Competition between dynamic ordering and disordering for vortices driven by superimposed ac and dc forces

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Abstract
When a small periodic shear is applied to randomly distributed vortices, they progressively transform into an organized configuration, which is called random organization or dynamic ordering. By contrast, when the vortices with a moderately organized configuration are driven by a small dc force over a random substrate, they are gradually pinned by random pinning sites and finally reach disordered plastic flow, which is indicative of dynamic pinning or dynamic disordering. From the time-dependent voltage (i.e. average velocity), we find that random organization caused by the ac drive is suppressed with an increase in the dc drive superimposed with the ac one, and finally vanishes as the dc voltage becomes equal to the amplitude of the ac voltage in the steady state, where the vortices move in the forward direction only. The steady-state vortex configuration formed with the superimposed ac and dc drives is, in general, not uniform microscopically but comprises organized and disordered regions.

1. Introduction
It has been shown experimentally as well as numerically in colloidal suspensions that when randomly distributed many particles are periodically sheared, they self-organize to avoid further collisions, thus transforming into an organized configuration. Associated with this dynamic-ordering or random-organization phenomenon, a novel non-equilibrium transition, termed a reversible-irreversible transition (RIT), has been revealed with increasing the displacement of ac shear [1–3]. We have shown [4] that RIT is also observed in periodically sheared superconducting vortices [5], although there is some difference between the two systems. The colloidal system [1–3, 6, 7] is a three-dimensional and dilute system, whereas the vortex system is a 2D and more strongly interacting system. For the vortex system in amorphous (α-)
Mo6Ge1−x films studied in this work, the length scales characterizing the vortex core and vortex-vortex interaction are of order of ≈ 1 × 10 nm and 102 nm, respectively, which correspond to the superconducting coherence length and London penetration length. Thus, the collisions between the vortices do not occur directly, which is contrasted with the case of the colloidal system. It is a nontrivial and interesting issue why the critical behavior of RIT reported in the colloidal suspensions [1], where a long-range interaction is absent, is observed experimentally in a vortex system, where the long-range electrodynamic fields are important, as shown theoretically [8, 9]. The mean spacing between the vortices can be readily controlled by changing the strength of applied magnetic field B, which is of the order of the core size ≈5 × 10 nm for B ~ 1 T. The results from the vortex system are compared with those from more strongly interacting systems, such as dense, amorphous solid [10]/jamming systems [11–16], and from more dilute colloidal systems [1–3, 6, 7], which undergo random organization or also RIT.

In our earlier work demonstrating RIT in the vortex system, we firstly investigated superconducting films with the Corbino-disk (CD) contact geometry [17–20]. In CD, the vortices are rotated periodically around the CD center without crossing the sample edges by feeling a global shear inversely proportional to the radius of rotation [4, 21]. We also demonstrated the occurrence of RIT [22] in conventional strip-shaped films of...
$a$-Mo$_x$Ge$_{1-x}$ with moderate pinning that yields local shear [5], instead of the global shear, consistent with the theoretical prediction [5]. It has been known experimentally [18, 20] and theoretically [9] that for the conventional crystal samples with edges, vortices entering through the sample edges would seriously influence the vortex dynamics. We have confirmed, however, that this so-called edge-contamination effect in the vortex dynamics is negligibly small in the film samples [23], such as those studied in our work.

Although we have shown that RIT is ubiquitous in many-particle systems subjected to periodic shear, the nature of random organization remains elusive. For the vortex system, a similar phenomenon related to random organization may be the vortex shaking effect (e.g. the acceleration of current relaxation in the vortex state caused by ac field), which has been found experimentally [24–26] and explained theoretically [27–29]. To examine how random organization proceeds with increasing the number of shear cycles $n$, we have recently performed [30] two-step measurements [6, 7] for the vortex system in the strip-shaped $a$-Mo$_x$Ge$_{1-x}$ film [5, 22]. In the first experiment, which we name an ‘input’ experiment, a highly disordered initial vortex configuration [31] was subjected to ac shear with a small displacement $d_{\text{inp}}$ just above the critical one $d_c$ for RIT. Applying the periodic shear for $n$ cycles, we froze the distribution of vortices by abruptly turning off the current that drove the vortices [31–34]. When $n$ is large enough ($n \to \infty$), the system relaxed toward the irreversible-flow state in the vicinity of the reversible one, namely, the frozen configuration was relatively organized. In the second ‘readout’ experiment that follows, the thus prepared frozen configuration in the input experiment was periodically sheared by ac drive with various displacements $d$, and the time-dependent voltage $V(t)$ induced by vortex motion was measured. Our results showed that the information of input $d_{\text{inp}}$ was imprinted inside the input vortex configuration not only in the final steady state ($n \to \infty$) but also in the transient one ($0 < n < \infty$), and it is readable. From the analysis of readout $V(t)$, it was found that the transient configuration of vortices created during the random-organization process is not uniform, at least in microscopic scale, but comprises organized and disordered regions (DRs) [30].

