PHYSICAL REVIEW B **71**, 104507 (2005)

Longitudinal and transverse noise in a moving vortex lattice

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(Received 19 March 2004; revised manuscript received 22 July 2004; published 14 March 2005)

We have studied the longitudinal and the transverse velocity fluctuations of a moving vortex lattice (VL) driven by a transport current. They exhibit both the same broad spectrum and the same order of magnitude. These two components are insensitive to the velocity and to a small bulk perturbation. This means that no bulk averaging over the disorder and no VL crystallization are observed. This is consistently explained referring to a previously proposed noisy flow of surface current whose elementary fluctuator is measured isotropic.

DOI: 10.1103/PhysRevB.71.104507 PACS number(s): 74.25.Qt, 72.70.+m, 74.70.Ad, 74.40.+k

INTRODUCTION

Recent theoretical studies have pointed out that the vortex lattice (VL), as an example of driven disordered system, could exhibit different topological order during its motion.[1] The experimental problem is to have access to a signature of disorder in the VL. Voltage and magnetic-field fluctuation measurements appear to be a quite natural tool. Indeed, it has been established for years that such noise measurements turned out to be very efficient to collect information on the dynamical behavior of a moving VL and on the way it can be associated to its pinning properties.[2] In order to analyze the fluctuating part of the VL submitted to the driving force, the most direct experiment consists in a measure of the noisy electromagnetic fields for different points of a voltage versus current $[V(I)]$ characteristic. The dissipative part of this curve usually presents two regimes. Just above the depinning threshold (critical current I_c), in the low-current regime (LCR), the average voltage response does not scale as $(I-I_c)$. This implies inhomogeneous depinning, i.e., different onset of motion, coming either from intrinsic reasons ("plastic phase") (Ref. 3) or from extrinsic reasons (simple dispersion of critical current),[4] or eventually from both of them. Nevertheless, in each case this can be formalized as a plasticlike flow with VL chunks moving at different velocities. When increasing the current, the linear regime (the flux-flow where dV/dI is a constant) is reached. This flux-flow regime corresponds to the whole VL in motion. Its long time averaged movement is coherent, which justifies the description in terms of an elastic response of an ordered media. If one supposes that the pinned state is disordered, one can realize that the VL should average its pinning efficiency through disorder to finally order at a threshold current. This crossover between two dynamical states can be formalized in terms of a dynamical crystallization.[5] Including the periodicity of the VL, the formation of elastic channels with transverse barriers at high velocities is predicted.[6] Numerical simulations support this picture of flowing channels[7] and some give rise to a growth of the transverse order driven by the current, leading to a transverse freezing.[8] A common point between those predictions is that a high drive implies a healing of defects present in the VL. This is expressed in a dynamical averaging at least in one of the directions in the plane of the flow. A loss of noise, i.e., a loss of interaction with the pinning centers, is thus expected. We note that in contrast with the very active field of theoretical work and numerical simulations, only very few experiments have been devoted to the verifications of the preceding points. There are even opposite results. For example, Plaçais *et al.* investigated the high-current regime without finding any decrease of the voltage longitudinal noise.[9] In view of the above cited theories, it appears that the fluctuations in the direction perpendicular to the flow should also contain pertinent signatures. Maeda *et al.* measured the correlation of the fluctuations in the flux density along this direction,[10] but did not extend into analyzing the transverse noise itself when the driving force is increased.

