

Research Article

Magnetic Vortex Dynamics and I-V Characteristics in Type-II Superconductors

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Abstract

We study the dynamics of flux vortices and I-V characteristics of a type-II superconductor in which the flux-pinning centers are randomly distributed with various contents and applied with a transport current and an external magnetic field. When an external magnetic field and transport current are applied to a superconductor, the vortex dynamics inside the superconductor is very complex. This is especially true if the flux-fixing centers are randomly distributed. We have performed simulations by choosing the transport current through the type-II superconductor in which the first vortex motion is observed and the value of the applied external magnetic field. The simulation results of vortex dynamics inside superconductors are analyzed through electric field profiles and E-t curves. We emphasize here that the electric field profile and total energy have a very close relationship. We found that the change in total energy is the most significant at $\omega=0.2$, in terms of the content of the flux-pinning centers distributed inside the superconductor. This indicates that the distribution of flux-pinning centers plays a very large role in the properties of the type-II superconductor. We also found from our study of the I-V characteristics of superconductors that when a superconductor transitions from a superconducting state to a normal conducting state, the I-V characteristics are linearized, especially as the content of the flux-pinning centers increases faster.

Keywords

Time Dependent Ginzburg-Landau Model, Type-II Superconductor, Vortex Dynamics, Pinning Center, Content, I-V Characteristic

1. Introduction

Ginzburg-Landau (GL) theory is the powerful theory to study type-II superconductors [1, 2]. The main idea of the Ginzburg-Landau theory is to treat phase transitions as transitions from ordered to disordered phases.

In last works, they have investigated the several behaviors of type-II superconductors, with regularly distributed pinning

centers or no pinning centers, using GL equations, particularly mixed state and vortex dynamics including penetration and motion of vortices. Also, vortex dynamics in case that External current and magnetic field are applied to the superconductor is studied.

For modeling the external current in ideal superconductors

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without flux pinning centers, a self-consistent boundary conditions within the finite element method are implemented [7]. In ref. [8], they have used typical κ and σ values to demonstrate that polarity vortices are created at opposite two boundaries of the high temperature superconductor, and they pass through the material and are injected to opposite polarity sides when they reach near the center. Machida and Hideo have solved numerically the Time dependent Ginzburg-Landau (TDGL) equations coupled with the Maxwell equations in the 2D region for the type-II superconductors of thin film to obtain the V-I characteristics [9, 10]. They have observed sequent pulses with the time of the measured voltages and showed that these pulses are directly related to the penetrations and annihilations of vortices.

The vortex dynamics of superconductors with pinning centers have been studied. In ref [14], they have studied the dependence of the vortex dynamics on the exit fields and position, number, and size of surface defects for thin circular [3], squared [16], and rectangular [15, 20] superconductors. For specific vortex configurations, they have found that vortices do not enter through the surface defects in the sample by the effect of vortex-defect interaction and the vortex-vortex repulsion. Hardiyanto et al. have determined the density of free energy in the type -II superconductor influenced by an external magnetic field with variation of pinning position as the form of normal state defect [11], and Prawitasari et al. have studied the influence of a defect in the side of squared superconductor in the dynamics of vortex-anti-vortex annihilation and have concluded that the presence of the defects on the superconductor can increase superconductivity of superconductor as well [12]. Dependence of the vortex motion on different shapes and sizes of pinning centers as the form of normal state in the presence of transport current and external magnetic field had studied. The shapes and sizes of pinning centers have a great influence on the vortex motion, which is related to not only the penetration barrier but also the effective path of vortices in superconductors. Oliveira have calculated the vortex configuration and the Gibbs free energy as function of time in the superconductor with a slit [1]. Here, they used COMSOL Multiphysics to apply the finite element method. Their results show stable vortices configurations for several different magnetic field values and temperature values. In ref [5], they have carried out the simulation to compare two superconductors which only nano-rods [21] or only nano-particle [21] pinning centers are distributed.

Oripov et al. have studied the electrodynamics of superconductors influenced by rf magnetic field using TDGL numerical simulations [13]. They have demonstrated the creation of rf vortices semiloops if a surface of superconductor with a single-point defect parallel to a rf magnetic field. The critical current of the type-II superconductors have been determined decisively by relation between the distribution of defects in the material and vortex lines [17, 19, 22, 23]. Also, developed computer algorithm is used for the simulation the TDGL equation and dynamics of vortices in confined

geometries for its application [18].

In this paper, we numerically simulate the flux vortex dynamics in a square type-II superconductor with various contents of the flux-pinning center using Matlab and COMSOL Multiphysics software. The electric field profiles obtained through simulations were also used to analyze the I-V characteristics in the superconductor.

