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Voltage noise of current-driven vortices in disordered Josephson junction arrays

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Abstract

Dynamical phenomena of moving vortices and voltage noise spectra are studied in disordered Josephson junction arrays (JJAs). The plastic motion of vortices, smectic flow, and moving Bragg glass phases are separated by two dynamic melting transitions driven by current. From the voltage noise spectra of moving vortices, it is found that the driving current plays an important role in the melting of pinning vortices glass and ordering of moving vortices. The features of noise spectra obtained in the disordered JJA model have been observed recently in the high-temperature superconductor $Bi_2Sr_2CaCu_2O_y$ near the first-order melting transition, indicating that both of them are related to each other.

1. Introduction

In recent years much theoretical and experimental effort has been made to study the dynamic phenomena of vortex motion driven by an external current in type II superconductors. Many complex dynamic phenomena in the vortex system arise from a competition between spontaneously periodic structures of interacting vortices and disordered factors. Previous studies [1–8] have discussed possible dynamic phases of driven vortices in superconductors. It is found that the dynamical characteristic of vortices is highly dependent on the magnitude of the transport current. For a small driving current, the vortices flow in a plastic manner, i.e. in some channels vortices move with a finite velocity, whereas in other channels vortices remain pinned. With increasing driving current, the vortices tend to reorder, and form a coherent motion of the whole vortex lattice [1, 2].

Koshelev and Vinokur [3] first proposed a dynamic melting transition (DMT) of a vortex lattice under a finite driven current. Through the dynamic melting, the stationary vortex lattice changes into a moving vortex lattice. This DMT is different from the first-order transition (FOT) of vortex lattice melting in the equilibrium state at a critical field or at a critical temperature. Giamarchi and Le Dossal [5] suggested a moving Bragg glass (MBG) phase, which is characterized by the presence of translational order in the directions both parallel and perpendicular to the motion of vortices. On the other hand, Balents *et al* [6] suggested a smectic phase, which is another type of dynamical phase for the moving vortices. The smectic phase lacks translational order in the longitudinal direction of flow, even in the case of weak disorder. This was based on the experimental fact that the washboard noise had not been observed in the vortices of superconductors before, except in a system with artificially introduced strong periodic pinning centres. However, fast imaging by the scanning tunnelling microscopy [1] of moving vortices in $NbSe_3$ under an external field revealed velocity modulation with a translational period a_0/v in the creep regime of the vortex lattice system, where v and a_0 are the averaged velocity and the spacing of the periodic lattice, respectively. The Fourier transform picture of the longitudinal velocity shows a peak at a washboard frequency v/a_0. Quite recently, Kokubo *et al* [2] presented experimental evidence for the DMT of driven vortices at a given velocity, which were observed just above the peak effect regime of $NbSe_2$. In this literature [2], the signature of velocity-dependent DMT for moving vortices reveals a crossover from the coherent to the liquid-like incoherent flow state. The coherent flow of driven vortices is connected to internal frequencies $f_{\mathrm{int}} = pv/a_0$ of moving vortices, with p as an integer.

Voltage noise measurements of vortex motion in type II superconductors under a swept magnetic field and with various bias currents provide important information for studying the non-equilibrium dynamical properties of moving vortices on the microscopic scale. Recently, the conduction noise spectra near the FOT for vortex lattice melting were reported in high-temperature superconductors $Bi_2Sr_2CaCu_2O_y$ (BSCCO) [8–10] and $YBa_2Cu_3O_{7-\delta}$ (YBCO) [11]. A broad-band noise (BBN) occurs just when the pinned vortices start moving. As the vortex velocity increases, the BBN disappears, and a narrow-band noise (NBN) appears near the melting field in the solid phase as well as in the liquid phase. The appearance of BBN is determined by the plastic flow of vortices, whereas the NBN is found to originate from the presence of the washboard modulation of the translational velocity of the driven vortices. From the above experimental results, it follows that there exists coherent motion in the driven vortices in type II superconductors.