More precisely, most of the interest resides in the VL correlation functions for the theories or in the positions of vortices for the simulations. The associated fluctuating quantities are essentially the velocities. As the vortex flow is associated to dissipation, theoretical predictions can be checked by measuring the voltage noise. A first important issue is to collect what really corresponds to velocity fluctuations when measuring the voltage noise along a path that connects the two voltage contacts. Indeed, irrespective of any precise noise model, a look at the Josephson equation $\mathbf{E}=-\mathbf{v_L}\times\mathbf{B}$ evidences that both velocity fluctuations $\delta\mathbf{v_L}$ and magnetic-field fluctuations $\delta\mathbf{B}$ can play a role. This discrimination between $\delta\mathbf{v_L}$ and $\delta\mathbf{B}$ has been a central point for the understanding of the origin of the VL noise. Historically, first experiments which gave evidence that the voltage noise was coming from vortex motion were performed by Van Ooijen and Van Gurp.[11] They interpreted their results as shot-noise implying strong $\delta\mathbf{B}$. The central idea is that flux bundles with short-range correlation are generating pulse voltages with finite lifetime. It could have clearly demonstrated the existence of flux bundles, but in spite of numerous developments,[12] this model has not been confirmed by experiments.[2,9,13] Discriminating tests which invalidate this "flux bundle" approach are the absence of correlation between magnetic-field noise and voltage noise in the flux-flow regime and the smallness of the magnetic-field noise,[14] whereas the shot-noise analogy predicts strong correlations and large field noise.[9] This leads to the conclusion that the moving VL noise is not generated through local-density fluctuations, which is not consistent with flux bundles as independent entities.[9] If the magnetic-field noise is not at the origin of the moving VL noise, the other scenario is pure vortex velocity fluctuations $\delta\mathbf{v}_\mathbf{L}$.[14] Unfortunately, the simple picture of a quasiperfect two-dimensional (2D) moving lattice cannot describe the field noise, and consequently cannot explain the absence of correlation between field noise and voltage noise. In order to answer to this latter question, it is necessary to know and to locate the fluctuators. Cross-correlation experiments in the flux-flow regime in low T_c alloys and metal strongly suggest that there are surface current fluctuations.[9] Now in the region close to the peak effect, additional large voltage fluctuations are present and are associated with non-Gaussian averaging of the noise.[15,16] A model of this excess noise proposes a dynamical mixture of two VL phases.[17]

Our present study deals with a more conventional case, i.e., the study of the VL noise when a unique VL phase is present. First we propose to isolate the velocity fluctuations with a special care to the component perpendicular to the direction of the flow. As far as we know, the response of this component to the driving force has never been experimentally investigated and compared to the predictions. To fulfill this gap would bring precious hints on how the vortex order is determined by the velocity. In particular, we show that the fluctuations stand without averaging, meaning that no crystallization is observed. Furthermore, this noise regime is not affected by an artificial bulk perturbation, but turns out to be dominated by surface effects.

I. SAMPLE AND EXPERIMENTAL RESOLUTION

All data presented here are measured using a sample of Pb-In (10.5% of In by weight, size $12.4\times4.1\times0.15$ mm^3). All basic parameters are in agreement with tabulated values [$\rho(T_c)=6.15\ \mu\Omega$ cm, $T_c=7$ K, $B_{c2}(4.2\text{ K})=0.29$ T].[18] This ensures the good bulk homogeneity of the sample. As usual for a metallic alloy, the sample exhibits a mirrorlike shape at the optical scale and atomic force microscopy (AFM) inspection evidences a moderate surface roughness at the scale 0.1–1 μm (mostly self-similar surface with a corrugation of about 10 nm over 100 nm in this scale). Our experimental setup is drawn in Fig. 1. The space between the longitudinal and transverse contacts is, respectively, $d=4$ mm and 1 mm. The sample was supplied by noise-free current made by car batteries and thermalized power resistances. Noisy voltages were recorded and amplified by ultralow noise preamplifier (SA-400F3) with a resolution of 0.7 nv/$\sqrt{\text{Hz}}$. Magnetic-flux noise δB_z was picked up by a ten-turn coil largely surrounding the sample, so as to avoid a nonperfect coupling.[9] The signal was then amplified by an original setup consisting of a highly linear transformer (Vitrovac) with turns ratio (1/1000), coupled with a low-current noise amplifier (INA114). Taking care of external electromagnetic perturbations, it was possible to measure field fluctuations less than one $\mu G/\sqrt{\text{Hz}}$.

