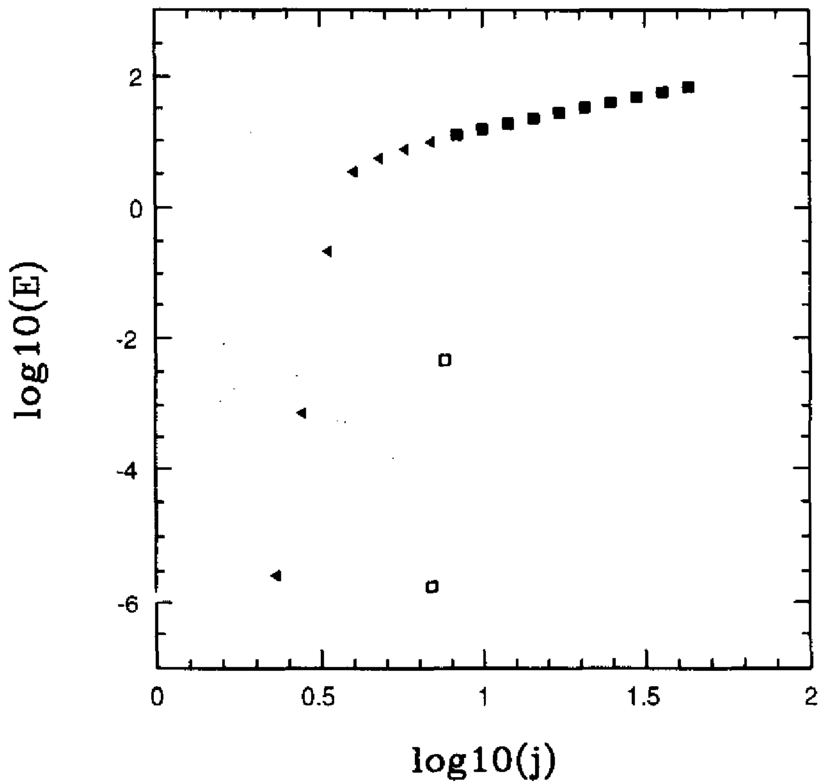

Fig.1

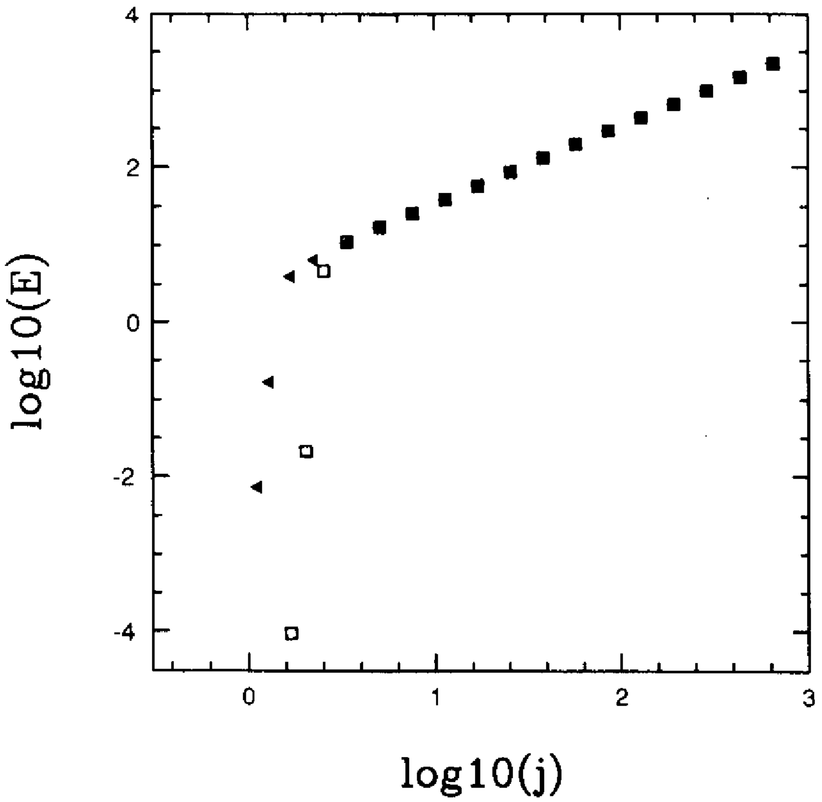

Fig.2