2. Model and Validation

2.1. TDGL Model

The state of superconductor is determined by order parameter Ψ . $|\Psi|^2 = 1$ and $|\Psi|^2 = 0$ appear the superconducting state and normal state, respectively. We use dimensionless TDGL equation to simulate numerically the behaviors in Type-II superconductor. This follows as [24]:

$$\frac{\partial \Psi}{\partial t} = - \left(-\frac{i}{\kappa} \nabla - A \right)^2 \Psi + (1 - T) \Psi [p(r) - |\Psi|^2] \quad (1)$$

$$\sigma \frac{\partial A}{\partial t} = (1 - T) \left[\frac{1}{2i\kappa} (\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) - |\Psi|^2 A \right] - \nabla \times \nabla \times A \quad (2)$$

There, κ is Ginzburg-Landau parameter, T is the ratio of temperature and critical temperature, σ is normal electric conductivity, $\Psi(r, t)$ is order parameter, $A(r, t)$ is vector potential. And $p(r)$ is the function which appear the pinning regions, it is defined as user's random function with Matlab. In this work, we use the zero electric scalar potential gauge.

Here, distance is scaled by λ and time is scaled by ξ^2/D . Here, D is phenomenal absorption coefficient. The transport current is acted with x-direction and the external magnetic field is acted with z-direction. We used the function described in ref [3] and defined the function $p(r)$ in Matlab.

2.2. Boundary Conditions

We used the boundary conditions described in ref [6] to solve Eqs (1) and (2),

$$\left(\frac{i}{\kappa} \nabla + A \right) \Psi \cdot n = 0; \nabla \times A = B_e; -\sigma \frac{\partial A}{\partial t} \cdot n = 0 \quad (3)$$

$$\Psi = 0; \nabla \times A = B_e; -\sigma \frac{\partial A}{\partial t} \cdot n = J_e \cdot n \quad (4)$$

Where n is the outgoing unit normal vector to the superconductor boundary $\partial\Omega$ and J_e is the external current density. The total magnetic field B_e is the sum of the applied external magnetic field B_a and current induced magnetic field B_c : $B_e = B_a + B_c$. Here, we assume that current induced magnetic field B_c is linear [3],

$$B_c = \pm J_e y e_z \quad (5)$$

In our simulation, Eq (3) is corresponded to top and bottom

boundaries of superconductor, and Eq (4) is corresponded to besides boundaries.

Figure 1 shows the physical system model for our simulation. A side of the superconductor is $l=10\lambda$ length and Ginzburg-Landau parameter is $\kappa=4$, normal electricity conductivity is $\sigma=4$. We distributed the flux pinning centers randomly with the content, $\omega=0.1, 0.2, 0.3$ in superconducting region. And also we had the temperature value of the superconductor for $T=0, 0.1, 0.2, 0.3$ respectively.

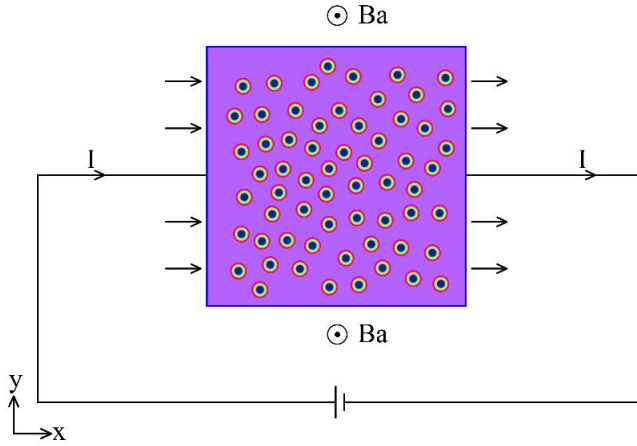


Figure 1. Physical system model of the type-II superconductor.

The equations for calculation of energy into the superconductor follows as [4];

$$E_{sup} = \frac{1}{\kappa^2} |\nabla \Psi|^2 - |\Psi|^2 + \frac{1}{2} |\Psi|^4 \quad (6)$$

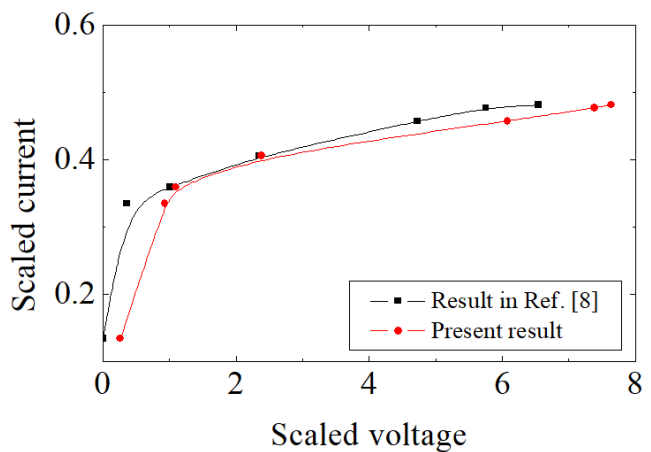
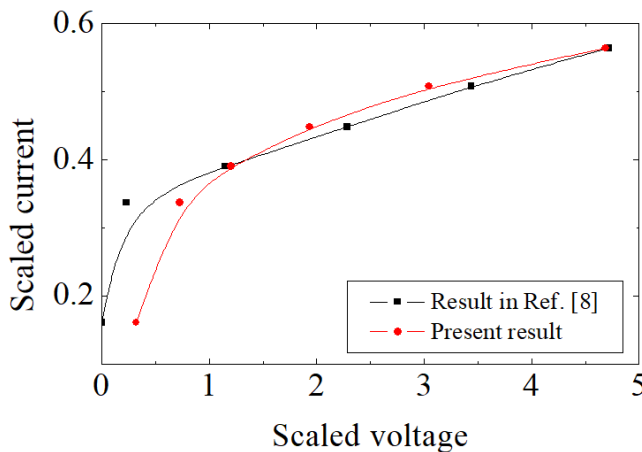


Figure 2. Comparison of V-I characteristic curve for result in ref [8] and present study. Former is to use $\sigma=150$ and $\kappa=150$, later $\sigma=40$ and $\kappa=150$.