However, the dynamics and precise nature of driven vortices with sufficiently strong disorder in high-T_c superconductors are far from being fully understood, and have been a subject of much debate, since the ceramic superconductors, especially in their polycrystalline form, behave in many respects like a random arrangement of weak links between superconducting grains. Thus a discrete lattice structure of two-dimensional (2D) Josephson junction arrays (JJAs), with controlled disorder and controlled Josephson coupling, may shed light on such layered superconductors or film materials. Non-equilibrium dynamical properties in the disordered JJAs have been studied successfully by using the frustrated XY model with time-dependent Ginzburg–Landau dynamics, and the resistively shunted junction (RSJ) model [12–18]. But some important dynamic features of moving vortices, especially the motion-induced noise spectra extracted from recent experimental measurements in high-T_c superconductors [1, 2, 8–11], have not been well-studied theoretically.

In this work we study the dynamical phenomena of moving vortices and voltage noise features in disordered JJAs by calculating the voltage drop across the array, the vorticity due to the excitation of vortex and antivortex pairs (VAPs), and the voltage noise spectra of the moving vortices. We propose two dynamic melting transitions driven by current: one is at I_p to separate the plastic flow from the smectic flow, and the other is at I_g to separate the smectic flow from the MBG phase. The low-frequency BBN, Lorentzian NBN, and washboard NBN in the three current regimes are studied seriously. From the change of the vortex-motion-induced noise spectra, it is found that the dynamic nature of vortex motion is determined by a competition between the interacting forces and randomness. For low driving currents, the motion of driven vortices is dominated by the random pinning due to the quenched disorder, the noise spectrum exhibiting a large BBN in the plastic regime. As the current increases beyond a threshold I_p, the inhomogeneous plastic flow is frozen into a smectic flow with transverse ordering. In this case, the disordered bulk-pinning-induced BBN turns to decrease and a surface-pinning-induced Loretzian NBN appears. As the driving current is further increased beyond another threshold I_g, the influence of quenched disorder becomes negligible and the elastic interaction of the internal periodic structure becomes dominant, resulting in the washboard NBN. While the timescale of the Lorentzian NBN was argued to be the transit time of vortices across the sample and induced by the surface pinning [9], the timescale of the washboard NBN is found to be modulated by the constant lattice spacing, exhibiting coherent motion with a quasi-long-range order for the VAP flow. As a result, the driving current plays an important role in the melting of pinning vortices glass and ordering of moving vortices, as mentioned in previous work [3–8]. It seems that the smectic flow of moving vortices is a crossover between the disorder-induced transition at smaller threshold I_p and the interaction-dominated transition at larger threshold I_g.

2. Model and equation

The magnetic field penetrates a superconductor through an array of vortices. Each vortex carries one quantum of flux that is surrounded by a circulating supercurrent. If the vortices are moving with a mean velocity $\mathbf{v}$ under a current-driven motion, an electric voltage appears and there is a finite resistance. At the microscopic level, there will always exist fluctuations in the vortex motion either of thermal origin or due to the influence of crystalline defects. The voltage can then be separated into a time-averaged component and a fluctuating noisy component. Measurements of the average component permit one to study the macroscopic motion of the vortex ensemble as a whole, and study of the voltage noise gives a powerful probe of microscopic details of the vortex motion.

The motion of vortices in a 2D JJA can be described by the resistivity shunted junction model. We first consider the JJA consisting of a 2D array of superconducting grains with $N = N_x \times N_y$ ($N_x = 18$ and $N_y = 19$) square lattice structure, in which each pair of nearest-neighbour grains are connected by a Josephson junction in either the x- or y-directions, and then we introduce positional disorder in the grain configuration. In order to analyse the time evolution of superconducting phases, the equations of motion for $\phi_i(t)$ are given by a set of N-coupled nonlinear differential equations [18],

