Ratchet Effects for Vortices in Superconductors with Periodic Pinning Arrays

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Using numerical simulations we show that novel transport phenomena can occur for vortices moving in periodic pinning arrays when two external perpendicular ac drives are applied. In particular, we find a ratchet effect where the vortices can have a net dc drift even in the absence of a dc drive. This ratchet effect can occur for ac drives which create orbits that break one or more reflection symmetries.

Recently there has been considerable interest in using ratchet effects to control the motion of vortices in superconductors [1–4]. In a ratchet, a net dc flow can arise under the application of a strictly ac drive [5]. Typically, the symmetry breaking which can allow for this effect is produced by an asymmetric underlying substrate, such as a saw-tooth potential. However, ratchet effects can occur in systems with symmetrical substrates when some other form of symmetry breaking is introduced. One possible source of such a symmetry breaking is the applied ac drive itself. For example, it was recently shown that a particle moving in a two-dimensional (2D) periodic substrate can exhibit a ratchet effect when crossed ac drives are applied, where the ac drives cause the particle to move in orbits that have broken reflection symmetries [6]. In this paper, we show that for vortices moving in a periodic pinning array at fields $B/B_\phi > 1.065$, so that the interstitial vortices are far apart and in general do not interact. We apply an ac drive of the form $f_{AC} = A\sin(\omega_B t) + \sin^2(\omega_A t)\hat{x} + B\cos(\omega_B t)\hat{y}$, where $\omega_B/\omega_A = 1.25$. In this case a symmetry breaking arises from the shape of the orbits. In Fig. 1 we show $< V_y >$
for a system where $A = 0.49$ is fixed and $B$ is varied. For $B < 0.24$, the average vortex velocity is zero with the interstitial vortices moving in closed orbits. For $B > 0.24$, there are a series of phases which have a net dc flux in the $y$-direction. This flux can be in either the positive or negative direction. In general most of the rectified phases give a drift velocity of 0.024. We also find evidence for some rectifying phases that produce dc drifts that are fractional multiples of the maximum drift value. However, these phases appear only for very small regions of $B$. Additionally, as $B$ is further increased, we find regions where the interstitial vortices become repinned and $< V_y > = 0.0$. Each of the rectifying regions corresponds to different dynamical phases where the vortices move in distinct periodic orbits.

In Fig. 2 we illustrate some of the dynamical phases for the system in Fig. 1. The positive rectifying phase at $B = 0.265$ is shown in Fig. 2(a). Here a very intricate periodic pattern forms, with the vortices moving in a long time zig-zag pattern. In Fig. 2(b) the negative rectifying phase is shown for $B = 0.325$. Here another distinct orbit forms with the vortex moving in lobes that slant alternately. In Fig. 2(c) we show another positive rectifying mode at $B = 0.39$, where the orbit is similar to that in Fig. 1(b) but the net drift is in the opposite direction. In Fig. 2(d) we illustrate a non-rectifying orbit. Here the vortices move in complex periodic closed orbits without a net drift.

We next consider the case where $B$ is fixed to $B = 0.34$ while $A$ is varied. In Fig. 3 we plot $< V_y >$ vs $A$. Here we find similar behavior to that in Fig. 1, with both positive and negative regions of net dc drift appearing along with pinned regions. In both Fig. 1 and Fig. 3, we find no ratchet effect for low values of $A$ or $B$.

In Fig. 4 we illustrate some of the dynamical orbits for the system in Fig. 3. In Fig. 4(a), we show the first rectifying phase which occurs at $A = 0.256$. Again, very intricate periodic vortex
motions occur. In Fig. 4(b) we plot the positive rectifying phase that occurs at $A = 0.286$, where the net dc motion is in the positive $y$-direction. The orbit consists of the vortex moving in loops around a pining site with a series of much smaller sub-loops. In Fig. 4(c) we show the pinned phase for $A = 0.289$ that occurs just after the phase in Fig. 4(b). In Fig. 4(d) we illustrate a rectifying phase at $A = 0.792$. Here the orbit is much wider in the $x$ direction, corresponding to the increased amplitude of the $x$ component of the ac drive. We find similar intricate orbits at the other rectifying phases, not shown here.

We have also considered other parameters and different ac drive forms and find similar behaviors, indicating that the ratchet behaviors we observe are a very general feature of 2D systems driven with perpendicular complex ac drives.

In conclusion, we have shown that with perpendicular ac drives applied to vortices in periodic pinning arrays, a remarkably rich variety of dynamical phases can be achieved including ratchet effects. The ratchet effect arises in this system even though the periodic substrate is symmetrical due to a symmetry breaking by the ac drive itself.

Our results open a new avenue for controlling flux motion in superconductors. For instance, it may be possible to exercise additional control over the ratchet effect by changing the periodicity of the pinning array within a single sample. If, under the same ac drive, one type of pinning causes the vortices to move in the positive direction, while another type of pinning causes them to move in the negative direction, then it should be possible to create a fluxon focusing effect where vortices can be constricted in small regions. Conversely, it may be desirable to remove the flux from other regions, which is useful for certain applications such as flux sensitive devices.

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