Meanwhile, it is well known that when the vortices or many particles with relatively organized configurations are driven over a random substrate by a small dc force slightly larger than the depinning one, they are gradually pinned by random pinning sites. This is detected from the decrease in the mean velocity to a steady-state value, which is indicative of dynamic pinning or dynamic disordered [31]. The finally reached steady state is pinning-dominated disordered flow called plastic flow. We have demonstrated in earlier work that the transient dynamics of vortices associated with dynamic disordering exhibits a critical behavior of the nonequilibrium depinning transition, which would fall into the class of RIT and the absorbing transition [5, 35–43], consistent with the theoretical prediction [5, 42, 44].

Then, interesting questions arise as to how random organization due to the ac drive is suppressed by superimposing the dc drive, and what configuration such vortex assemblies should take finally. To answer the fundamental and non-trivial questions, here we have performed two-step measurements of $V(t)$ similar to those as mentioned above [30]. In the first input experiment, a highly disordered initial vortex assembly was sheared by an ac current $I_{\text{ac}}$ with a square waveform that yields a small displacement $d_{\text{inp}}$ and voltage amplitude $V_{\text{ac}}$ at $t \to \infty$. The transient voltage, $[V(t)]$, induced by vortex motion shows a gradual increase and saturation to the final state $[V(t \to \infty)](\equiv V_{\infty})$, implying the occurrence of random organization or dynamic ordering. We repeated the measurement using the same input ac drive, but with the superimposed dc current of various amplitudes. As far as the dc voltage at $t \to \infty$, $V_{\text{dc}}$, is smaller than $V_{\infty}$, $V(t) - V_{\text{dc}}$ shows qualitatively the same behavior as that for $V_{\text{dc}} = 0$, although the relaxation behavior of $[V(t) - V_{\text{dc}}]$ to the steady state becomes less pronounced for larger $V_{\text{dc}}$. As $V_{\text{dc}}$ is increased and becomes equal to $V_{\infty}$, the relaxation of $[V(t) - V_{\text{dc}}]$ is no longer visible, indicative of the disappearance of random organization.

The vortex motion with respect to the random pinning centers is different depending on whether $V_{\text{dc}}$ is smaller than $V_{\infty}$ or not. In the case where $V_{\text{dc}}$ is equal to or larger than $V_{\infty}$, no vortices retrace the path they just traveled, but they move in the forward direction only. Thus, the present result implies that for random organization to occur by ac drive, return motion with respect to the random pinning centers is indispensable.

To obtain the information on the final vortex configuration in the input experiment, we froze the configuration of vortices by abruptly turning off the input driving currents in the steady state, and then carried out the readout measurement of $V(t)$ generated responding to periodic shear with different displacements $d$. What is striking is that the final ($t \to \infty$) input vortex configuration formed with the superimposed ac and dc drives satisfying $0 < V_{\text{dc}} < V_{\infty}$ is not uniform microscopically but comprises two regions. One is the DR characterized by plastic flow due to the small dc drive and the other is the organized region (OR) characterized by the ac drive with small $d_{\text{inp}}$ of $n \to \infty$. With increasing $V_{\text{dc}}$, the ratio of OR to the total sample area, $\alpha$, shows a monotonous decrease from unity and eventually falls to zero at $V_{\text{dc}} = V_{\infty}$, where random organization disappears.
2. Experimental