Velocity noise measurement procedure

1. Numerical representation

The analog signals $u_i(t)$ at the input of the acquisition card of the computer are converted into digital signals and then numerically processed. Since vortex noise is a random signal, power spectra are not relevant and one must consider the autocorrelation function of the noise instead:

$$A_{ii}(\tau)=\lim_{T\to\infty}\int_{-T/2}^{T/2}u_i(t)u_i(t+\tau)dt. \qquad (1)$$

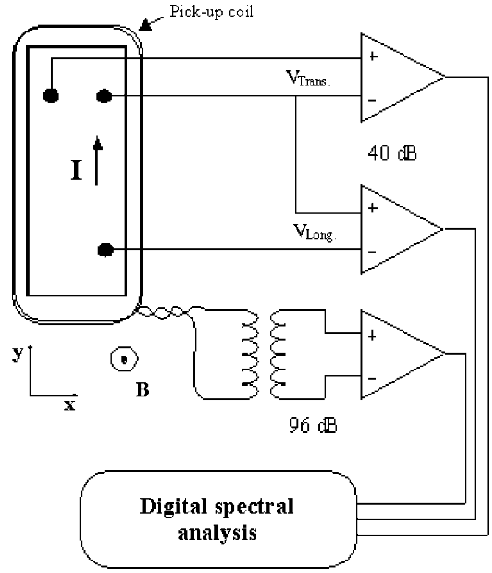

FIG. 1. Electric-field and magnetic-field noise experimental setup. The current is supplied by batteries and yields noise-free currents. All amplifying equipments are electromagnetically shielded.

According to the Wiener-Kintchine theorem, the Fourier transform of the autocorrelation function is the power spectral density (PSD):

$$\delta U(f)=\int_{-\infty}^{\infty}A_{ii}(t)e^{-2j\pi ft}dt\equiv\lim_{T\to\infty}\left\langle\frac{U_i(f)U_i^*(f)}{T}\right\rangle. \qquad (2)$$

We did not focus on the shape of the power density spectra because it does not vary much with magnetic field or current in our experimental conditions. In this paper, we represent noise either by the PSD [$\delta U(f)$] or by the PSD integrated over the frequency bandwidth [$\delta U*=\sqrt{\int_{10}^{1000}\delta U(f)df}$], which corresponds to the rms noise value. The detail of the spectra envelop will be discussed in later works.

2. The Josephson equation

As stated in the Introduction, as we are interested in velocity fluctuations, it is necessary to isolate the different noisy fields. In our experiments, we measure physical quantities averaged over large length scales (the sample is relatively large and the distance between the voltage pads is about few millimeters). Such mean quantities are properly described by the Josephson equation:

$$\mathbf{E}=-\mathbf{v}_\mathbf{L}\times\mathbf{B}. \qquad (3)$$

In our geometry (see Fig. 1), Eq. (3) can be differentiated as follows:

$$\delta E_{long} = \delta E_y = \delta v_{Lx} B_z + v_{Lx} \delta B_z, \tag{4}$$

$$\delta E_{trans} = \delta E_x = \delta v_{Ly} B_z + v_{Ly} \delta B_z. \tag{5}$$

In flux flow, the Hall voltage is negligibly small so that $v_{Ly} \approx 0$, and the mean electric field can be written as

$$\langle E \rangle \approx E_{long} = v_{Lx} B_z = R_{FF}(I - I_c)/d, \tag{6}$$

where R_{FF} stands for the flux-flow resistance and d is the distance between the voltage pads.