As above figures, two V-I curves have a little difference in a division in all. We still emphasize that different two mesh

methods lead to those differences. From this validation, we successfully proceeded below simulation result.

$$E_{mag} = (B_e - \nabla \times A)^2 \quad (7)$$

$$E_{int} = \frac{i}{\kappa} A(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) + |\Psi|^2 |A|^2 \quad (8)$$

$$E_{tot} = E_{sup} + E_{mag} + E_{int} \quad (9)$$

$E_{sup}, E_{mag}, E_{int}$ are superconductivity energy, magnetic energy and interaction energy respectively. And total energy E_{tot} is sum of these energies.

2.3. Validation

We simulated the 2D square superconductor. For validation, we used the parameters and the sizes of geometry which are reported in ref [8]. They considered the I-V characteristics for different κ and σ of the superconductor which dimensionless length of its side 2λ .

For those parameters, Figure 2 shows comparison with results in our simulation and in ref [8].

In Figure 2, black points appear the simulation result of ref [8] in case that $\kappa=150, \sigma=150$ and $\kappa=150, \sigma=40$ respectively, and black curves appear approximation on those points. In otherwise, red points appear our simulation result with the parameters as ref [8] and red curves appear approximation on those points.

In ref [8], they simulated flux-flow behavior in high temperature superconductor by current-induced magnetic field, particularly I-V characteristics. They used different value of normal electric conductivity σ and Ginzburg-Landau parameter κ and found that voltage is increased with increasement of current and total annihilation occurs is nearly linear.

3. Results and Discussion

3.1. Flux Vortex Motion with Various Contents and Temperatures

For our physical system, the superconductor contacts to normal wires on both sides and transport current flows through the normal conductor and superconductor by electric source. We assumed that a magnetic field is applied to the superconductor in this system by considering various factors of electromagnetic circuit. To analysis easily, we applied a constant magnetic field to the superconductor.

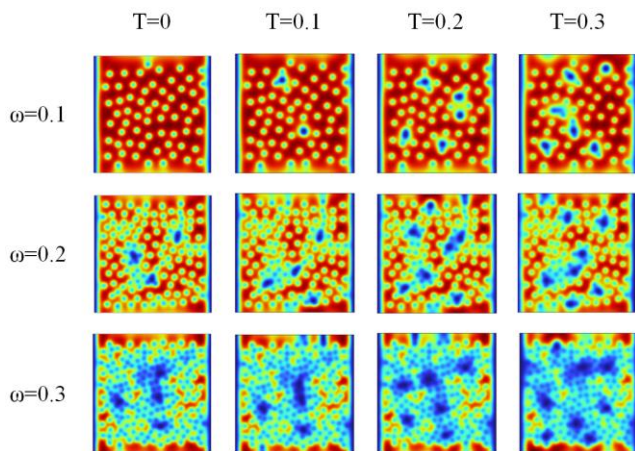


Figure 3. Vortex dynamics of superconductor in the case that only the external current is applied. Time $t=200$ using $I=1.1$, $\omega=0.1, 0.2$ and 0.3 , respectively, $T=0, 0.1, 0.2, 0.3$, respectively.

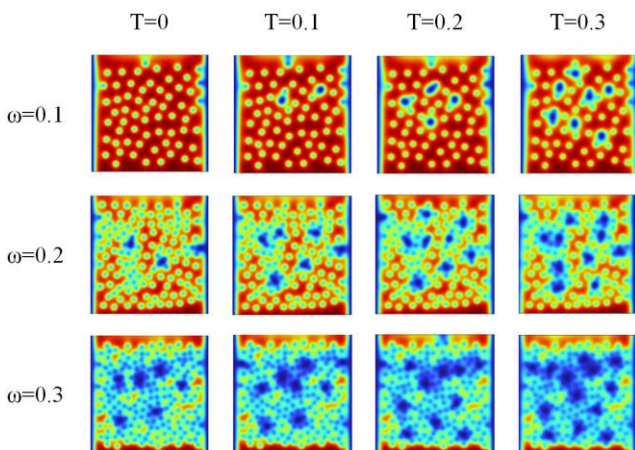


Figure 4. Vortex dynamics of superconductor in the case that the external current and magnetic field are applied. Time $t=200$ using $I=0.4$, $B_a=0.35$, $\omega=0.1, 0.2$ and 0.3 , respectively, $T=0, 0.1, 0.2, 0.3$, respectively.