We fabricated a 0.33 μm thick film of $\alpha$-Mo$_2$Ge$_{1-x}$ by RF sputtering onto a Si substrate using our ultra-high vacuum chamber, where the substrate was mounted on a water cooled Cu stage that rotates at 240 rpm [4, 21–23, 30, 31, 45]. The zero-resistivity transition temperature at zero magnetic field ($B = 0$) is about 6.3 K. The field $B$ was directed normal to the film surface. By applying transport currents, the vortices move in the direction along the sample width of 0.3 mm. The voltage $V$ induced by vortex motion was measured with voltage contacts separated at $l = 1.2$ mm. The resistivity was measured in the ohmic regime using a standard four-probe method. The time-dependent voltage $V(t)$ immediately after applying the dc current $I$ and/or the ac current $I_{ac}$ of square waveform was measured by means of an FFT spectrum analyzer with a resolution of 40 kHz [4, 21–23, 45]. We adjusted the amplitudes of $I$ and $I_{ac}$ to yield the dc voltage $V_{dc}$ and ac voltage $V^{\infty}$ with desired amplitudes at $t \to \infty$, respectively. The sample was directly immersed into the liquid $^4$He.

3. Results and discussion

To realize random organization, it is favorable to prepare the highly disordered initial vortex configuration. Thus, all the data in this work were acquired in the so-called peak-effect regime [46–52] at 3.5 T and 4.1 K, where the pinning is very effective [4, 23]. From the field value of 3.5 T, the mean intervortex spacing is estimated to be 26 nm. The vortices were driven periodically by the ac current $I_{ac}$ with amplitude giving rise to the ac voltage with a fixed amplitude of $V^{\infty} \approx 50 \mu V$ at $t \to \infty$. Our dc–$V$ data show that dc vortex flow below about $V \sim 1$ mV corresponds to disordered plastic flow dominated by pinning [23]. We changed the displacement $d$ for the ac-driven vortex motion in the range $1–5 \mu m$ by changing a frequency $f$ of $I_{ac}$ in the range $1200–6000$ Hz, where $d$ is given from the simple relation $d = V^{\infty}/(2fB)$. To realize larger $d$ for fixed $V^{\infty}$, $f$ must be set to a smaller value. This also implies that we must use slightly larger ac drive $|I_{ac}|$, because at fixed $|I_{ac}|$, the ac voltage $|V^{\infty}|$ shows a trend to decrease with lowering [33, 53].

We perform the two-step experiments. First, in the input experiment, we prepared the highly disordered vortex configuration by applying small $I$ that yields $V_{dc} = 100 \mu V$ at $t \to \infty$, corresponding to plastic flow [31]. After the vortex configuration of the plastic flow was frozen by turning off $I$, the vortices were then driven periodically by square $I_{ac}$ that was applied at $t = 0$, and time-dependent $V(t)$ induced by vortex motion was measured. The displacement was kept to be $d_{inp} = 1 \mu m$, which was immediately above $d_c \approx 0.1 \mu m$ of RIT [30], and $V^{\infty}$ was fixed to be 50 $\mu m$. After many cycles of the ac drive ($n \geq 10^4$ cycles), the system reached the steady state, which corresponds to the irreversible-flow state in the vicinity of the reversible-flow state, i.e. corresponding to nearly the organized configuration.

The red line in figure 1(a) represents the data of the voltage response $V(t)$. It is noted that the height of the first voltage pulse, $V_{in}$, is much smaller than $V^{\infty}$ and that $|V(t)|$ increases monotonically with $t$ or cycle numbers $n$, relaxing to the steady-state voltage $V^{\infty}$. $|V(t)|$ is reproduced by a relaxation function [4, 30] using a single relaxation time $\tau$:

$$\quad |V(t)| = V^{\infty} - (V^{\infty} - V_0)\exp(-t/\tau).$$

(1)

Shown with the dotted line in figure 1(a) is the result of the best fit of $|V(t)|$ to equation (1). The substantially smaller value of $V_0$ than $V^{\infty}$ at $t \approx 0$ implies that the vortices are hard to move initially, reflecting the fact that the initial flow state corresponds to a disordered flow dominated by pinning. A periodical shearing force helps rearrange the configuration of vortices to avoid next collisions and the vortices become more mobile with $n$, relaxing to the steady-state voltage $V^{\infty}$. $|V(t)|$ is reproduced by a relaxation function [4, 30] using a single relaxation time $\tau$:

$$\quad |V(t)| = V^{\infty} - (V^{\infty} - V_0)\exp(-t/\tau).$$

(1)