$$\frac{1}{R}\sum_j \frac{\mathrm{d}}{\mathrm{d}t}[\phi_i - \phi_j] = \frac{2e}{\hbar}\left\{ I_i - J\sum_j [\sin(\phi_i - \phi_j - A_{ij}) + L_{ij}] \right\}, \tag{1}$$

where J is the critical current of the junction, R is the junction resistance, and $\sum_j$ indicates the summation over the nearest-neighbour sites j. The bias currents in the y-direction are injected at the top row $I_i = I$, taken out at the bottom row $I_i = -I$, and $I_i = 0$ otherwise. The effects of magnetic field and structural disorder are taken into consideration in vector potential $\mathbf{A}$ with the Landau gauge, where $A_{ij} = (2\pi/\phi_0)\int_i^j \mathbf{A}\cdot \mathrm{d}\mathbf{l}$, yielding

$$A_{ij} = -\frac{2\pi H}{\phi_0}\frac{(r'_x - r_x)(r'_y + r_y)}{2}. \tag{2}$$

Random displacements δ_i are introduced into the positions of superconducting sites [15, 18]. The position of the ith site is given by $\mathbf{r}_i = (n_x + \delta_i^x, n_y + \delta_i^y)$, where n_x (n_y) is the integer where the lattice constant of the array is set to be unity for $\delta_i^{x,y} = 0$, and the deviation of the ith site, $\delta_i^x(\delta_i^y)$, is given by a random number in the range $[-\Delta/2, \Delta/2]$. Notice that

$\langle \sum_R A_{ij} \rangle = 2\pi H a^2/\phi_0 = 2\pi f$, where the average number of flux quanta per plaquette is set to be $f = n + 1/m$, with n and m integers. In the absence of disorder, the magnetic field gives rise to a ground state with a periodic structure of vortices. In this case, each vortex has a unit-cell size of $m \times m$ [14], with a large m corresponding to a dilute vortex configuration in the array. The effective amount of disorder is taken to be $W = n\Delta$, so that the disorder can be increased by increasing n.

At finite temperatures, the shunt resistance will exhibit a fluctuating noise current $L_{ij}(t)$, which is characterized by the time correlation functions $\langle L_{ij}(t+\tau)L_{kl}(t)\rangle = 2k_\mathrm{B}T g_{ij}\delta_\tau\delta_{ij,kl}$, where $\langle\cdots\rangle$ denotes an ensemble average. Under this assumption, the noise currents in different shunt resistances are uncorrelated, and the noise current within a given bond has a zero correlation time, corresponding to the white-noise approximation.

Taking into account both vector potential and thermal noise currents in the disordered system, one can rewrite the N coupled first-order differential equation (1) as [14]

$$M\frac{\mathrm{d}}{\mathrm{d}t}\Phi = \frac{2e}{\hbar}C, \tag{3}$$

where Φ is a column vector with N components ϕ_i for the N unknown phases. The N-component vector $C(t)$ is defined as $c_i(t) = I_i - J\sum_j[\sin(\phi_i - \phi_j - A_{ij}) + L_{i,j}]$. The matrix elements of M are given by $M_{ij} = \sum_j g_{ij}$ for $i = j$ and $M_{ij} = -g_{ij}$ for $i \neq j$ with $g_{ij} = 1/R$.

It seems that equation (3) could be rewritten by inverting the matrix M and expressing $\mathrm{d}\Phi/\mathrm{d}t$ in terms of C. However, M is not invertible as it stands [14]. To remedy this problem, one can fix one of the phases, which amounts to deleting one row and one column from M. The N coupled equations of motion given in equation (1) can then be written in the form $V' = G'C'$ with $G' = M'^{-1}$, where M' is the matrix constructed by deleting one column and one row from M, and V' and C' are the corresponding vectors with $N-1$ components. The coupled equations can now be solved numerically using the Runge–Kutta algorithm with time step $T = 141\,072$ and time interval $\Delta t = 0.05$ after a transient of 10^4 steps. The periodic and free boundary conditions are used in the x- and y-directions, respectively, and $2e/\hbar = 1$, $J = 1$, $R = 1$, and $L_{i,j} = 0$ are set at zero temperature. The array with strong disorder ($\Delta = 0.15$, indicating the effective disorder $W = n \times \Delta = 0.75 > 0.5$, [18]) and dilute vortex configuration ($m = 9$) is chosen to have frustration $f = 5 + 1/9$, with f in units of flux quantum ϕ_0.

