Oscillatory dynamics and organization of the vortex solid in YBa$_2$Cu$_3$O$_7$ single crystals

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We report on the degree of order of the vortex solid in YBa$_2$Cu$_3$O$_7$ single crystals observed in ac susceptibility measurements. We show that when vortices are “shaken” by a temporarily symmetric ac field they are driven into an easy-to-move, ordered structure but, on the contrary, when the ac field is temporarily asymmetric, they are driven into a more pinned disordered state. This is characteristic of tearing of the vortex lattice and shows that ordering due to symmetric ac fields is essentially different from an equilibration process or a dynamical crystallization that is expected to occur at high driving currents.

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Vortex lattices (VL) in type II superconductors provide a unique system with tuneable parameters for exploring driven dynamic phases. A characteristic feature of driven dynamics in quenched disorder is the existence of a depinning transition. Experimental [1] and theoretical [2] results have shown evidence of a two-step process in the depinning transition of the VL as the driving force is increased: first it undergoes plastic flow, where neighboring parts of it move at different velocities, and then, above a threshold force $F_T$, a dynamic crystallization occurs as proposed by Koshelev and Vinokur [3] (K-V) where all the vortices move at the same average velocity $\bar{v}$. With the use of fast current ramps and ac techniques [4], the attention has been focused on the evolution of the VL as it depins and starts moving. Though the idea of this annealing process is accepted in steady driven VL’s, a number of new puzzling phenomena were observed with these techniques that cannot be ascribed to it such as complex history dependent dynamic response and memory effects [4, 5]. To explain these phenomena, it has been proposed [6] that the overall vortex structure surges as a balance between the injection of disordered vortices through surface barriers and an annealing by the driving current. However, this seems not to be the case in the high $T_c$ twinned YBa$_2$Cu$_3$O$_7$ (YBCO) single crystals, where similar effects have been observed, but only bulk pinning appears to be relevant [6]. In the latter investigation, it was found that an “easy- to-move” more ordered VL can be stabilized by the shaking movement induced by a temporarily symmetric ac field (e.g. sinusoidal). Very recently, it has been suggested that this reordering may be a consequence of a current-assisted transition from a supercooled metastable phase to the stable equilibrium phase [7]. The fluctuation energy produced in the sample under cyclic field variation would be a key element within this scenario [8].

In this Letter, we show that if the shaking field is temporarily asymmetric (e.g. sawtooth) a disordered VL can be recovered. The “hard-to-move” state so obtained would have a high density of topological defects due to the plastic flow of vortex bundles sliding one past another. The fact that the degree of order is strongly dependent on the temporal symmetry of the ac field would indicate that the reordering observed in Ref. [6] is due neither to a K-V transition nor to a current-assisted equilibration but to a process of a fundamentally different kind which involves repeated interaction of neighboring vortices.

We also propose that when the VL is pushed in and out of the sample with an asymmetric ac field, it is torn up in a “ratchet-like” fashion as a consequence of the different Lorentz forces involved in the ramp up and ramp down of the field. Important related results show that these plastic distortions are partly reversible when the temporal evolution of the ac field is reversed.

The results shown here are for a single crystal sample of YBCO [9] (dimensions $0.56 \times 0.6 \times 0.02$ mm$^3$) with $T_c = 92$ K and $\delta T_c = 0.3$ K determined by ac susceptibility ($h_{ac}=1$ Oe) at zero dc field. The same sample was used in previous studies on plasticity and memory effects [8]. Measurements were done with the standard mutual inductance technique, with the ac field parallel to the $c$ axis of the sample. The in-phase and out-of-phase (90°) signals were collected with a lock-in amplifier. Data were recorded for an angle $\theta = 20^\circ$ between the dc applied field, $H_{dc}$, and the $c$ axis to avoid the Bose-glass phase. The dc field was oriented out of all twin boundaries simultaneously (see inset in Fig. 1).

Fig. 1 presents ac susceptibility measurements that correspond to different thermomagnetic histories of the sample. Measurements were performed by varying $T$ (in the direction indicated by the arrows) at a rate of 0.2 K/min, at fixed $H_{dc}$ (3 kOe), $h_{ac}$ (1.6 Oe) and frequency (10.22 kHz) (default parameters). Dashed curves were obtained in the usual field cooled procedure ($F_{ac}C C$) while solid ones were obtained on warming after zero (ac and dc) field cooling (ZFC W) (the ac field is turned on after the dc field has reached its final value $\bar{h}_{ac}$). We believe that the ZFC W case corresponds to a disordered state because of the plastic motion of vortices as they penetrate into the sample. In addition, in the $F_{ac}C C$ case, the VL is partially annealed by the shaking move-
ment induced by the ac field during the cooling process \[1\]. As discussed previously \[3\], the history effects are observed because of a change in the mobility of the VL and the fact that the inner disordered state in the ZFC W case can sustain a higher current without vortex movement thereby enhancing the shielding \(|\chi'|\) and reducing the dissipation \(\chi''\) (for small measuring ac fields).