We repeated the measurement using the same input ac drive yielding $V^{\infty} = 50 \mu V$ and $d_{inp} = 1 \mu m$, but with superimposed dc drive giving rise to dc voltage $V_{dc}$ of various amplitudes. Shown with the orange line in figure 1(a) is $V(t)$ generated in response to $V_{dc} = 10 \mu V$ superimposed with the ac drive (with $V^{\infty} = 50 \mu V$ and $d_{inp} = 1 \mu m$). In order to see only the ac component of the voltage, the voltage subtracting $V_{dc}$, $V(t) - V_{dc}$, is displayed in figure 1(b) with the same color as in figure 1(a). The amplitude of this voltage signal again exhibits a gradual increase and relaxation to $V^{\infty}$. Note, however, that with an increase in $V_{dc}$, $V_0$ increases and the relaxation time decreases. In figures 1(a) and (b), the results for $V_{dc} = 20$, 30, and 40 $\mu V$ are shown with the green, blue, and purple lines, respectively. The dotted lines in figures 1(a) and (b) denote the results of the fits of $|V(t)|$ using equation (1). In figure 1(b) the asymptotic value of $\pm |V(t) - V_{dc}| = \pm 50 \mu V$ at $t \to \infty$ is indicated by the dashed horizontal lines. As far as $V_{dc} < V^{\infty}$, $V(t) - V_{dc}$ shows qualitatively the same behavior as that for $V_{dc} = 0$ (red line), although the relaxing behavior of $|V(t) - V_{dc}|$ to the steady state becomes less pronounced for larger $V_{dc}$. The faster relaxation indicates the more disordered final steady state, as discussed.
later. As shown with the black line, when \( V_{dc} \) is increased and becomes equal to \( V^\infty \), the relaxation of \( |V(t) - V_{dc}| \) is no longer visible, indicative of the disappearance of random organization.

The vortex motion with respect to the random pinning centers in the sample is different depending on whether \( V_{dc} \), is smaller than \( V^\infty \) or not. Figures 1(c)–(e) schematically illustrate the time evolutions of the vortex position \( x(t) \) for \( V_{dc} = 0, 0 < V_{dc} < V^\infty \), and \( V_{dc} = V^\infty \), respectively. For \( V_{dc} = 0 \), the vortices almost retrace the path they have just traveled and return to the position close to their initial position at the end of each cycle of the ac drive. For \( 0 < V_{dc} < V^\infty \), however, the vortices partially retrace the path they have just traveled and never return to their initial position. In the case where \( V_{dc} \) is equal to (or larger than) \( V^\infty \), no vortices retrace the previous path, even partially, during the periodic motion but they move in the forward direction only. When the vortex configuration is completely frozen in the time duration of each half cycle where \( V(t) = 0 \), the periodic vortex motion is equivalent to the dc flow with \( V_{dc} = 100 \mu V \), which was used to prepare the initial vortex configuration. Therefore, it is reasonable to consider that no relaxation of \( |V(t)| \) is observed for \( V_{dc} = V^\infty \). From these results, we conclude that for random organization to occur by ac drive, return motion with respect to the random pinning centers is indispensable. The present result also implies that one can change the transient vortex dynamics from the state where random organization (dynamic ordering) is dominant to the state where random organization is suppressed by simply increasing the dc drive superimposed on the ac drive.