Substituting Eq. (6) into Eq. (4), one obtains

$$\delta E_{long} = \delta v_{Lx} B_z + \frac{R_{FF}(I - I_c)}{B_z d} \delta B_z, \tag{7}$$

$$\delta E_{trans} = \delta v_{Ly} B_z. \tag{8}$$

This relation between the voltage noise and the velocity fluctuations is *a priori* valid for any noise model, simply assuming that Josephson relation applies at our experimental length scale (millimeter scale). This does not depend on the source of $\delta \mathbf{v_L}$ versus $\delta \mathbf{B}$. Looking at Eq. (8), one can realize that the transverse voltage noise gives a direct measurement of the velocity fluctuations in the y direction. Yet, the longitudinal voltage noise has an extra contribution involving the magnetic-field fluctuations. In order to collect the velocity fluctuations in the x direction, one should measure simultaneously the longitudinal voltage noise and the magnetic-field noise, and then subtract the magnetic-field component.

II. EXPERIMENTAL RESULTS

In this study, we report on the influence of the driving force on the in-plane fluctuations of the VL velocity (δv_{Lx} and δv_{Ly}) at 4.2 K for several magnetic fields. To begin with, we check the experimental validity of the above-described procedure. The study is then divided into two parts. In the first part, we present experiments with a dc driving force: the velocity fluctuations are measured for different points of the *I-V* characteristics. Second, we discuss the noisy response of a moving lattice driven by a small perturbation force.

A. Velocity fluctuation measurement

As a preliminary step, we check the experimental validity of Eqs. (7) and (8). The longitudinal electric-field rms noise (δE^*) is collected for different currents in the flux-flow regime, and reported in Fig. 2(a). The results are similar if the noise is considered at a given frequency rather than integrated over the whole frequency bandwidth. In order to determine the flux-flow regime where the Josephson equation applies at the measurement scale, the $V(I)$ curve is also drawn in Fig. 2(b). This corresponds to the regime where the differential resistance is a constant. It can be realized from the experimental data that δE^* can be divided into two terms: a constant term and a term which varies linearly with $(I - I_c)$. This observation stands for all the magnetic fields we have investigated (from $0.32H_{c2}$ to $0.93H_{c2}$). An identification with the Josephson equation (7) suggests that the two fluctuating components δv_{Lx} and δB_z are constant with respect to $(I - I_c)$. This result is confirmed by a direct measurement of the magnetic-field noise δB_z by the pick-up coil. The obtained value is then compared to the estimation of δB_z calculated from the slope of the δE_y versus $(I - I_c)$ curve, using Eq.(7). The agreement was very satisfactory for all the magnetic fields at which we made measurements; the result reported in Fig. 2(a) corresponds, for example, to $0.23T = 0.7H_{c2}$. In the rest of the paper, δB_z will refer either to the directly measured value or to the estimation from the slope. On the other hand, the transverse component of the noisy electric field is measured constant in flux flow, as predicted by Eq. (8). This shows an interesting property: a measure of pure velocity fluctuations. It will be analyzed in more detail below.

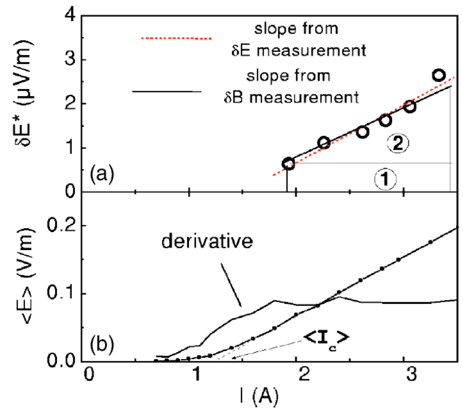

FIG. 2. (a) Electric-field noise integrated over two frequency decades (10–1000 Hz) δE^*, plotted against the current (∘) (4.2 K, 0.23 T). The dashed line represents the linear fit of the FF noise, yielding $\delta B_z^* = 32$ mG using Eq. (7). The solid line represents the slope calculated from the direct δB_z measurement. The background noise integrated over two decades has been subtracted. (1) represents the amount of excess noise independent of the current and (2) the amount of noise dependent of the current as explained in the text. (b) Solid line and ∘: mean electric field $\langle E_y \rangle$ against the current. The thin line represents dE/dI against the current. The main critical current is defined by the extrapolation of the linear part of the $E(I)$ curve.