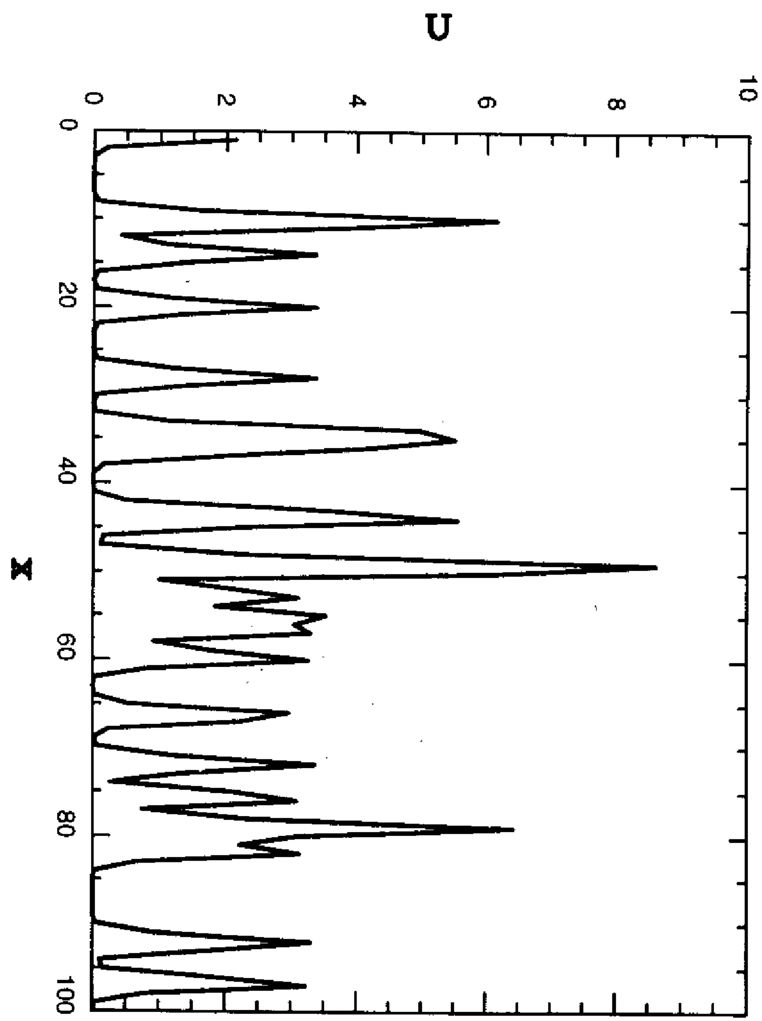

Fig.3

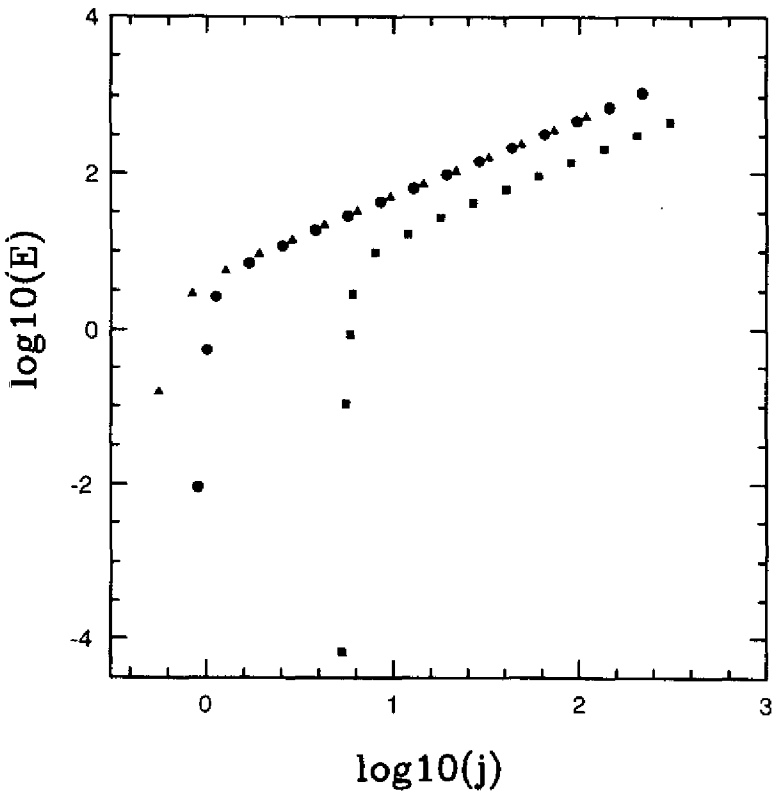

Fig.4