Next, we focus on the readout experiment, which was carried out to obtain the information on the steady-state vortex configuration in the input experiment. Here, we applied the ac currents with amplitudes and frequencies yielding the fixed \( |V(t)| \) at \( t \to \infty \), \( V^\infty = 50 \mu V \), and different displacements \( d \) ranging from 2 to 5 \( \mu m \). Figure 2 displays the typical data of readout \( V(t) \) for final input configurations prepared with \( V_{dc} = 0 \) (red line), 20 \( \mu V \) (green line), and 50 \( \mu V \) (black line) superimposed with the ac drive with \( V^\infty = 50 \mu V \) and \( d_{inp} = 1 \mu m \). Here, \( V(t) \) is generated responding to ac shear with \( d = 2 \mu m \) slightly above \( d_{inp} = 1 \mu m \). A horizontal dashed line indicates the position of \( |V(t \to \infty)| = 50 \mu V \). For \( V_{dc} = 0 \), the amplitude of the

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**Figure 1.** (a) \( V(t) \) for the highly disordered vortex configuration (prepared with \( V_{dc} = 100 \mu V \)), generated responding to ac drive with fixed \( d_{inp} = 1 \mu m \) and \( V^\infty = 50 \mu V \), but with superimposed dc drive yielding \( V_{dc} \) of various amplitudes at \( t \to \infty \) : \( V_{dc} = 50, 40, 30, 20, 10, \) and 0 \( \mu V \) from top to bottom. Dotted lines represent the fits of \( |V(t)| \) to equation (1). (b) \( V(t) - V_{dc} \) for different \( V_{dc} \) shown with the same color as in (a). The horizontal dashed and full gray lines mark the position for the steady-state voltages of \( \pm |V(t \to \infty) - V_{dc}| = \pm 50 \mu V \) and \( V(t) - V_{dc} = 0 \), respectively. Dotted curves denote the fits of \( |V(t)| \) using equation (1). (c)–(e) Schematic illustration of time evolutions of the vortex position \( x(t) \) for (c) \( V_{dc} = 0 \), (d) \( 0 < V_{dc} < V^\infty \), and (e) \( V_{dc} = V^\infty \).
readout voltage \(|V(t)|\) shows a monotonic decrease and saturation to the steady-state voltage, whereas for \(V_{\text{dc}} = 50 \mu V\), \(|V(t)|\) exhibits a monotonic increase to \(|V(t \to \infty)| = 50 \mu V\).

These results are interpreted as follows. The input configuration prepared with \(V_{\text{dc}} = 0\) (i.e. only ac shear with \(d_{\text{ap}} = 1 \mu m\) is applied) is most organized. The whole sample area is occupied by vortices with configuration formed by ac shear with \(d_{\text{ap}} = 1 \mu m\) for many cycles. In the upper left diagram of figure 2, this organized vortex configuration is schematically drawn in light blue color. Since we know that in the irreversible regime \((d > d_f)\), the ac drive with larger \(d\) creates a less organized final vortex configuration [4, 5], the final configuration formed by \(d = 2 \mu m\) is considered to be less organized than the input one formed by \(d_{\text{ap}} = 1 \mu m\). Actually, the observed decrease in \(|V(t)|\) to \(|V(t \to \infty)| = 50 \mu V\) reflects the fact that the vortices experience more collisions and get less mobile during the readout process. The diagrams of figure 2 schematically depict this dynamic—disordering phenomenon as a change of color from light blue (upper left) to blue (right).

By contrast, an input configuration prepared with superimposed \(V_{\text{dc}} = 50 \mu V\) is most disordered. The whole sample area is occupied by vortices whose configuration at \(t \to \infty\) is characterized by dc plastic flow with 100 \(\mu V\). This is illustrated schematically by dark blue in the lower left diagram of figure 2. The increase of \(|V(t)|\) with \(t\) observed during the readout process is indicative of random organization [4]. After being subjected to the ac drive with \(d = 2 \mu m\) for many cycles, the final vortex configuration becomes organized compared to the initial one [54–57]. This change is drawn schematically by lighter blue in the right diagram than in the lower left one of figure 2. \(|V(t)|\) for the red and black lines in figure 2 can be fitted using a relaxation function with appropriate single relaxation times (not shown here).

