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Rocking ratchets in nanostructured superconducting–magnetic hybrids

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Abstract

Two rectification mechanisms in vortex lattice dynamics in Nb films have been studied. These two effects are based on ratchet effects, that is, an ac driving force induces a net dc vortex flow. In our case, an input ac current applied to the Nb films, grown on top of arrays of Ni nanotriangles, yields an output dc voltage. These two rectification effects occur when the vortex lattice moves in periodic asymmetric potentials. These pinning potentials are induced by the array of Ni triangles. In one configuration (longitudinal effect) the driven force is applied perpendicular to the triangle reflection symmetry axis; in the second one (transverse effect) the input current is injected parallel to the triangle reflection symmetry axis. In the framework of the rocking ratchet mechanism, the appropriate Langevin equation allows us to model the experimental data, taking into account the vortex–vortex interaction.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The ratchet effect is the directional motion of out-of-equilibrium particles induced by a periodic asymmetric potential, without the need for being driven by non-zero average forces or temperature gradients. The realm of this remarkable effect spans from applied mathematics to molecular biology [1]. There are two main types of ratchet behaviour: flashing or pulsating ratchets and tilting ratchets. In the former the temperature is crucial and the ratchet potential is time dependent; the simplest example could be an on–off potential ratchet. The two kinds of flashing ratchets are: (i) fluctuating potential ratchets, when the ratchet potential amplitude is modulated, and (ii) travelling potential ratchets, when the ratchet potential moves. In the second main type of ratchet (tilting ratchets) the ratchet potential is not time dependent and zero average driving force $F(t)$ is needed. There are two kinds of tilting ratchets: (i) rocking ratchets, when the driving force $F(t)$ is periodic, and (ii) fluctuating force ratchets, when the driving force $F(t)$ is stochastic.

Therefore, a rocking ratchet needs two ingredients: (1) fluctuation motion of particles with zero average oscillation and (2) periodic structures which lack reflection symmetry. A few years ago, a superconducting vortex rocking ratchet was reported [2]. In this case, the particles are vortices; the ac current ($I_{\mathrm{ac}} = I_0 \sin \omega t$) injected into the superconducting film is the driving force which induces the fluctuation motion of particles with zero average oscillation and, finally, the periodic structures which lack reflection symmetry are periodic asymmetric potentials (pinning triangles) embedded in the superconductor. The main properties of this vortex rocking ratchet are adiabatic behaviour [3, 4], reversed vortex motion [2, 5] and collective vortex lattice behaviour [6, 7]. Recently, a transverse vortex ratchet effect has been measured in the adiabatic limit and with non-magnetic asymmetric pinning traps [8]. The transverse ratchet effect was theoretically studied by Derenyi and Astumian [9] and later, in the framework of superconductivity, by several authors [10]. In the transverse ratchet effect the driving force is applied parallel to the reflection symmetry axis of the asymmetric potentials, and the net output signal is measured perpendicular to this direction. Otherwise, in the usual longitudinal ratchet effect the driving force is applied perpendicular to the reflection symmetry axis and the output signal is recorded on the same direction.

In the present work, we are dealing with transverse and longitudinal rocking ratchet effects on superconducting–magnetic hybrid samples with input ac current up to 10 kHz and, besides, for the transverse rocking ratchet we have performed numerical simulations based on the Langevin equation for interacting and overdamped two-dimensional Brownian particles. So far we know [6, 11] that the usual ratchet (longitudinal ratchet) can be modelled by the Langevin equation of interacting particles. We will show that for the transverse ratchet the same approach allows us to obtain the experimental magnitude and shape and reveal the origin of this striking transverse ratchet effect.