The measured voltage drop V_y across the array in the direction of the bias current is proportional to the velocity of vortex motion, and hence is averaged temporally and spatially for the evolution of the phase movement:

$$V_y = \frac{1}{N_x(N_y-1)}\left\langle \sum_{i=1}^{N_x}\sum_{j=1}^{N_y-1}\frac{\mathrm{d}}{\mathrm{d}t}[\phi_{i,j}(t) - \phi_{i,j+1}(t)]\right\rangle. \tag{4}$$

The summation for i is over N_x parallel rows, each containing N_y-1 junctions in the series, and the summation for j is over all the nearest-neighbour superconducting grains in the y-direction. Another quantity that we calculate is the total vorticity Ne, which is the sum of absolute values of vorticities due to excitations of vortices and antivortices in the array,

$$Ne = \langle n_e(t)\rangle = \left\langle \frac{1}{(N-1)^2}\sum_R |n(R,t) - f|\right\rangle, \tag{5}$$

with $n(R,t) = -\sum \mathrm{nint}[(\phi_i - \phi_j - A_{ij})/2\pi]$. Here the summation goes around the plaquette R, nint$[x]$ is the nearest integer to x, and $\langle\cdots\rangle$ is averaged temporally. It means that the number of vortex excitations, Ne, basically counts the number of VAPs that exist around the background integral vorticity f.

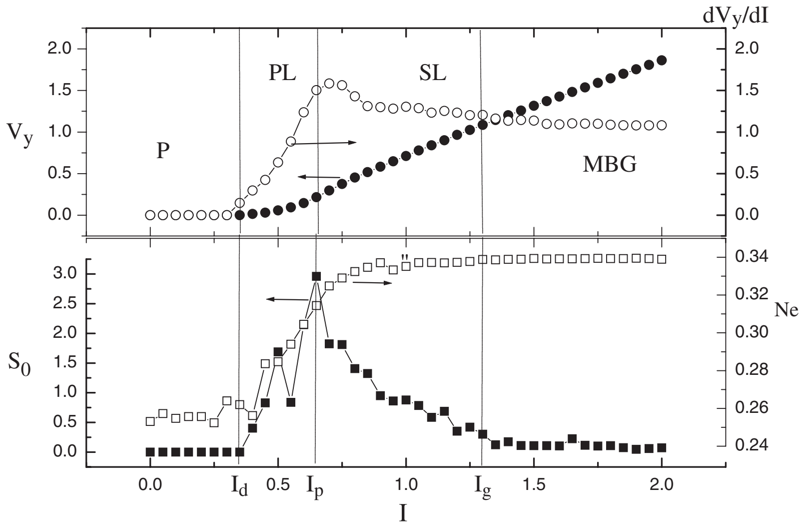

Figure 1. Voltage drop V_y (solid circles), differential resistance $\mathrm{d}V_y/\mathrm{d}I$ (open circles), low-frequency voltage noise power S_0 (solid squares), and vorticity Ne (open squares) as a function of driving current I.

The longitudinal voltage noise power indicates the dissipation in the flow direction, which is given by $S_0 = \int_{f_1}^{f_2} S(f)\,\mathrm{d}f$, with $S(f)$ as the voltage noise spectrum. The integral over frequency is chosen in the low-frequency region from $f_1 = 27/T$ to $f_2 = 54/T$ with $T = 131\,072$ steps. The noise spectrum density is defined as the Fourier transform of the voltage–voltage correlation function

$$S(f) = \frac{1}{T}\left|\int_1^T \mathrm{d}t\, V_y(t)\exp(\mathrm{i}2\pi f t)\right|^2, \tag{6}$$

with $V_y(t)$ being the time response of voltage in the y-direction.