The most remarkable finding is the readout signal \(V(t)\) for the input configurations which were prepared with intermediate values of \(V_{\text{dc}}\) between 0 and 50 \(\mu V\) superimposed with the ac drive of \(V_{\text{ac}} = 50 \mu V\) and \(d_{\text{ap}} = 1 \mu m\). The green line in figure 2 typically shows \(V(t)\), which is generated responding to the \(d = 2 \mu m\) ac drive, for the input configuration prepared with superimposed \(V_{\text{dc}} = 20 \mu V\). Clearly, we cannot fit \(|V(t)|\) with a single relaxation time. Instead, it is characterized by an initial fast drop which is followed by a slower increase and saturation to \(|V(t \to \infty)| = 50 \mu V\). We obtain essentially the same results for all values of \(d > d_{\text{ap}}\) studied ranging from 2 to 5 \(\mu m\). It is found that \(V(t)(\equiv V_{20}(t))\) for the input vortex configuration created with superimposed \(V_{\text{dc}} = 20 \mu V\) is reproduced by a superposition of \(V(t)(\equiv V_{30}(t))\) for the input configuration created with superimposed \(V_{\text{dc}} = 0\) and \(V(t)(\equiv V_{50}(t))\) for the input one created with superimposed \(V_{\text{dc}} = 50 \mu V\).

Specifically, \(V_{20}(t)\) can be fitted by a weighted average of \(V_0(t)\) and \(V_{50}(t)\) as:

\[
V_{20}^{in}(t) = \alpha V_0(t) + (1 - \alpha) V_{50}(t)
\]

with a suitable weight parameter \(\alpha\). Here, the best fit \(V_{20}^{in}(t)\) is achieved using \(\alpha = 0.44\), which is shown by the purple line in figure 2. In figure 3, the \(\alpha\) values thus extracted from readout ac drive with different \(d\) in the range 2–5 \(\mu m\) are plotted as a function of \(V_{\text{dc}}\) with different symbols. It is found that for all \(V_{\text{dc}}\) studied, \(\alpha\) measured with different \(d\) covers a limited region about the \(V_{\text{dc}}\)-dependent mean value of \(\alpha(V_{\text{dc}})\). With increasing \(V_{\text{dc}}\), \(\alpha\) decreases monotonically from 1 and falls to zero at \(V_{\text{dc}} = 50 \mu V\).
Based on these results, we suggest that the final vortex configuration created after the input dc drive with $V_{dc}$, satisfying the relation $0 < V_{dc} < 50 \mu V$, superimposed with the ac drive is not uniform microscopically but comprises two regions. One is the most OR created by applying only the $d_{inp} = 1 \mu m$ ac drive for $n \rightarrow \infty$ cycles to the disordered initial vortex configuration. The other is a highly DR characterized by the 100 $\mu V$ dc drive. Therefore, $\alpha$ is interpreted as the area ratio of OR to the whole sample area. The middle left diagram of figure 2 schematically depicts the coexistence of OR and DR. Here, the light and dark blue areas correspond to OR and DR, respectively, and the direction of vortex motion, as indicated by a thin arrow, is parallel to the vertical side of the square. The input vortex configurations formed with $V_{dc} = 0, 0 < V_{dc} < 50 \mu V$, and $V_{dc} = 50 \mu V$ superimposed with ac drive with $V^\infty = 50 \mu V$ and $d_{inp} = 1 \mu m$, together with the evolutions of the vortex position $x(t)$, are illustrated schematically from top to bottom. A darker blue color in the diagrams indicates a more disordered vortex configuration. Light and dark blue regions in the middle diagram schematically represent OR and DR, respectively, where the direction of vortex motion is parallel to the vertical side of the square, as indicated by an arrow. Assuming channel-like flow that fluctuates in time and space, we speculate that OR and DR are stretched along the direction of the driving force.

For the coexistence vortex configuration shown in the middle diagrams of figures 2 and 3, we are unable to specify the shape nor the size of OR (or DR) formed in DR (or OR). However, as concluded in [30], the characteristic size of OR (or DR) is not macroscopic, since the critical behavior associated with RIT is clearly visible. In the present work, we speculate that the shape of OR (or DR) is most likely stretched along the direction of the driving force. Here, we imagine the appearance of channel-like flow that fluctuates in time and space in the plastic flow state [44, 58].

The coexisting configuration of OR and DR found in this work is interpreted in two ways. One is the emergence of DR in OR by superimposing the dc drive on the ac drive; i.e. the degradation of OR induced by the superimposed dc drive or, equivalently, by the suppression of return motion with respect to random pinning centers. The other is the emergence of OR in DR by superimposing the ac drive on the dc drive; i.e. the partial ordering of plastic flow induced by the superimposed ac drive or, equivalently, by the growth of return motion with respect to the random pinning centers. In our previous work, where only the ac drive was applied to the sufficiently disordered initial vortex configuration, the coexisting OR and DR were observed only in the transient state [30]. This is in contrast to the present result, where by applying the superimposed ac and dc drives to the sufficiently disordered configuration, the coexisting OR and DR are observed even in the final steady state.

