Plastic flow of periodic structures

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Abstract

Dynamics of deformable periodic structures in random media, such as charge density waves or vortex lattices in type II superconductors, is numerically studied based on a 3D random field XY model with uniform torque which express external driving force. We find that as a driving force increases, the moving state changes from static pinned state to plastic flow which consists of spatially nonuniform dc current and finally into coherent elastic flow. At the latter transition, a long range order of phase grows.

Key words: vortex lattice; CDW; dynamics; plastic flow

1. Introduction

Collective transport of macroscopic condensed objects in quenched random media, such as a vortex lattice (VL) [1] and a charge density wave (CDW) [2], has attracted much attention. When external driving force is applied, these systems show highly complex and nonlinear response due to randomly distributed imprities, large internal degrees of freedom and interactions between them.

For these systems, an elastic manifold model has been well investigated, which treats these systems as elastically deformable objects obeying to classical dynamics, e.g. Fukuyama-Lee-Rice model for CDW [3–5]. But there are some experimental facts that the elastic model cannot explain, such as plastic flow, switching and broad band noise [2,6].

Here we numerically investigate a simple model which allows plastic deformation i. e. "phase slip" and has a periodicity of the systems. The model is equivalent to a random field XY model with uniform torque [7,8].

2. Model and Method

We employ dynamical variables which express the phase fluctuations. The spatial gradient of the variable represents distortion of the structure relative to perfectly periodic state, and its time derivative can be translated to flow of CDW or VL. We assume that the system is divided into a number of domains, which couple each other, and phase variable is constant in each domain. In our calculation, domains are disposed as a simple cubic lattice.

The overdamped equation of motion for phase of i-th domain, u_i, is shown below. We numerically solve these equations by Runge-Kutta method.

$$u_i = -\frac{1}{z}\sum_j \sin(u_i - u_j) - h\sin(u_i - \beta_i) + f \qquad (1)$$

The first term on the right hand side is inter-domain coupling force and j-sumation is over z nearest neighber sites (domains). When relative phase difference, $|u_i - u_j|$, is enough smaller than π, the model reduces to the conventional elastic model. The second term is impurity pinning force and β_i is a quenched random variable in the range $[0, 2\pi)$. The last term f is driving force, which comes from external electric field for CDW and current for VL.

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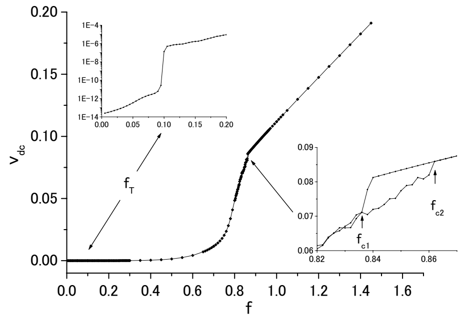

Fig. 1. Driving force dependence of dc velocity. System size is 32^3 and $h = 1.0$. At f_T, first depinning happens (zoomed in the left inset) and f_{c1} and f_{c2} separates elastic and plastic flow phase (zoomed in the right inset).

This model was analized by mean field approximation [7] in which the spatial fluctuation is ignored. Here we study three dimensional systems and we get a quite rich picture which is different from the mean field approximation model. In the next section, we show the results of our simulation, remarking on two quantities, spatially averaged dc component of phase velocity $v_{dc} = \langle \dot{u}_i(t) \rangle_{i,t}$ and order parameter $r = \left| \left\langle e^{iu_i} \right\rangle_{i,t} \right|$, which is the magnitude of magnetization in the context of spin systems. Here, $\langle \cdots \rangle_{i,t}$ means site and time average at constant f.

3. Results

Here we concentrate ourselves to the case of $h = 1$. Without driving force f, whole system is stopping and local random field pins the phase of each domain. Therefore the structure is highly disorderd ($r = 0$). Although finite f is added, system remains pinned below first threshold force f_T (See Fig.1).

At $f = f_T$, one or a few sites are depinned [8], and start creep motion with plastic deformaiton. As f become larger, more and more sites are depinned. Then v_{dc} gradually grows, but local dc velocity of each site has wide distribution. Therfore relative phase differences between nearest neighber sites overcome π, so plastic deformation happens. We call this plastic flow. Wide velocity distribution causes broad band noise.

As f grows larger than second threshold f_{c2}, all sites move with the same local dc velocity and make no plastic deformation. Additionally, phase of all sites begin to allign, then r has a finite value of $O(1)$ (shown in Fig.2). This means that the long range order is established and the periodisity of the structure is recoverd. Phase differences between nearest neighber sites are small, so we call this moving state elastic flow. When elastic flow is realized, v_{dc} contains typical oscillation, the so called "washboard noise". Its power spectrum has peaks at the frequency $v_{dc}/2\pi$ and its higher harmonics. This is because phase of each site periodically evolves over impurity potential which has 2π periodicity. For further large f, v_{dc} is asymptotically propotional to f.

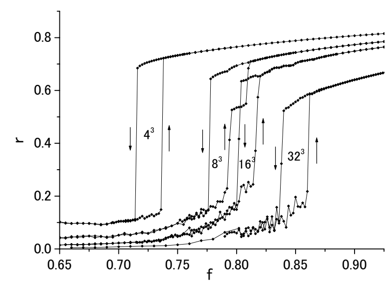

Fig. 2. Driving force dependence of coherence around f_{c1} and f_{c2}. Both f increasing case and decreasing cases for some samples which have different system size, 4^3, 8^3, 16^3 and 32^3, are shown.

So far, the case that f is gradually increased is studied. Next, we investigate the f decreasing case starting at elastic flow regime. Elastic flow phase is stable even below f_{c2}, and at f_{c1} pinned or non-cohernt velocity sites are created, then return to plastic flow. Below f_{c2}, the long range order is destroyed. This results a hysteresis loop in both v_{dc}-f and r-f curves.

4. Summery and Discussion

We studied here the dynamics of plastically deformable periodic structures by numerical analysis of a random field XY model. The dynamical state is divided into three dynamical phases by increasing external force, pinned and deformed lattice, plastic flow and elastic coherent flow.

The second transition between plastic and elastic flow regimes seems to be a first order transition which shows hysteresis and switching. However it is not clear that bistable region really exist for larger samples, because plastic flow state shows so large fluctuation and has long relaxation time below and near f_{c2}.

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