If a constant magnetic field is applied to a superconductor, it is easy to consider vortex dynamics into the superconductor. Under these conditions, it becomes difficult when transport

current flows through the superconductor. The reason is that transport current forms current-induced magnetic field [7], which changes the external magnetic field applied to the superconductor.

Figure 3 shows the vortex dynamics of superconductor penetration into the superconductor at time $t=200$ in the simulation unit time for $T = 0, 0.1, 0.2, 0.3$ and the content of the flux-pinning centers distributed inside the superconductor, respectively, when the transport current is only flowing through the superconductor. We set the value of dimensionless transport current I to 1.1 in this simulation. If the value of the dimensionless transport current is less than this, the first vortex dynamics we are considering does not appear.

As shown in Eq (5), in the case of a transport current flowing in a superconductor, the current-induced magnetic field produced by the transport current is induced by a gradient inside and outside the superconductor, which leads to the penetration of vortices and anti-vortices from both sides of the superconductor, respectively. In the simulation, we assumed that the transport current flows along the x-direction, so that the vortices and anti-vortices penetrate from the top and bottom sides, respectively. As shown in Ref. [7], if there is no flux-pinning center inside the superconductor or if the flux-pinning center is not distributed at the edge, only the transport current is allowed to penetrate simultaneously the vortices and anti-vortices from the upper and lower sides, and thus the penetrating vortices and anti-vortices are vanished each other at certain locations inside the superconductor.

In our simulations, for $\omega=0.1$ and $T=0$, the first vortex penetrates from the top edge, depending on how the flux-pinning centers distributed inside the superconductor are deflected towards the edge of the superconductor. The eddy thus introduced is fixed to the flux-pinning center located in the nearest position and again moved to the flux-pinning center inside the superconductor.

As the value of temperature T increases, the penetration and motion of vortices become more active, especially from the value of $T = 0.2$ to the superconductor interior, where two vortices penetrate simultaneously. The reason why the vortices penetrate faster with increasing value of temperature T is that the transition to steady state is accelerated by increasing the internal energy of the superconductor. Thus, temperature plays a very important role in the vortex dynamics of superconductors, and it is a considerable term in the study of Ginzburg-Landau equations.

The vortex dynamics in the case of the applied transport current and an external magnetic field are shown in Figure 4. The vortex dynamics in Figure 4 is similar to the vortex dynamics when only the transport current flows, but different effects of the current-induced magnetic field and the external magnetic field produced by the transport current result in different penetration and movement of vortices. The vortex dynamics is also different depending on the content of the flux-pinning centers distributed inside the superconductor. As the content ω increases, vortices that penetrate from the

edges of the superconductor will penetrate more rapidly into the superconductor interior. It is reasonable to assume that the distance between the flux-pinning centers is close as the content ω increases, due to the random distribution of the

flux-pinning centers. Thus, we have simulated the effect of temperature T and the content ω on the vortex dynamics in a superconductor.