2. Experimental method and theoretical model

The samples are superconducting–magnetic hybrids. The superconductors are Nb films and the magnetic materials are Ni nanotriangles. The Nb films have been grown on top of arrays of Ni nanotriangles. These Ni nanotriangles act as pinning centres for the vortex lattice. The vortex lattice could be pinned by these magnetic traps. But, once the driving force is enough to unpin the vortex lattice (applied current above the critical current) the vortex lattice dynamics show many interesting and remarkable phenomena, such as matching effects [12] and channelling effects [13], induced by the interplay between the vortex lattice and the lattice of pinning centres. The most interesting result of these commensurability effects is that for chosen values of the applied magnetic field we know the number of vortices per array unit cell and where they are placed: interstitially or in the triangles. Therefore, we can tune the number of ratchet particles (number of vortices) with the applied magnetic field values.

The samples are fabricated following several steps. The first step is e-beam writing on a resist (PMMA) covering the Si(100) substrate; next there is developing and magnetron sputtering deposition of Ni. Once lift-off is performed, only nanometric Ni triangles remain on top of the substrate, which is then covered by a thin film of Nb, also by the sputtering technique. The thickness is, for Ni (triangle height), 40 nm, and the Nb film is 100 nm thick. The nanotriangle side is around 600 nm. The array period is the same as that in [2]. Samples were lithographed for magnetotransport measurements with a cross-shaped bridge (40 μm wide) using ion etching and standard photolithography techniques. This cross-shaped bridge allows us to inject transport current and measure voltage drops along two perpendicular directions. All magnetotransport experiments were carried out in a commercial liquid He cryostat provided with a superconducting magnet and a variable temperature insert. The frequency of the ac applied current is always 10 kHz. The magnetic field is always applied perpendicular to the substrate.

The details of the longitudinal and transverse ratchet experimental layouts are another area that is worth considering. Figure 1(a) sketches the direction of the driving force, the vortex motion, the dissipation and the Lorentz force on a vortex taking into account the Lorentz and Josephson expressions. Therefore, applying a current to the sample and measuring the output voltage, we can extract the force on the vortex and the vortex velocity. Finally, we have to keep in mind that the voltage drop in one direction probes the vortex motion along the perpendicular direction.

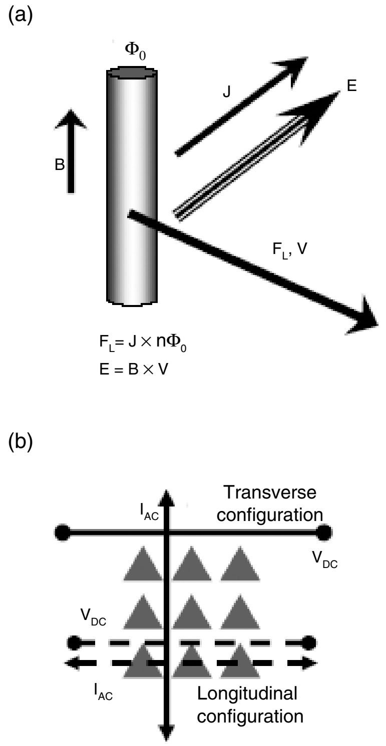

Figure 1. (a) Sketch of the applied magnetic field (B) fluxoid (Φ_0), applied current density (J), Lorentz force (F_L), velocity (v), electrical field (E) and Lorentz and Josephson expressions. (b) Sketch of the longitudinal (dashed lines) and transverse ratchet configurations.

Figure 1(b) shows the two experimental configurations. In the usual longitudinal ratchet configuration the driving current is applied perpendicular to the triangle reflection symmetry axis (tip to base axis) and the output voltage signal is recorded in the same direction. The Lorentz force induces vortex motion parallel to the triangle reflection symmetry axis, but the output (dissipation) voltage arises, following the Josephson expression, in the direction perpendicular to the triangle reflection symmetry axis, i.e. the voltage drops in the direction of the injected current and, therefore, perpendicular to the vortex lattice motion direction. Otherwise, in the case of transverse rectification, the input current is applied parallel to the triangle reflection symmetry axis, and the output voltage drop is measured perpendicular to the input current direction, i.e. perpendicular to the triangle reflection symmetry axis. This Hall-like configuration and the possible misalignment of the contacts could jeopardize our experimental data. There are several reports in the literature on how to avoid experimental artefacts in Hall-like measurements, in patterned or unpatterned cases [14]. In our patterned samples this problem has already been taken into account [8] and the possible longitudinal contribution could be neglected.