B. Noise in dc biasing

Figures 3(a) and 3(b) show the detailed results in both directions for different dc currents ($B = 0.1$ T). The fluctuations appear at the first dissipative current, i.e, when the VL starts to move. In the nonlinear part of the $E(I)$ curve [Fig. 3(c)], the longitudinal fluctuations exhibit a fuzzy behavior. In this range of driving forces the whole VL is not in flux flow yet, and the Josephson equation is not valid at the sample scale. Neutron experiments have pointed out that inhomogeneity of the critical current can lead to the following depinning:[4] slices of VL along which the critical conditions are similar depin in sequence, until the whole VL is in flux flow. Therefore, the longitudinal noise signature in this range of currents can be seen as a succession of depinning peaks. This mimics plastic deformations such as those observed through fingerprints in the differential resistance in $NbSe_2$.[1]

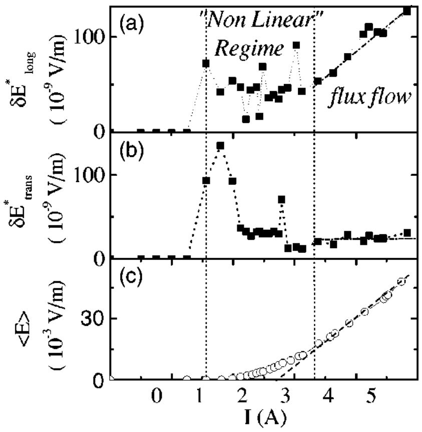

FIG. 3. Electric-field noise power spectral density integrated over two decades (10–1000 Hz) and plotted against the current for the different dynamical regimes (T=4.2 K, B=0.1 T): (a) in the y direction ($E*_{long}$) and (b) in the x direction ($E*_{trans}$)). Dashed lines are guides for the eyes. The mean electric field $\langle E\rangle$ is represented against the current in (c). $\langle E\rangle$ is measured in the y direction; $\langle E_x\rangle$ =0 within our experimental resolution.

The fact that the longitudinal noise exhibits a more jagged behavior than the transverse one can be explained by an excess of magnetic-field noise due to fluctuations in the number of (moving) vortices. The velocity, even if spatially inhomogeneous, would not fluctuate much more than in flux flow.

As soon as the flux flow is reached, Eqs. (7) and (8) apply, and δv_{Lx} and δv_{Ly} can be extracted from the electric-field noise (Fig. 4). We observe that the velocity fluctuations in the longitudinal direction do not depend on the current. δv_{Ly} reveals the same behavior in the transverse direction. In addition the ratio $\alpha=\delta v_{Ly}/\delta v_{Lx}$ is constant and equals 0.5 ± 0.1. This means that the velocity fluctuations are large in the two directions. More importantly, they are not averaged by the motion. It must be emphasized that neutron-scattering experiments carried out in a similar sample give the evidence of a well ordered VL (crystallinelike) in the same conditions.[19] Thus we study the noise signature of a moving crystal of vortices or a moving Bragg glass of vortices, i.e., the high velocity ordered state seen in simulations. Nevertheless, it is important to realize that large velocity fluctuations in the two directions (both longitudinal and transverse to the motion) are present in this regime. The velocity independence of these fluctuations shows that the disorder responsible for these velocity fluctuations is not averaged to zero. This contrasts with the disappearance of the fluctuating part of the pinning component as predicted in the dynamic crystallization developed in Ref. 5. For a VL propagation through channels at high driving force, large transverse barriers are expected to keep the channels rigid. If the large transverse noise in the LCR with $\alpha>1$ is in a qualitative agreement with the simulations of Kolton *et al.*, no transverse velocity fluctuations are expected in flux flow (*transverse freezing*) whereas we observe substantial ones. The persistence of an equivalent transverse noise power over the whole range of current, outside the depinning peaks (Fig. 3), tends to prove that the nature of flow is not fundamentally different in the LCR and in FF. We conclude that the measured noise signatures are not consistent with a dynamically induced phenomenon with a healing of defects in the VL. This has to be brought close to the simple fact that the mean dc response of the sample is strongly non-Ohmic and the critical current does not disappear at high drive. The system keeps the memory of its pinned configuration, i.e., the pinning force does not disappear with the increase of the velocity. Even in motion, the VL still interacts with the pinning sites: the critical current remains and noise is generated. As a result, vortex noise can be fundamentally decomposed into a static part (the "memory" of the system) and possibly a dynamical part which expresses the dependence of the interactions on the mean velocity of the lattice. But as no velocity dependence is observed here, both velocity fluctuation components originate from fluctuations of the pinning force which are not influenced by the mean velocity of the lattice.