3.2. E-t Curve

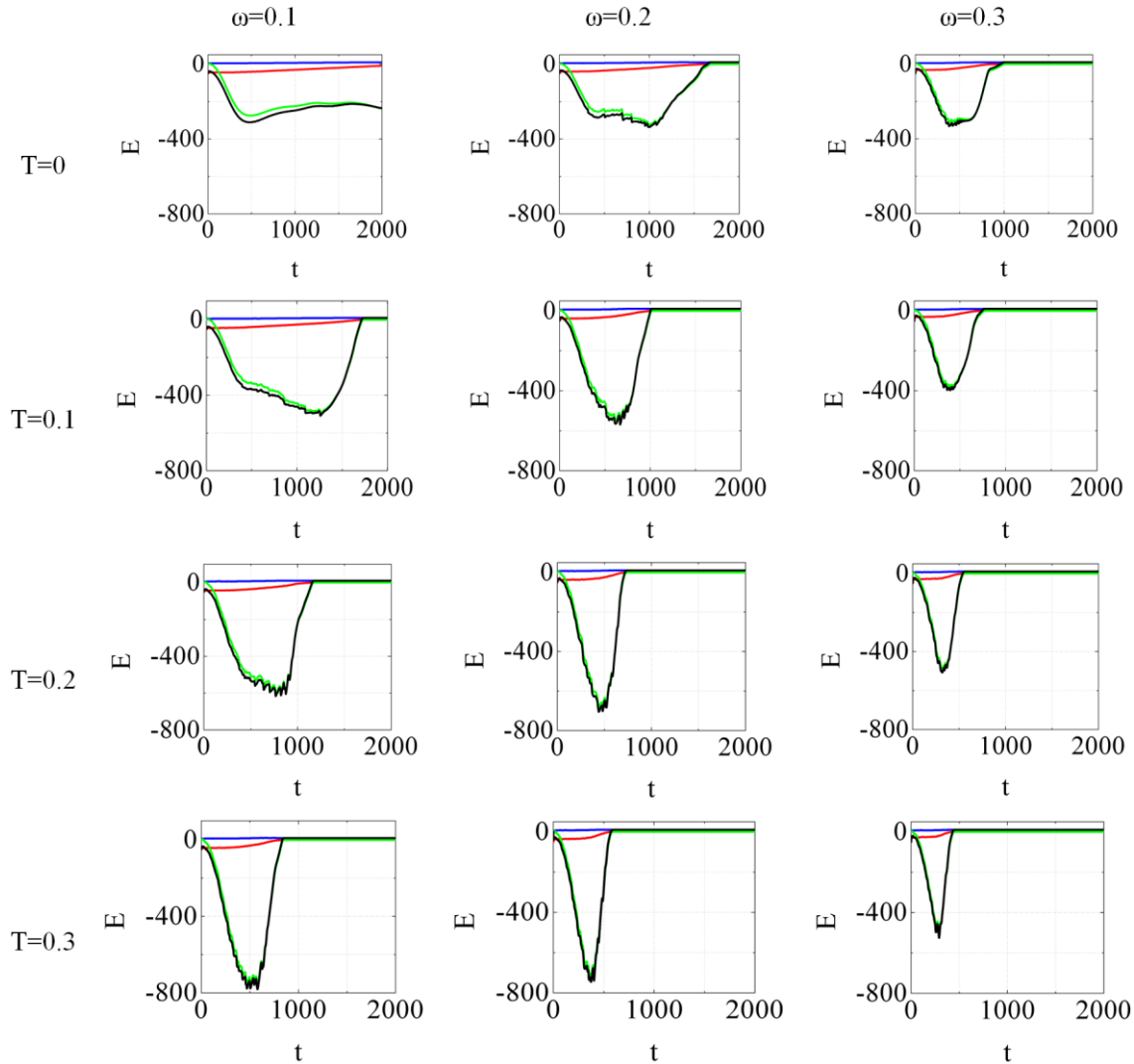


Figure 5. The E-t curve for time in the case that the external current is applied to the superconductor. $I=1.1$, $\omega=0.1, 0.2$ and 0.3 , respectively. Red, blue, green, black curve are corresponded superconductivity energy, magnetic energy, interaction energy and total energy respectively.

In this section, we have calculated the energies of the system using the energy calculation equations using Eqs (6)-(9). The analysis of the electric field profile and the calculated results for total energy can be explained in detail by the simulation results obtained above. Figure 5 shows the E-t curves for different temperatures and contents when only the transport current is applied to the superconductor.

As shown in the figure, before the superconductor enters the steady state, the total energy has a maximum value, since the vortices penetrate rapidly, the total energy decreases rapidly. Finally, the type-II superconductor enters a mechanical

equilibrium state, from which the superconductor is in equilibrium with a certain average value with a small energy fluctuation. From these figures, it can be concluded that each curve with different temperature and content rates has a similar behavior. Also, the lower the temperature and the smaller the content of the flux-pinning centers distributed inside the superconductor, the longer the time it takes for the superconductor to enter the mechanical equilibrium.

As can be seen, the difference between the superconducting energy and the magnetic energy is very small, but the fluctuations of the interaction energy curve are strong and

the value is the largest. Therefore, it can be seen that the total energy depends most on the interaction energy.

In particular, the fluctuations of the curves are more severe in the mixed state where the superconducting and steady state coexist. The reason for the high fluctuation in the mixed state is that the vortex generation and disappearance are most pronounced in this state.

According to the vortex generation and quenching relation,

there are many peaks on the interaction energy curve in the E-t curve. The peaks in the curve indicate the generation and disappearance of the vortex. The upward peaks indicate the generation of vortices and the downward peaks show the disappearance of vortices, respectively. As the content of flux-pinning centers, the transport current, and temperature increase, the number of peaks will be higher.

