Dynamical Melting and Transverse Pinning of Moving Vortices Interacting with Periodic Pinning

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Abstract

Dynamical phases and phase transitions of moving vortices in clean films driven by an uniform force and interacting with periodic pinning are investigated at low temperatures by numerical simulations of a London model. Three dynamical phases are identified: moving commensurate and incommensurate lattices and moving liquid. Two dynamical transitions are reported: dynamical melting of a moving incommensurate lattice into a moving liquid and from a moving liquid into a commensurate lattice, where tranverse pinning occurs. The transition lines are obtained as a function of the driving force magnitude and direction for a typical vortex density.

Key words: dynamical phases; moving vortices, periodic pinning

A problem of current interest is the study of moving vortices interacting with periodic arrays of pinning centers. One reason is that they provide examples of dynamical phases and phase transitions where theoretical predictions can be tested in superconducting films with artificial defect lattices[1], and in Josephson junction arrays (JJA)[2]. Previous theoretical works on the subject investigate square pinning lattices with driving forces along the [1,0] (or [0,1]) directions, in which case the directions of drive and motion coincide[4–6,3]. In these cases dynamical melting of the moving vortex lattice(VL) into a moving vortex liquid is reported. Transverse pinning is also investigated in some of these works[4–6] by studying the response of the VL to a small force transverse to the direction of drive. In this paper dynamical melting and tranverse pinning are investigated at low temperatures as functions of the driving force magnitude and direction for a typical vortex density: two vortices per pin ($B = 2B_\phi$).

The dynamics of vortices interacting with periodic pinning simplifies in the limit of large driving forces. The moving vortices average the pinning potential in the direction of motion and the dynamical phases reduce to the equilibrium ones for vortices interacting with the averaged pinning potential[3]. In cases of experimental interest, the averaged pinning potential is essentially constant, except for high-symmetry directions of the pinning lattice, where it is a washboard periodic in the direction perpendicular to that of motion. In these particular directions the low temperature dynamical phases are moving VL, commensurate or incommensurate with the washboard potential. In other directions it is a triangular lattice.

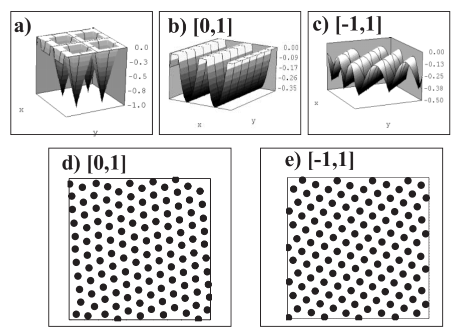

Fig. 1. a) Periodic pinning potential. b) and c) Average of a) along [0,1] and [-1,1]. c) and d) Infinite-drive phases at low-T for motion along [0,1](incommensurate VL) and [-1,1](commensurate VL).

The model used in this paper is discussed in detail in Ref.[3]. It consists of a lattice London model in which the vortices are placed on a square mesh with lattice parameter d containing 256×256 sites. The vortex core is a 4×4 square. Vortex-vortex interactions are essentially logarithmic, and the periodic pinning potential, shown in Fig. 1 a), is that of a square lattice of identical defects. Each defect creates a potential well with square equipotentials that gives rise to a force of constant magnitude, F_p, if the vortex is within a square of side $R_{cd} = 12d$ centered in the defect. The periodic pinning potential averaged in the [1,0] and [-1,1] directions are the washboards shown in Fig. 1 b) and c). The model has the square lattice symmetry, so that averages in the [1,0] and [1,1] also give washboards, related to the ones shown in Fig. 1 b) and c) by symmetry. Averages in other directions give essentially constant pinning potentials. The corresponding dynamical phases at high drives, hereafter called infinite-drive phases, are moving VL at low temperatures. For $B = 2B_\phi$ the moving VL is incommensurate (essentially triangular) for motion along [0,1] and [1,0] and commensurate for motion along [-1,1] and [1,1]. For other direction the moving vortex-lattice is essentially triangular. The VL for motion along [0,1] and [-1,1] are shown in Fig. 1 d) and e).

Numerical simulations of the Langevin equations of motion for the model are carried out at a temperature $T = 0.83T_m$, where T_m is the equilibrium melting temperature of the incommensurate VL for $B = 2B_\phi$. First the vortices are initialized in the incommensurate VL shown in Fig. 1 d) and a run with a driving force magnitude F_d large compared with F_p and direction α relative to [0,1] in the range $0^o < \alpha < 45^o$ is carried out. In subsequent runs α is kept constant and F_d is progressively lowered.

The results are depicted in the dynamical phase digram shown in Fig. 2. Melting of the moving incommensurate VL into a moving vortex liquid is found to take place along the dynamical melting line shown in Fig. 2. For drive directions close to [-1,1]($\alpha \sim 45^o$) the moving liquid reorders into a moving commensurate VL with the spatial order shown in Fig. 1 e). Within the whole commensurate VL region in Fig. 2 vortex motion remains pinned in the [-1,1] direction and tranverse pinning occurs. The magnitude of the critical tranverse force to depin vortex motion from [-1,1] is given by the value of $F_d \sin(45^o - \alpha)$ along the line separating the liquid and commensurate VL in Fig. 2. The present simulations find that the moving incommensurate and commensurate VL are always separated by vortex-liquid, suggesting that a dynamical transition between the commensurate and incommensurate VL does not take place. The direction of vortex motion, θ, does not coincide with that of drive (α) in general. The θ vs. F_d curves for various α is shown in Fig. 2. Within the incommensurate VL $\theta \sim \alpha$. Within the vortex liquid θ changes rapidly with F_d, starting at the dynamical melting line, and the vortex direction of motion approaches [-1,1] for all α. Simulations at other temperatures and vortex densities find for $T < T_m$ results similar to the ones reported above. These are reported in detail elsewhere [7].

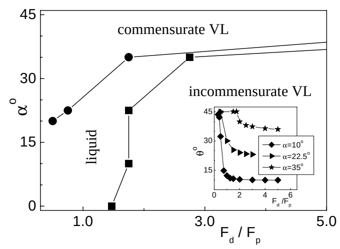

Fig. 2. Dynamical phase diagram for $B = 2B_\phi$ and $T = 0.83T_m$. Commensurate and incommensurate VL have the spatial order shown in Fig.1 d) and e).Inset: direction of motion θ vs. driving force magnitude F_d for some drive directions α

In conclusion then, numerical simulations of a London model for vortices interacting with periodic pinning identify three dynamical phases at low temperatures, moving incommensurate and commensurate VL and moving liquid, and two dynamical phase transitions between them: dynamical melting of an moving incommensurate VL into a moving vortex liquid and tranverse pinning of vortices accompanied by a transition between a moving commensurate VL and a vortex liquid.

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