Finally, we summarize the flow of the input and readout experiments, and how the information of the final vortex configuration in the input experiment is deduced from the readout experiment. Typically shown in figures 4(a)–(c) are $V(t)$’s in the input experiment, where the highly disordered initial vortex assembly formed by dc drive with 100 $\mu V$ is subjected to the dc drive with $V_{dc} = 0, 20$, and 50 $\mu V$, respectively, superimposed with the ac drive with $V^\infty = 50 \mu V$ and $d_{inp} = 1 \mu m$. The inset in each figure schematically illustrates the $t$-dependent vortex position $x(t)$. When the steady state is reached, the distribution of the moving vortices is frozen by turning off the driving currents, which is then subjected to the ac drive with $V^\infty = 50 \mu V$ and $d = 2 \mu m$ in the readout experiment:

(i) As shown in figure 4(g), for the input configuration created with superimposed $V_{dc} = 0$, which yields the most organized configuration in this work, the readout voltage $|V(t)|$ induced by ac-driven vortex motion.
shows a simple decreasing relaxation toward $|V(t \to \infty)| = 50 \, \mu V$ marked by a horizontal dashed line. This data, which is also shown with the red line in figure 2(a), indicates the dynamic disordering from the organized configuration characterized by $d_{\text{inp}} = 1 \, \mu m$, as schematically drawn by light blue color in figure 4(d), to the more disordered one characterized by $d = 2 \, \mu m$ ($>d_{\text{inp}}$).

(ii) Figure 4(h) shows the readout signal $V(t)$ generated responding to $d = 2 \, \mu m$ ac drive for the input configuration created with superimposed $V_{dc} = 20 \, \mu V$. $|V(t)|$ can be fitted to equation (2), $|V_{\text{out}}(t)|$, using a proper value of $\alpha$, but cannot be fitted to a simple relaxation function. The input vortex configuration deduced from $\alpha$ is schematically illustrated in figure 4(e), where OR (DR) coexisting with DR (OR) is indicated by light (dark) blue. We have shown that $\alpha$, which represents the area ratio of OR, decreases monotonically with increasing $V_{dc}$.

(iii) For the input configuration prepared with superimposed $V_{dc} = 50 \, \mu V$, which gives rise to the most disordered configuration corresponding to dc plastic flow with $V_{dc} = 100 \, \mu V$, the readout signal $|V(t)|$
generated responding to $d = 2 \mu m$ ac drive can be fitted by a simple relaxation function, as depicted in figure 4(i). Accordingly, the input vortex assembly recovers to the uniform configuration, which is occupied only by DR, as schematically illustrated by dark blue in figure 4(f).

In the input experiment mentioned above, $V_{dc}$ is superimposed on the ac drive with a symmetric square waveform, where the time duration, as well as the amplitude, of the positive and negative pulses is identical. This yields return motion of vortices with a velocity smaller than that of forward motion for $0 < V_{dc} < V_{\infty}$ and causes translational vortex motion in the forward direction. To support our assertion in this work, we have conducted additional experiments using a different type of input drive. Here, without superimposing dc drive, we apply only ac drive with an asymmetric square waveform where the time duration of the positive pulse, $T_p$, is longer than that of the negative one, while the amplitude of the positive and negative pulses stays identical, as schematically illustrated by $x(t)$ with red color in the middle inset of figure 5. In this case, the velocities $|dx/dt|$ for the forward and return motion are identical, and the net translational vortex motion in the forward direction is caused by the asymmetric time duration ($T_f > T_r$). By systematically changing the ratio of $T_r/T_f$ from 1 to 0, we again find the competition between dynamic ordering and disordering, the coexistence of DR and OR in the steady state, and the monotonic suppression of OR with a decrease in $T_r/T_f$ from 1 to 0. The results are summarized below.