3. Results and discussions

Consider a 2D JJA system with strong crystalline disorder under a transverse magnetic field and at zero temperature to study dynamic properties of the current-driven vortices. By choosing parameters $f = 5+1/9$ and $\Delta = 0.15$, we calculate the voltage drop V_y across the array in the bias current direction, differential resistance $\mathrm{d}V_y/\mathrm{d}I$, vorticity Ne, and low-frequency voltage noise power S_0 versus external current I; the results are shown in figure 1. To characterize these curves in different current regimes, we define three critical threshold currents: I_{d}, I_{p}, and I_{g}.

(I) I_{d} (= 0.35) is the depinning threshold current above which a finite V_y ($>10^{-6}$) appears. For $I < I_d$, it is the pinned regime for the current-driven vortex system, without dissipation by shunt resistivity and with low vorticity ($Ne \simeq 0.25$) due to the quenched randomness. For $I_{\mathrm{d}} \leqslant I \leqslant I_{\mathrm{p}}$, voltage drop V_y, vorticity Ne, differential resistance $\mathrm{d}V_y/\mathrm{d}I$, and low-frequency noise power S_0 grow nonlinearly with increasing I. This is called the 'plastic flow' regime, in which some VAPs are excited by freed vortices due to the interacting force, and the dynamics of vortex motion is dominated by the strong disorder pinning. The system exhibits very inhomogeneous flow with complicated flow paths, where the vortices break up into pieces moving with different velocities or not moving at all, indicating strong fluctuations of the vortex motion generated by the random bulk pinning centres.

(II) I_p (=0.65) is the threshold current separating the plastic flow from the smectic flow for the moving vortices. At I_p there is a peak in either I–dV_y/dI or I–S_0 curve [7]. As the current is increased beyond I_p, all the vortices are depinned and they are moving mostly parallel to the current, forming straight channels [15, 18–22]. In this regime, both the differential resistance and the noise power decrease with increasing I. At the same time, the internal degrees of freedom of freed vortices begin to be frozen due to the interaction, and the excited vorticity gradually increases and approaches a saturated value. This means that the vorticities are recombined from an inhomogeneous motion to a metastable VAP flow. I_p is a characteristic current, corresponding to the onset of transverse orientational ordering or a metastable VAP flow, which is called smectic ordering. In the smectic flow, temporal correlations of vortices were reported in the direction perpendicular to the flow [15, 18–22]. The critical threshold current I_p is taken as an indication of a DMT of the driven vortex lattice. This DMT for driving vortices is somewhat similar to the FOT of the vortex lattice in high-T_c superconductors observed by a kink in a resistivity curve or a step of magnetization [8–10].

(III) I_g (=1.3) is the threshold current separating the smectic flow from a moving Bragg solid for the moving vortices. For $I \geqslant I_g$, the differential resistance approaches unity, S_0 almost disappeared [7], and the excited vorticity is saturated to a constant value ($Ne = 0.34$). This means that all excited VAPs move almost at the same velocity, and the motion of VAPs forms a 'coherent flow' in the array together with the elastic flow of the moving vortices. Both the linear dependence of the VAP flow and the vanishing longitudinal voltage noise power show that at I_g there is a DMT of moving vortices from a longitudinal inhomogeneous smectic flow state to a MBG state with quasi-long-range translational ordering in the flow direction. From the variation of vorticity in different current regimes, it also follows that there exist two DMTs at I_p and I_g in the present strong disordered system. The depinning of vortices is driven by the excitation of VAPs, so that VAPs appear at the critical current I_d. Since the excited vortices and antivortices are a nucleation phenomenon and have a stochastic nature, the VAPs first move inhomogeneously in the plastic flow, then in part homogeneously in the smectic flow, and finally transit to a coherent flow with a stable vorticity in the MBG phase.