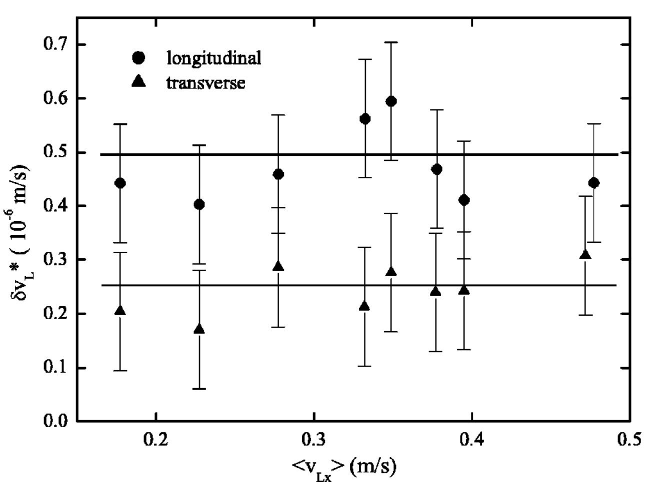

FIG. 4. Velocity fluctuations in the longitudinal (•) and transverse (▲) directions plotted against the mean velocity of the lattice $\langle v_{Lx}\rangle$ (T=4.2 K, B=0.1 T). This range of velocities corresponds to the flux-flow regime. Dotted lines are guides for the eyes.

C. Static noise versus dynamical noise

The question of the origin of both transverse and velocity fluctuations is thus linked to the very nature of the pinning. We recall that in Pb-In the pinning properties are dominated by the (quite standard) surface roughness.[4] A consistent noise model has been proposed and the surface origin of the fluctuations evidenced.[9] While in motion, the VL experiments the roughness of the surface and, consequently, the boundary conditions are modified in time and space. The VL explores randomly the different metastable pinning configurations, and the critical current (or surface current) fluctuates locally and temporarily, in absolute value and in direction. Such surface current fluctuations are compensated by opposite bulk current fluctuations in order to keep constant the total transport current inside the sample. Velocity fluctuations are then generated along with the noisy component of the driving force. Besides, the noisy bulk current induces a (possibly substantial) magnetic-field noise on behalf of Maxwell law. The surface current fluctuations behave like a noise generator of vortex velocity and density. As a consequence, $\delta v_{Lx,y}$ and