It is clearly seen for the input experiment (not shown here) that a gradual increase in $|V(t)|$ and saturation to $|V(t \to \infty)| = 50 \mu V$ indicative of random organization (or dynamic ordering), which is most pronounced for $T_r/T_f = 1$, is suppressed as $T_r/T_f$ is decreased from 1, and finally vanishes as $T_r/T_f$ approaches 0, where the vortices move only in the forward direction. The results again show that in order for random organization to occur, the return motion of vortices with respect to the random pinning centers is necessary. We have also performed the readout experiment for the frozen steady-state vortex configuration in the input experiment. It is again found (not shown here) that the time evolution of voltages, $V(t) = V_{50/50}(t)$, for the final input configurations created with the ac drive of different values of $T_r/T_f$ (=40/60, 30/70, 20/80, and 10/90) can be fitted by a weighted average of $V_{50/50}(t)$ (for the most organized configuration) and $V_{50/100}(t)$ (for the most disordered configuration) with a weight parameter $\alpha$. Here, we use an equation analogous to equation (2): $V_{50/70}^{fit}(t) = \alpha V_{50/50}(t) + (1 - \alpha) V_{50/100}(t)$.

In figure 5, we plot the area ratio of OR, $\alpha$, deduced from the readout experiment as a function of the ‘return ratio’ of vortex motion defined as $r \equiv x_r/x_f$, where $x_f$ and $x_r$ are the lengths of the forward and return paths per cycle, respectively. Black and red symbols in figure 5 represent the data extracted from figure 3 and from the additional experiment mentioned here, respectively. Symbols with different shape correspond to the ac drive with different $d$ values used in the readout experiment, which are indicated inside the figure. Interestingly, it is found that both data with black and red colors collapse onto nearly a single line, indicating that $\alpha$ is determined only (or mainly) by $r$ and independent of (or insensitive to) the velocity $dx/dt$ at least in the velocity range studied. Although there is no available theory to explain the finding at present, the simple and consistent results,
showing the importance of $r$ as a parameter determining $\alpha$, revealed from the two experiments with a different type of input drive support our view that the experiments using vortices indeed probe the competition between dynamic ordering and disordering.

To obtain stronger evidence for our view mentioned in this work and deeper insight into the phenomena, further experiments, such as exploring direct visualization of the vortex configuration [32, 59], as well as theoretical investigation, may be needed. We believe that the present study will stimulate similar experiments and analysis in other systems where the dynamic ordering and disordering would be observed [10, 16, 41, 48, 60–75].

4. Conclusions

Employing the vortex system with weak random pinning, we study the fundamental, general problems on how random organization caused by the periodic shear is suppressed by superimposing dc drive and what configuration such vortex assemblies should take. To answer the questions, we perform the two-step measurements of $V(t)$ [30]. In the first input measurement, we find that random organization caused by ac drive with small shear $d_{\text{inp}}$ is suppressed with increasing dc drive superimposed on the ac one and finally vanishes as $V_{\text{dc}}$ becomes equal to $V^\infty$, above which the vortices move in the forward direction only. Thus, we conclude that for random organization to occur by ac drive, return motion with respect to the random pinning centers is indispensable. This result also implies that one can change the transient vortex dynamics from the state where random organization is dominant to the state where random organization is suppressed by simply increasing dc drive superimposed on ac drive.

We also find from the subsequent readout measurement of $V(t)$ responding to ac drive with different $d$ that even in the steady state, the vortex configuration created with the superimposed dc and ac drives is, in general, not uniform microscopically but comprises two regions: DR characterized by plastic flow due to dc drive for $t \to \infty$ and OR characterized by ac drive with $d_{\text{inp}}$ for $r \to \infty$. This is in contrast to the behavior of the ac drive only [30], where the coexisting OR and DR appear only in the transient state. With increasing $V_{\text{dc}}$, the area ratio of OR, $\alpha(V_{\text{dc}})$, decreases monotonically from unity and eventually vanishes at $V_{\text{dc}} = V^\infty$, where random organization disappears. We obtain additional data showing that $r = x_r/x_f$, rather than the velocity $d_x/dt$, is an important parameter determining $\alpha$. Finally, the present results also imply that OR emerges dynamically in disordered plastic flow, when the ac drive is superimposed on the dc drive.

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