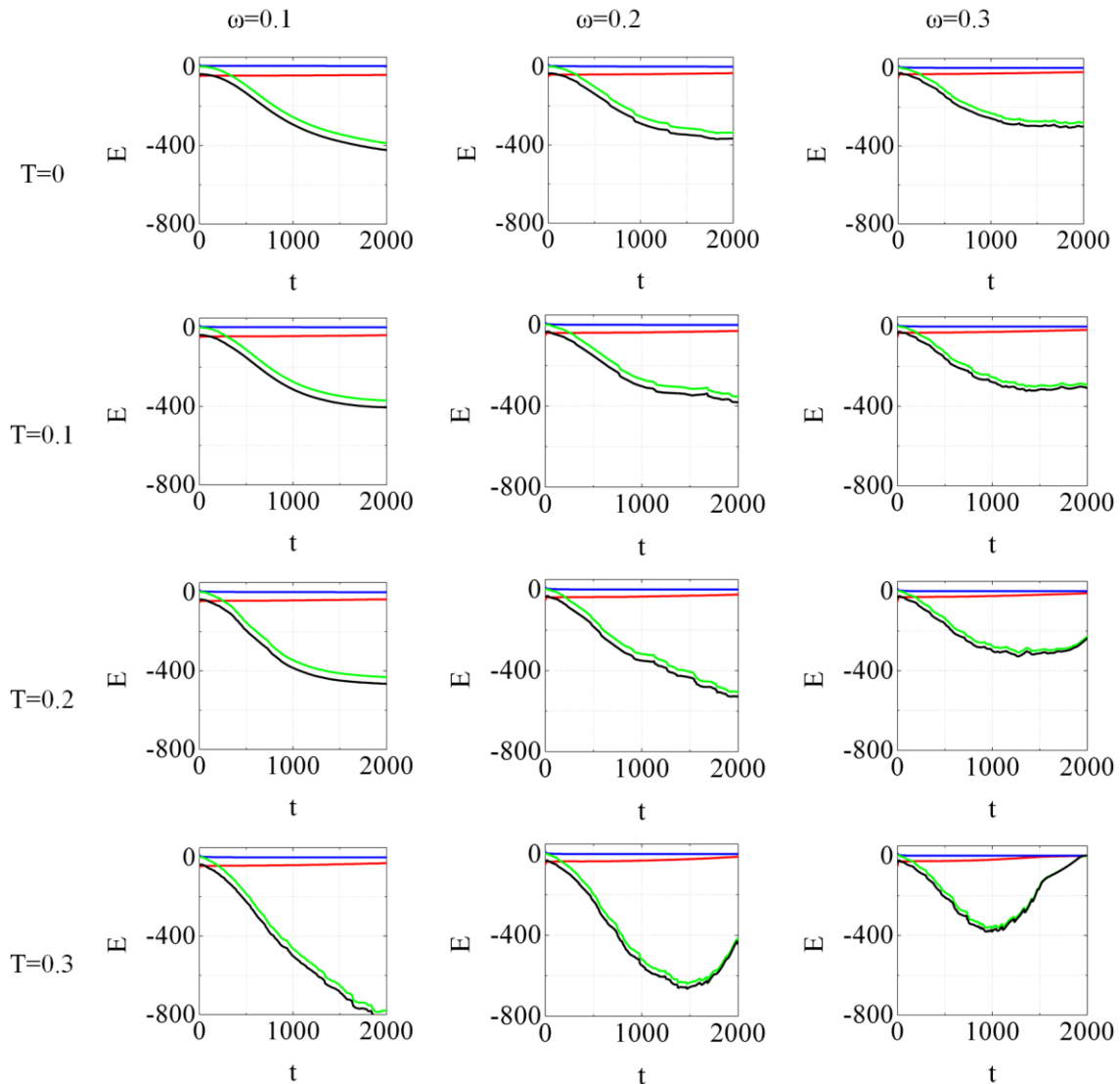


Figure 6. The E-t curve for time in the case that the external current and magnetic field are applied to the superconductor. $I=0.4$, $B_a=0.35$, $\omega=0.1, 0.2$ and 0.3 , respectively. Red, blue, green, black curve are corresponded superconductivity energy, magnetic energy, interaction energy and total energy respectively.

The reason for the large portion of interaction energy compared to electric energy and magnetic energy is the large number of flux-pinning centers inside the type-II superconductor.

This leads to the vortex-vortex, flux pinning center-flux pinning center, flux pinning center-vortex, and hence the interaction energy becomes larger compared to other energies.

In particular, it is more pronounced than in the type-II superconductors without flux-pinning centers. We see here that the interaction between the flux pinning center and the flux pinning center is larger than that between the vortex and the flux pinning center.

And the vortex-vortex interactions are considered to be the smallest. Therefore, it is expected that the more the content

of the flux-pinning center, the greater the interaction energy of the whole system. However, as shown in Figure 5, the larger the content ω , the more distinct the phenomenon is at the maximum of the interaction energy and total energy. That is, the largest interaction energy and total energy values are obtained for $\omega=0.2$. This indicates that in this case, the vortex-flux pinning center interaction is larger than flux pinning center-flux pinning center interaction. In the result, it can be seen that at other contents, the vortex-flux pinning center interactions cancel each other and weakens.

As shown in Figure 6, in contrast to the case of only transport current in a type II superconductor, the characteristics of the energy curve with time are very similar under the applied current and external magnetic field, and if there is a difference, it is directly related to the change in the external magnetic field exerted on the superconductor due to the influence of the current-induced magnetic field produced by the transport current.

3.3. I-V Characteristics

The electric field profile can be used to study the vortex

dynamics in a type-II superconductor. Figure 7 shows the electric field profile with time for only the transport current $I = 1.1$. In Figure 7, we can see many peaks before reaching the steady state, which show the generation and disappearance of vortices. As shown in the figure, the electric field profile exhibits a similar behavior to the total energy curve mentioned above and is closely related. That is, the peaks of the electric field profile correspond to the peaks in the total energy curve.

This fact means that in understanding the vortex dynamics in superconductors, it is necessary to consider the electric field profile as well as the total energy, which can give an interpretation of the vortex generation and quenching relationships and the stabilization state of the type-II superconductor.

To understand further, we look at the difference in external conditions between the two cases. In the first case (Figure 7) only the external magnetic field is applied to the superconductor, and in the second case (Figure 8) the external magnetic field and the transport current are applied. In Figure 8, the transition time from the type-II superconductor to the stable state is relatively long.