To clarify the nature of the moving vortex state in different dynamic regimes, we calculate the variation of vortex velocity v_y in the flow direction with time for different applied currents, which is proportional to the voltage drop V_y. From $v_y(t)$ shown in figure 2, we can see that $v_y(t)$ is highly disordered and ruleless, either in the plastic flow regime (e.g. $I = 0.6$) or in the smectic flow regime (e.g. $I = 1.0$). For a current well above I_g (e.g. $I = 1.8$ and 2.8), it is found that the velocity of the flux flow exhibits a periodic modulation and the oscillation frequency increases linearly with I.

The time response of the voltage fluctuation is conveniently expressed in terms of voltage noise spectra $S(f)$. Figure 3 shows $S(f)$ for different currents ($I = 0.64, 0.80, 1.02, 1.20$). It is found that, for current in the plastic flow regime (e.g. $I = 0.64$), the noise spectrum $S(f)$ characterizes a BBN feature. The intensity of the noise spectrum is large at very low frequencies, $S_f \sim 1$, and decreases with increasing frequency in the $1/f$ form. As the current is across I_g to enter the smectic flow regime (e.g. $I = 0.8$), the BBN drops abruptly. As the current increases to $I = 1.02$, the BBN decreases to $S(f) < 0.05$ at low frequencies and, at the same time, a NBN with a principle peak appears at a special frequency $f_p(\mathrm{NBN}) \sim 0.0012$. As the current increases further to $I = 1.20$ near I_g, the BBN almost disappears ($S_f \sim 0.001$) and the NBN peak shifts to a higher frequency $f_p(\mathrm{NBN}) = 0.0017$. We can see that the NBN at high frequencies is in the Lorentzian form: $S(f) = S(0)[1 - (f/f_p(\mathrm{NBN}))^2]^{-1}$, with $S(0)$ being the low-frequency noise level, exhibiting a singular peak at $f = f_p(\mathrm{NBN})$. As pointed

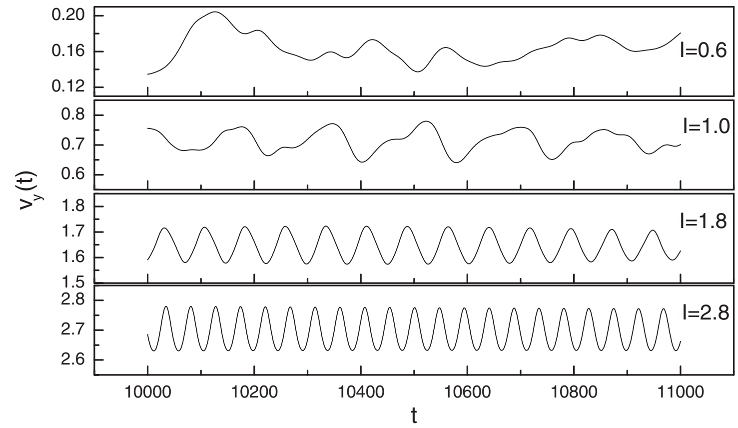

Figure 2. Variation of the vortex velocity with time, $v_y(t)$, for different applied currents $I = 0.6$, 1.0, 1.8, and 2.8.