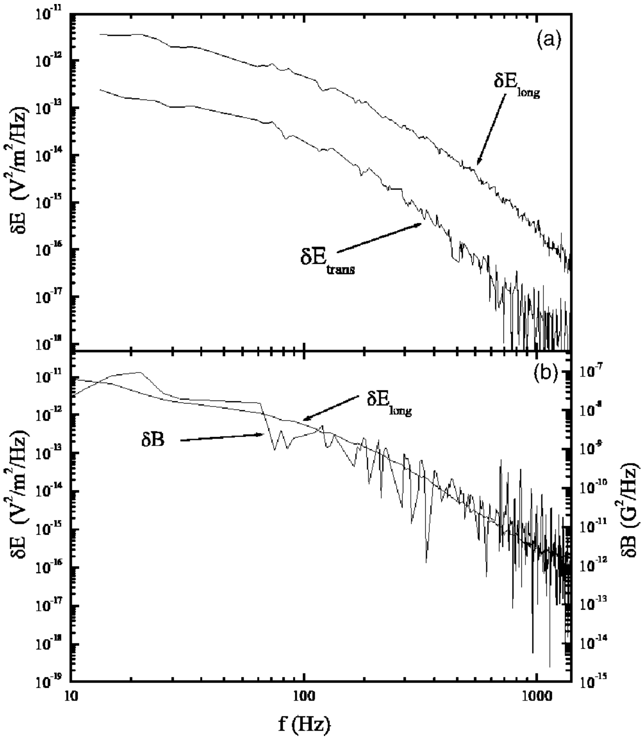

FIG. 5. Up: Longitudinal and transverse electric fields noise spectra. Down: Longitudinal electric-field noise and magnetic-field noise spectra. Both are taken in flux flow (B=0.23 T, T=4.2 K, I=6.9 A). Note the similarity of the shape for all the spectra.

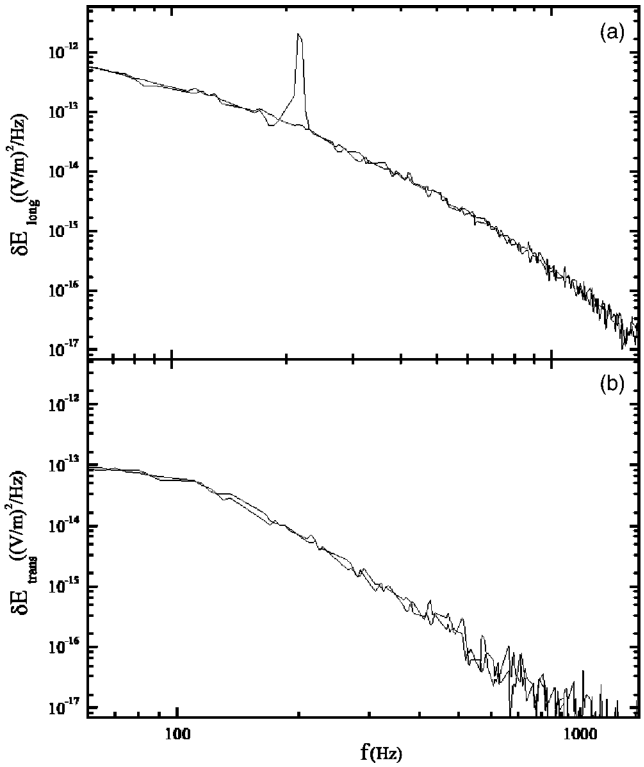

FIG. 6. (a) Flux-flow longitudinal noise with and without a superposing ac component. (b) The corresponding transverse noise, no ac component is observed and the noise is fully preserved.

δB_z have the same spectra.[9] This prediction is verified in our sample (Fig. 5).

From a quantitative point of view, it is also predicted that the amount of noise is determined by the correlation length C of the surface supercurrent. More precisely, with $\delta V_L = R_{FF}\delta I_c/dB$, and in the simplest case of 2D homogeneous and stationary fluctuations, one can write $\delta I_c \approx I_c\sqrt{C_x C_y/S}$ with S being the surface of the sample limited by the voltage pads and $C_{x,y}$ the correlation length. $C_{x,y}$ is the unique adjustable parameter. We verified the stability of the fluctuations by measuring the second-order spectrum $S^{(2)}(f_2)$, the spectrum of noise spectra.[20] The voltage signal was acquired during a very long time, (about an hour) then segmented, and finally each segment was Fourier-transformed. Time series of noise power was taken for different ranges of frequencies (a few hertz wide), and Fourier-transformed over a 2 mHz–1 Hz spectral bandwidth. We observe essentially a white spectral density, confirming the stability of the process. We obtain $\sqrt{C_x C_y} \approx 4-0.5$ μm for applied field ranging from $0.23H_{c2}$ to $0.93H_{c2}$. This range of values is realistic since it lies between the intervortex distance and the sample size. The order of magnitude of the size of the correlation length is also in very good agreement with the values found in Ref. 9 at lower temperature. As we measure here the two components of the velocity fluctuations, we find one has access to the vectorial form of the fluctuators. With a two-dimensional form for the spatial correlation length and using the experimental result $\delta v_{Ly}/\delta v_{Lx} = 0.5 \pm 0.1$, one finds that $C_x = 1(\pm 0.3)C_y$. The correlated domain of the surface current is finally found isotropic, what fits well with the idea that the surface is randomly explored and offers equivalent boundary conditions in all direction.