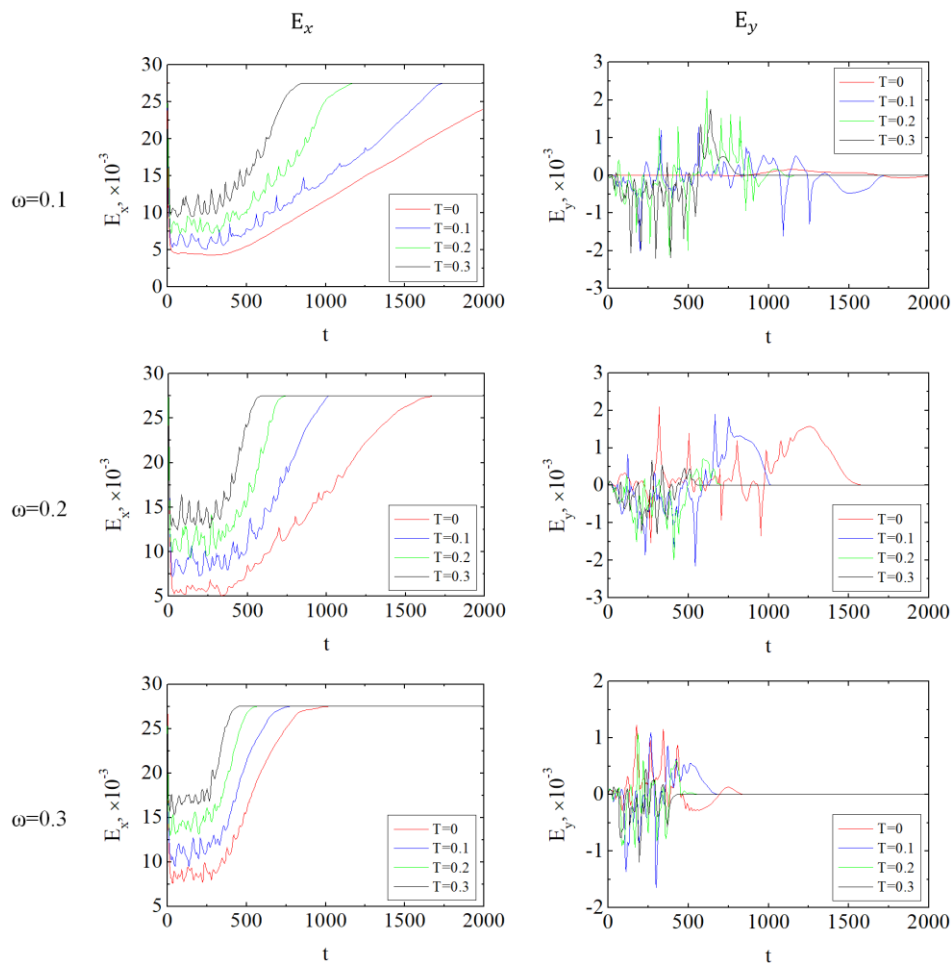


Figure 7. The Electric field profiles for time in the case that the external current and magnetic field are applied. $I=1.1$, $\omega=0.1, 0.2$ and 0.3 , respectively, $T=0, 0.1, 0.2, 0.3$, respectively.

We used 2000 time units in the electric field profile simulation. This time is sufficient to show the evolution and annihilation of vortices within the superconductor.