Through the \(F_{\text{ac}}C\) procedure one can obtain the most ordered state attainable with the measuring ac field. However, a more ordered VL can be obtained if the VL is shaken more intensely with a higher ac field. To illustrate this, we prepared a \(F_{\text{ac}}C\) state at 85.2 K (point A) and applied for a short time (ten seconds) a triangular ac field with \(h_{\text{ac}} = 6.5\) Oe and \(f = 10\) kHz. We turned the 6.5 Oe ac field off and measured the ac susceptibility. The result is indicated as point C in the lower curves of Fig. 1(a) and (b), where it is clearly seen that \(|\chi'|\) increases and \(\chi''\) decreases. On further warming, we found that the measured susceptibility (solid circles) goes close to the \textit{disordered} ZFC W curve. The difference in the response after the application of a symmetric or an asymmetric ac field is striking. The sawtooth ac field has brought the VL to a more pinned disordered state. It is worth noting here that one can go from point C to point B, or vice versa, by properly applying a high amplitude symmetric or asymmetric ac field as explained above.

Fig. 2(a) shows the dynamics of the VL’s ordering. Starting from a disordered hard-to-move state, the sample is cycled with a symmetrical (sinusoidal, triangular or square) ac field (\(h_{\text{ac}} = 6.5\) Oe, \(f = 10\) kHz). After \(N_a\) cycles, the ac field is turned off and the state of the VL is inspected by measuring \(\chi_{\text{ac}}\) with a smaller probe ac field (default parameters above). Before repeating the procedure for a new value of \(N_a\), the VL is brought again to the initial disordered state. It is seen that the dependence of \(\chi_{\text{ac}}\) on \(N_a\) is approximately logarithmic, and saturation, if any, occurs beyond 10\(^6\) cycles.

The evolution of the disordering was inspected in a similar experiment at the same temperature. In Fig. 2(b) we show \(\chi_{\text{ac}}\) as a function of \(N_a\) asymmetric ac field cycles applied to an initially easy-to-move ordered lattice. The asymmetry of the waveform is defined as \(\alpha = (t_+/t_-)\). In all cases, the preparation of the initial ordered state before the application of the next \(N_a\) asymmetric ac field cycles erases any eventual effects of the small ac probe used in the \(\chi_{\text{ac}}\) measurement.

Ordering due to the application of a driven current or an oscillatory perturbation has been frequently observed and proposed to explain some unusual behaviors \[4–8\]. Some of these results have been interpreted as an equilibration process \[7,8\] or as a combined effect of the injection of disordered vortices through the sample edges and

![Figure 1](image-url)
a crystallization assisted by the driving current \[3\]. In the former case, it has been proposed \[8\] that metastable to stable transformations occur in the regions of the sample where the local energy dissipation exceeds a threshold value.

In our experiments, it is clear that an asymmetric ac field will also produce an oscillatory perturbation; but then it is legitimate to inquire into why the VL disorders. The discrepancy that this implies suggests that the ordering process is unlikely to be a K-V crystallization and that it is surely not an equilibration transition where energy dissipation in the sample will always tend to order the VL \[3\].

In the K-V scenario \[2\], ordering is only achieved when the Lorentz force exceeds a certain threshold value, \(F_T\), while a plastic disordered motion occurs for forces below it. The induced current density in our experiments depends directly on the sweep rate of the applied ac field which, on the other hand, is proportional to its frequency. Dynamical reordering is observable, at least, for frequencies in the range of 0.1 Hz to 300 kHz for sinusoidal, triangular and even for the high sweep rate square waveform. Disordering shown in Fig. 2(b) is clearly discernible for a frequency (10 kHz) well within the range of frequencies in which ordering is achieved and for asymmetries as small as 3. This observation would indicate that for equal values of current density circulating in the sample one can either order or disorder the VL depending only on the asymmetry of the ac field and that, remarkably, ordering can be achieved with lower current densities (e.g., at 0.1 Hz) than those that are able to disorder the VL as shown in Fig. 2(b). On account of this, the K-V transition can be discarded as a possible explanation of our observations. In addition, the dynamically generated disorder with the asymmetric ac field is distinctive of tearing of the VL, which suggests that the driving force is below \(F_T\) and that the flow of vortices is plastic (first step in the depinning process \[2\,3\]). In these conditions, there are regions of the VL where the strain is large enough to cause phase slips and the number of vortices that participate in the movement strongly depends on the magnitude of the applied force, \(i.e\)., on the induced current.