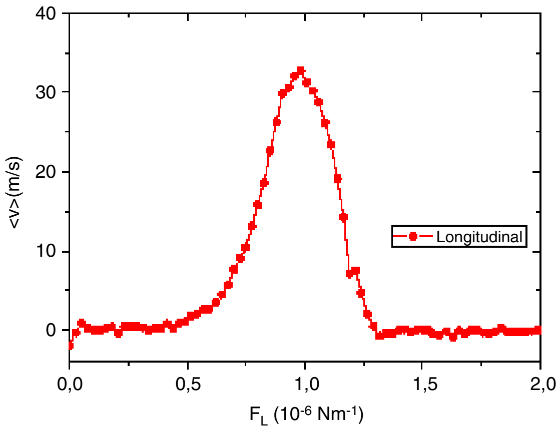

Figure 2. Longitudinal ratchet for $n = 3$ (three vortices per triangle). $T/T_c = 0.98$, ac current frequency 10 kHz. Nb film (100 nm thickness) on top of the array (periodicity 770 nm × 746 nm) of Ni triangles (triangle base 620 nm and height 477 nm).

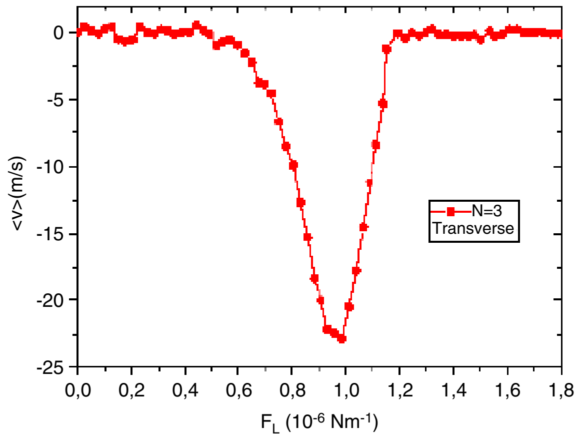

Figure 3. Transverse ratchet for $n = 3$ (three vortices per triangle). $T/T_c = 0.98$, ac current frequency 10 kHz. Nb film (100 nm thickness) on top of the array (periodicity 770 nm × 746 nm) of Ni triangles (triangle base 620 nm and height 477 nm).

Recently, the magnetic state of the Ni triangles has been published [15]; in summary the demagnetized ground state shows in plane aligned magnetization with three magnetic domains and a magnetic vortex in the centre of the triangle.

The theoretical model is based on the Langevin equation. The numerical simulation has been performed by numerically solving the Langevin equation for the motion of the vortices. This approach is similar to that of [11, 16]. In our case the simulation conditions are: periodic boundary conditions; the parameters are taken from the experiment; the simulation is with 144 particles (vortices); the array is 6 × 6 triangles with constant pinning forces in the Ni triangles and, finally, white thermal noise (stochastic).

The vortices are taken as a set of interacting and overdamped two-dimensional Brownian particles. The corresponding Langevin equation for position r_i of vortex i is

$$\eta \dot{\vec{r}}_i(t) = -\sum_{j\neq i} \vec{\nabla}_i U_{\mathrm{vv}}\left(\left|\vec{r}_i - \vec{r}_j\right|\right) + F_{\mathrm{p}}\left(\vec{r}_i\right) + F_{\mathrm{ac}}(t) + \Gamma_i(t)$$

where η is the friction, U_{vv} the vortex–vortex interaction, F_{p} the pinning force, F_{ac} the applied force and Γ_i the white Gaussian noise accounting for the thermal fluctuations. More details can be found in [6].

3. Results and discussion

The magnetotransport measurements have been done with magnetic fields applied perpendicular to the sample and with magnetic values which yield three vortices per triangle. Both configurations, longitudinal and transverse, have been explored. The experiments have been done at constant temperature and close to the critical temperature. The ac driving current frequency was 10 kHz; we have to note that the effect is adiabatic [3, 4]—it is not frequency dependent.