It appears that the transverse and low-frequency broadband noise (BBN) can be understood as a part of a global noise mechanism driven by a noisy surface current. It remains that the bulk of the sample is obviously not free from defects. As soon as the current penetrates the bulk, i.e., for $I > I_c$, the VL flow can interact with bulk defects. The reason why dynamically induced phenomena such as disorder averaged by the velocity, typical of a bulk process, are not observed has to be discussed. One can propose that the surface driven noise intensity strongly dominates a possible bulk driven noise, or that bulk signatures are at much higher frequencies (about megahertz for Washboard-like signature under similar experimental situations). To go deeper inside this question, one can superimpose low-frequency bulk perturbations in order to see if the noise is influenced. This experimental configuration originally comes from a technical hitch. Car batteries and connections turned out to require long thermalization time before being completely noise-free. Otherwise, one observes an excess of current noise ΔI in the longitudinal spectrum, which is simply due to the linear superposition of this noisy supply current ΔI on the noisy current due to the vortices. It is striking to realize that no trace of this spurious noise is observed in the transverse spectrum. This experiment shows that superimposing a noisy Lorentz force on the motion does not change the underlying velocity fluctuations. Furthermore, we applied a controlled sinusoidal force to the VL in flux flow. The ac current applied is denoted $i_{ac}\,sin(2\pi f_d t)$ with i_{ac} such as $v_{ac} = R_{FF} i_{ac}$ is of the order of magnitude of the voltage noise at the frequency f_d. Low-frequency values ($f < 2017$ Hz) are employed to avoid skin effect in order to be sure to perturb the bulk of the sample. Figure 6 represents an example of the longitudinal and transverse velocity spectra with and without a low-frequency sinusoidal component. For $i_{ac} > 0$, all the low-frequency BBN is preserved and v_{ac} is *entirely* dissipated in the y direction. The ac contribution to the velocity fluctuations simply stacks linearly to the noise regime but the broadband spectra are nonsensitive to this bulk perturbation. The bulk response of the sample is thus decoupled from the "static" and apparently robust noise regime. Compared to the surface, the bulk seems to be a quiet host for the VL as far as low-frequency BBN in flux flow is involved.

III. CONCLUSION

In conclusion, we have investigated the longitudinal and transverse components of the electric-field noise generated by a moving vortex lattice in a low-T_c sample. The transverse component was shown to contain only velocity fluctuations, whereas the longitudinal one contains also the noisy magnetic-field contribution and depends on the mean vortex velocity. The velocity fluctuations do not show any averaging effect in both directions when increasing the lattice velocity far inside the flux flow regime. In addition, they are not affected by a noisy bulk force or by a small ac bulk perturbation. This agrees with fluctuations originating from the surface and shows the small sensitivity of these fluctuations to bulk perturbations. A quantitative analysis provides a picture of isotropic noisy superficial current, in agreement with the model proposed in Ref. 9. We notice also that the study of the fluctuations perpendicular to the motion seems to be particularly appropriate to probe the intrinsic fluctuations sources in superconductors (and possibly other dynamical systems).

ACKNOWLEDGMENTS

We wish to acknowledge Bernard Plaçais (ENS Paris, France) for his advices during the adjustment of this experiment. This experiment was supported by "la région basse Normandie."

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