If the ac field is asymmetric, the vortices that move when the field is ramped up will not be the same ones that move when the field is ramped down. Then, after the application of one cycle of an asymmetric ac field, there should be a net displacement between vicinal bundles of vortices. This type of movement will cause lattice distortions that destroys the long range order of the VL and leads to the increase of \(|\chi'|\) and the decrease of \(\chi''\) for small ac fields. Note that these distortions are cumulative and increase with the number of cycles leading to a rapid saturation of \(\chi_{ac}\) after \(\sim 300\) cycles for the sawtooth waveform. When \(\alpha\) is decreased, the disorder also decreases and the number of cycles needed to reach maximum disorder increases.

Recovering an ordered VL requires a larger number of cycles of a symmetric ac field of the same amplitude. As seen in Fig. 2(a), after \(10^6\) cycles \(\chi'\) and \(\chi''\) still vary approximately as \(\ln N\). It is the overall symmetry of the ac field that drives vortices back and forth, with no net displacement between them. The effect of this shaking movement of vortices is to locally order the VL. Apparently, repeated interactions of vortices with their nearest neighbors seems to enhance ordering and favor the healing of defects.

A curious behavior is observed when \(\alpha\) is reduced: the change in \(\chi''\) is non-monotonous in the number of cycles. This is more clearly seen for the smaller asymmetries. Initially, \(\chi''\) rapidly decreases but after \(~10^4\) cycles this tendency is reversed and \(\chi''\) slowly starts to increase. This phenomenon could be explained through a process involving dynamic and static friction. The argument could be as follows. At the beginning, the VL disorders as described above as a consequence of the asymmetry of the ac field. However, as \(\alpha\) is small, the bundles of vortices that \(just\) start moving when subjected to the larger Lorentz force (higher field sweep rate), were at the static limit in the preceding part of the field cycle (lower field sweep rate). Once they move, it is established a new steady state determined by dynamic friction (which presumably is smaller than the static one) in which these bundles of vortices move coherently with the rest. If this picture is correct, it would take about \(~10^4\) cycles to reach a steady state in which vortices move coherently and the repeated interaction between them, that allows ordering, dominates in what \(\chi_{ac}\) is concerned.

Finally, we address the question whether the distortions produced by the asymmetric ac field can be released.
if we make a temporal inversion of the ac field. If vortex movement were completely reversible and we applied $N_+$ cycles of an asymmetric ac field, we would recover the initial configuration of the VL after applying the same number of cycles of an asymmetric ac field with the polarity inverted. The results in Fig. 3 suggest that a more ordered configuration can be recovered whenever the distortions generated are below certain level. As shown in the inset of Fig. 3, we first apply a given number of cycles, $N_+$, of sawtooth ac field to an initially ordered VL. As in Fig. 2, $\chi''$ decreases as $N_+$ increases. After $N_{+\text{max}}$ cycles, we invert the polarity of the ac field so that the next cycles represent a “temporal inversion” of the previously applied ac field. At this point it is observed that $\chi''$ starts increasing and, when the number of cycles of the inverted waveform, $N_-$, exceeds $N_{+\text{max}}$, $\chi''$ decreases again. We have followed this procedure for $N_{+\text{max}} = 5, 10, 20, 40$ and 256. When $N_{+\text{max}}$ is high enough to highly distort the VL and saturation of $\chi''$ is reached ($N_{+\text{max}} = 256$) almost no reversibility is observed. These results further support the scenario proposed of ratchet-like tearing of the VL by a temporarily asymmetric ac field.

To conclude, we have presented susceptibility measurements in a twinned YBCO single crystal after shaking the VL with an ac field. We find a dramatic change of the VL response when the asymmetry of the shaking ac field is increased. While a symmetric ac field orders the VL an asymmetric ac field produces the opposite effect. The experiments described demonstrate that ordering is not due to a K-V transition or to an equilibration process. The ordering of the VL appears to be a consequence of the repeated interaction of neighboring vortices while the disorder produced by an asymmetric ac field would be related to tearing caused by the different Lorentz forces involved in the ramp up and down of the ac field. We hope these results will stimulate both experimental and theoretical work on the dynamics of VL’s under an oscillatory perturbation to further test the hypotheses presented here.

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[11] Note that the $Z\chi_c \omega^2$ measurements (that result after cooling the sample in a dc field) are close to the ZFC $\chi_c$ values. See Ref. 5. For a discussion on the degree of order of these states see A.V. Pan and P. Esquinazi, EPJdirect B 3, 1 (2000).

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