Figure 2 shows the experimental results obtained for the rocking ratchet effect using a vortex lattice of three vortices per triangle ($n = 3$) in the longitudinal configuration.

In the case of measuring in the Hall-like configuration, that is, injecting the ac current in the direction parallel to the reflection symmetry axis (from the triangle base to the triangle tip) and probing the dc output voltage in the perpendicular direction, the experimental data show a signal of opposite sign and lower magnitude, and which shows up in the same experimental window as in the longitudinal case; see figure 3.

To explore the mechanisms behind these two effects extensive numerical simulations have been done. These simulations show that we are dealing with a collective behaviour; the vortex lattice keeps the governing role and the lattice as a whole governs the rocking ratchet behaviour. This behaviour is different from the 1D non-interacting particle approach which was reported in [2]. In the case of the longitudinal ratchet the *easy* motion direction from vortices seems to be from the triangle base to the triangle tip; the collective vortex lattice behaviour was explored in [6]. The simulations in [6] show the main feature of the experimental results of the longitudinal vortex ratchet effect.

In the case of the transverse configuration, taking into account that the asymmetric potentials are attractive potentials, the vortex trajectory is deflected for the triangles always in the same way, for instance downwards. The asymmetric potentials (triangles) do not distinguish whether the vortices are coming from the left or from the right when the vortex lattice is moving perpendicular to the reflection symmetry axis of the triangle.

In figure 4 we show a simulation for $n = 3$ using the same parameters as in the experiments. We can see that the simulation models the experimental data. Taking into account that the thickness of the film is 100 nm (vortex length), the magnitudes of the experimental and simulated driving forces are quite similar—only at high driving forces does the experimental ratchet vanish at lower values than the simulated signal. This deviation could be due to the differences between the real and the simulated pinning wells. The real pinning wells are rounded [2] in comparison with the sharp angular corners of the simulated triangles; the latter enhance the potential effect and the output signal vanishes smoothly, as can be

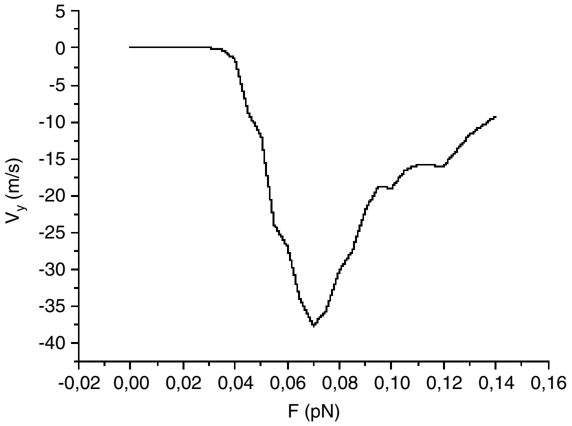

Figure 4. Numerical simulation of the transverse ratchet effect. $N = 3$ vortices per Ni triangle

seen in [6]. Therefore, the appropriate Langevin equation dealing with interacting particles in 2D is a remarkable tool for understanding the behaviour of the vortex lattice moving in periodic and asymmetric potentials.

4. Conclusions

The interplay between the vortex lattice in Nb film and the array of Ni triangles reveals rocking ratchet effects. The asymmetric traps could yield a very peculiar collective response of the vortex lattice: zero average ac driving forces induce a net flow of the vortex lattice. There are two possible rocking ratchet effects: the usual longitudinal one when the vortex lattice moves parallel to the reflection symmetry axis of the magnetic defects and a transverse rocking ratchet when the experimental configuration is a Hall-like one: the driving ac force and the vortex lattice motion are perpendicular to the reflection symmetry axis and the net flow occurs in the direction of the reflection symmetry axis, perpendicular to the ac force. The Langevin equation of 2D overdamped interacting particles allows us to model this experimental behaviour. In summary, the hybrid system Nb film on top of arrays of magnetic Ni nanotriangles behaves as a collective rocking ratchet of interacting particles with two possible ratchet configurations which could be modelled by appropriate numerical simulations.

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