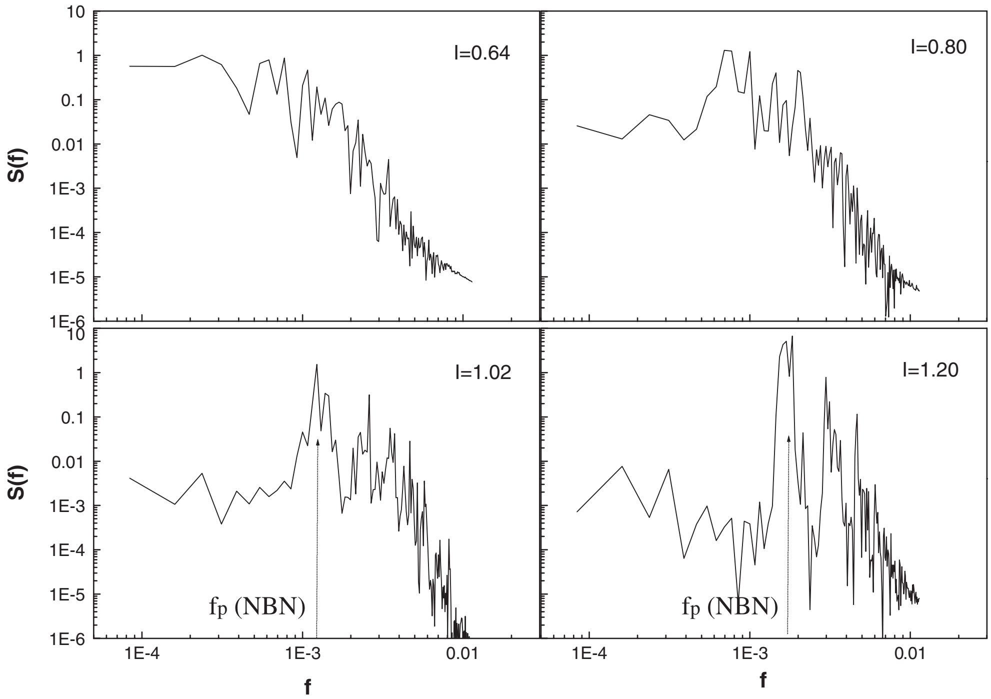

Figure 3. Voltage noise spectra $S(f)$ for different currents $I = 0.64$, 0.80, 1.02, and 1.20.

out by Anna *et al* [9], the surface barrier or surface pinning plays an important role in generating the characteristic Lorentzian NBN. When a channel is open, the vortices nucleate on one side and cross the sample of width d with a fixed velocity v_y, the transit time across the sample being $\tau_T = d/v_y$. Since the surface pinning controls the entry of vortices, for the smectic flow near I_g, the channel structure appears to be more regular, with more moving vortices producing noise with a characteristic roll-off frequency given by the inverse of the transit time. As a

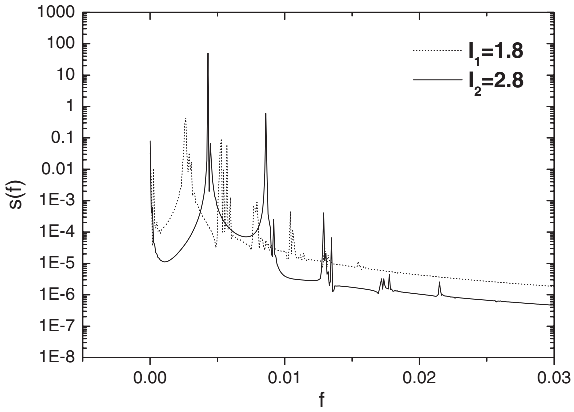

Figure 4. Voltage noise spectra $S(f)$ for currents $I = 1.8$ (dotted line) and $I = 2.8$ (solid line).

result, the noise peak appears at a certain frequency $f_p(\mathrm{NBN}) \propto v_y/d$, and the position of the characteristic frequency shifts to higher frequency with increasing velocity.