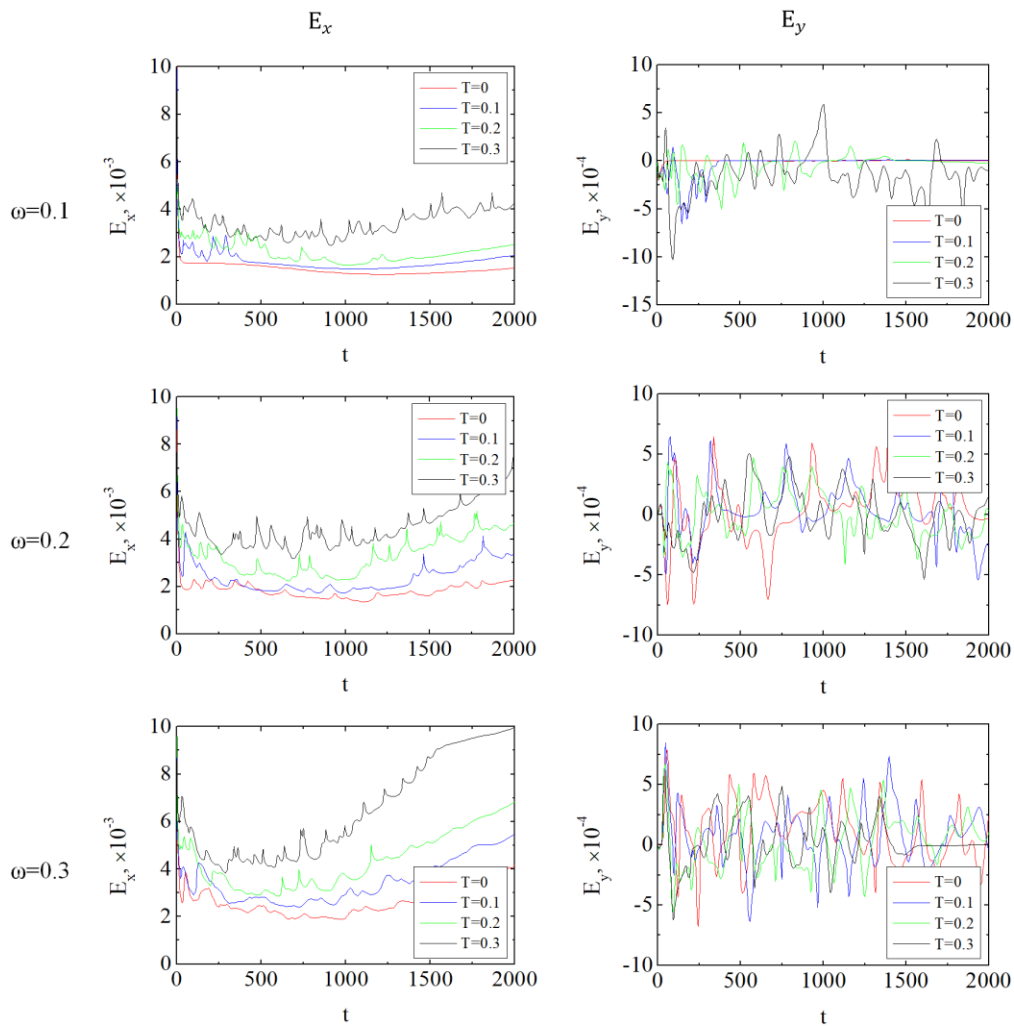


Figure 8. The Electric field profiles for time in the case that the external current and magnetic field are applied. $I=0.4$, $B_a=0.35$, $\omega=0.1, 0.2$ and 0.3 , respectively, $T=0, 0.1, 0.2, 0.3$, respectively.

We obtained the simulation points of the I-V characteristic curve as the electric field profile by averaging the voltage as a computing time step of 2000. In obtaining I-V characteristic points using the electric field profile, we refer to [9].

In Figure 9, I-V characteristics of the case when only the transport current is applied to the superconductor are analyzed. The points in the figure curves are the numerical results and the curves are the interpolation curves for the results at each temperature.

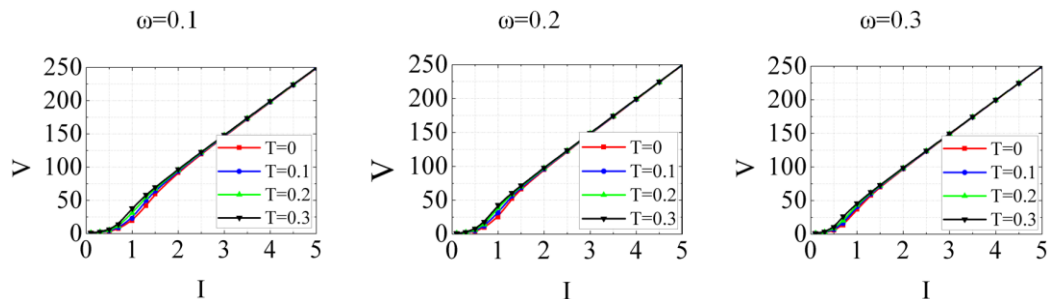


Figure 9. I-V characteristics in case that the transport current flows through the superconductor.

As can be seen from the figure, the I-V curve becomes linear with increasing superconductor temperature. When the I-V curve is close to linear, it means that the superconductor has shifted to a steady state. This result is in good agreement with that in ref [10]. As the content of the flux pinning center increases, the I-V curve tends to linear more rapidly. The reason is that the higher the content, the faster the vortex penetrates and the faster the transition to steady state takes place.

4. Conclusion

We have studied the magnet vortex dynamics and I-V characteristics of a type-II superconductor with randomly distributed flux pinning centers with various contents influenced by an external magnetic field and a transport current.

In the case of the transport current through the superconductor $I = 1.1$, the first vortex motion is observed, and the same occurs when the transport current and external magnetic field are applied simultaneously, i.e., $I=0.4$, $B_a=0.35$. Vortex dynamics can be determined through analysis of the electric field profile and E-t curves inside a superconductor, where the electric field profile and total energy are very closely related. The peculiarity here is that the change of total energy is greatest for $\omega=0.2$, in terms of the content of the flux pinning centers distributed inside the type-II superconductor. This indicates that the distribution of flux pinning centers plays a very large role in the properties of the type-II superconductor.

We also studied the I-V characteristics of superconductors. This characterization shows that when a superconductor transitions from a superconducting state to a normal conducting state, the I-V characteristics are linearized, especially as the content of the flux pinning centers increases faster.

Abbreviations

GL Ginzburg-Landau
TDGL Time dependent Ginzburg-Landau

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Author Contributions

Gwang-Il Mun: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft.

Yong-U Pak: Formal Analysis, Investigation, Methodology, Supervision, Software, Validation.

Yu-Gwang Ryu: Conceptualization, Resources, Visualization, Supervision, Validation.

Songchol Hong: Conceptualization, Data curation, Vali-

dation, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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