To show the temporal correlations of the moving vortices in the MBG phase far away from I_g, we calculate the voltage noise spectra $S(f)$–f for currents $I_1 = 1.8$ and $I_2 = 2.8$; the calculated results are shown in figure 4. It is found that the washboard NBN with a series of sharp peaks appears at $f_{i,w}(\mathrm{NBN})$ ($i = 0, 1, 2, \ldots$) in the spectrum with a fixed frequency interval $\Delta f_w = f_{i+1,w} - f_{i,w}$. As the applied current is increased from 1.8 to 2.8, the characteristic frequencies of washboard NBN peaks shift to higher values and the frequency interval increases. The appearance of the washboard NBN in the MBG phase indicates that it arises from the modulation of the translational velocity of the moving vortices, as shown by the v_y–t curves in figure 2. This washboard NBN was also obtained recently by numerical simulations at finite temperatures using a three-dimensional (3D) frustrated anisotropic XY model with weak random pinning potential in layered superconductors [12]. Since the washboard NBN corresponds to the time required for a vortex to move by one lattice constant, these characteristic frequencies are given by $f_{i,w}(\mathrm{NBN}) \propto \mathrm{i}v_y/a$, where a is the stable vortex spacing. From our calculations, it is found that the ratio of vortex velocities for the two currents is $v_y(I = 2.8)/v_y(I = 1.8) = 2.709/1.654 = 1.64$, and the ratio between the two characteristic frequency intervals is $\Delta f_w(I = 2.8)/\Delta f_w(I = 1.8) = 0.0043/0.0026 = 1.654$. It then follows that the vortex spacing a is almost constant in the MBG phase, independently of I or v_y. The washboard NBN spectra obtained here directly support the notion of formation of the translational order along the flow direction.

It is interesting to see that the low-frequency BBN of current-driven vortices in the plastic flow and Lorentzian NBN in the smectic flow are consistent with the experimental results near the FOT in BSCCO and YBCO [10, 11]. The obtained washboard NBN in the MBG phase is also consistent with the picture obtained from numerical simulations by Olson's group and Chen *et al* [7, 12] and with the results from recent experimental measurements [1, 8, 9]. However, there is a difference in the washboard NBN spectrum between the present results driven by current and the experimental results driven by magnetic field. In [9], with increasing magnetic field, the NBN peaks become lower and broaden, and further the noise spectrum becomes unclear. This behaviour stems from the fact that the coherence of the moving vortices deteriorates gradually with an increasing magnetic field. The present result in figure 4 is that the washboard NBN peaks become higher and narrower when the driving current is increased. This result indicates that the driving current does not have dephasing effects and the coherence of moving vortices becomes stronger with increasing current in the MBG phase. One common feature in the washboard NBN spectra driven both by current and by magnetic field force [8–10] is that the positions of the washboard NBN peaks in the noise spectrum shift to higher frequencies with increasing driving force.

By analysing the vortex-motion-induced noise spectra, it follows that the dynamic nature of vortex motion is controlled in common by a competition between interacting forces and randomness. For low driving currents, fluctuations of the vortex motion in the inhomogeneous plastic flow are due to the influence of disordered crystalline defects connected with the bulk pinning properties, so that the noise spectrum characterizes a low-frequency BBN. As the current increases beyond I_{p}, the inhomogeneous liquid is frozen into a smectic flow with transverse ordering, and the BBN decreases rapidly in the smectic regime. At the same time, a surface-pinning-induced Loretzian NBN appears. For a very large driving current in the MBG phase, the randomness is irrelevant compared with the strong interactions, and the dynamics is the interaction-dominated coherent flow. The washboard NBN observed in the MBG phase is strong evidence of the coherent nature of moving vortices. The timescale of the washboard NBN is found to be modulated by the constant lattice spacing, exhibiting coherent motion with quasi-long-range order for the moving vortices.

4. Summary

In summary, we have studied the dynamic features of moving vortices, especially the change of a motion-induced noise spectrum with increasing current, in strongly disordered JJAs. By comparing the present theoretical results with those extracted from the noise spectrum observed recently in high-T_{c} superconductors, it follows that an increasing current makes the driven vortices change from plastic motion to collective flow. The increase in vortex velocity leads to an enhancement of vortex–vortex interactions, which is favourable for the melting transition and formation of the ordered moving vortex lattice. These features obtained in the disordered JJA model have been observed in the high-temperature ceramic superconductor $Bi_2Sr_2CaCu_2O_y$, indicating that both of them are related to each other.

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