Behavior of a superconducting bulk in a running high- T_c superconducting maglev system (I): distribution of magnetic and electric field

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Abstract: A theoretical model of describing the electromagnetic and thermal dynamics of high- T_c superconducting bulks in a high- T_c superconducting Maglev system is built up. The model contains the effects of hysteresis-type loss, flux flow, flux creep, and thermal diffusion on the superconducting bulks in the Maglev system. As the first stage of this study, the behavior of magnetic and electric fields, as well as the distribution energy flow density in the superconducting bulk is studied. The results show that the flux flow and thermal diffusion affect the behaviors of the electromagnetic field in the high- T_c superconducting bulks in different ways; however, both of them contribute significantly to the energy dissipation of the superconducting bulks when they are used in the Maglev train.

Key words: YBCO; AC losses; critical frequency; self-heating

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1. Introduction

The modern development of magnetic levitation transportation systems, known as Maglev, started in the late 1960s as a consequence of low temperature superconductivity (LTS) technology. Now this LTS-based Maglev technology developed in Japan is quite mature and a high speed of more than 550 km/h has been achieved. Another mature Maglev technology, developed in Germany, is based on an active-controlled electromagnetic levitation system. The accomplishment of the commercial Maglev line in Shanghai demonstrates the great potential of Maglev technology in transportation industry. Although these two kinds of Maglev technologies have shown many superior performances as opposed to the conventional wheel-rail system in transportation, many challenges still exist in expanding the application market due to their high costs, extremely complex control system, and so on.

Magnetic levitation between high- T_c superconducting (HTS) bulks and permanent magnets provides another way to design a new-type of Maglev system, i.e., HTS

Maglev system [1-2] and related systems [3-4]. Compared to the conventional active-controlled electromagnetic levitation systems as well as the eddy-current-based dynamical levitation system, the HTS-permanent-magnet levitation system has many superior properties, including self-stabilization, power-supply-free levitation, high reliability, low costs, low noise levels, etc., thus promising to be used as ideal transportation in both intercity and inner city areas. However, many fundamental problems need to be solved before the HTS Maglev technology enters into the marketplace, in which the magnetic and thermal stabilities related to the flux movement in high- T_c superconducting bulks during a high speed movement, is a key issue.

In this paper, we established a model to describe the magnetic and thermal behavior of the superconducting bulks in a running high- T_c superconducting Maglev system, in order to provide useful information of the magnetic and thermal stability of the system. The characteristics of the system in some specific situations are studied.

2. Theoretical model

A superconducting bulk in a running high- T_c superconducting Maglev can be simply described as in Fig. 1, where the superconducting bulk is levitated above the permanent magnetic guideway (PMG), moving with a velocity of v_0 . The PMG is composed of a series of

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segments, of a length S_0 for each. The z -direction component of the magnetic field strength, $H_z(X_0, Y, Z_0)$ at a given height of $Z = Z_0$ above the PMG and at $X = X_0$ can be regarded as uniform along the PMG (in the Y -direction) except for at the joints where the magnetic field strength is deduced by a certain value of H_A . Therefore, $H_z(X_0, Y, Z_0)$ can be written as

$$H_z(X_0, Y, Z_0) = \begin{cases} H_D - H_A & (Y = nS_0, n = 1, 2, 3, \dots) \\ H_D & (\text{Others}) \end{cases}, \quad (1)$$

where H_D is the z -direction component of the magnetic field strength at a given height of Z_0 above the PMG. Since the superconducting bulk is moving with a velocity of v_0 , in order to describe the distribution of magnetic field inside the superconducting bulk, we take the moving reference frame with a velocity v_0 . In this case, an effective magnetic field applied to the superconductor can be written as

$$H_z(x_0, y, z_0, t) = H_D - H_A \cos(2\pi ft), \quad (2)$$

where $f = v_0 / S_0$ is the frequency of the magnetic field applied to the superconductor, and t is time. It is interesting to note that the effective magnetic field to the superconductor has two components, i.e., DC component H_D and AC component H_0 with $H_D \gg H_A$. The DC component H_D is dependent on the levitation height Z_0 . In addition, we take a linear E - J curve to reflect the effect of flux flow in the superconductor:

$$E = \begin{cases} 0, & J < J_c, \\ [\rho_f(|J| - J_c) + E_0] \text{Sgn}(J), & J > J_c, \end{cases} \quad (3)$$

where $\text{Sgn}(J)$ is the sign function, ρ_f the flux flow resistivity, E_0 the upper limit value of flux creep electric field, and J_c the critical current density.

As shown in Fig. 2, the linear E - J curve described by Eq.(3) which contains both the flux flow and flux creep, in which ρ_f is the flux flow resistivity. When ρ_f is infinity, Eq.(3) returns to the Bean model [5].

The temperature and field dependences of the critical current density are taken as

$$J_c(x, y, z, t, H) = J_{c0} \{1 - [T(x, y, z, t) / T_c]^2\} \exp(-H / H_0), \quad (4a)$$

where H_0 is the characteristic field at which the J_c is deduced to only $1/e$ of its value at $H = 0$, J_{c0} is the J_c value at $T = 0$ and $H = 0$, and T_c is the critical current which is dependent on H . Since $H_D \gg H_A$, Eq.(4a) can be further simplified as

$$J_c(x, y, z, t, H_D) = J_{c0} \{1 - [T(x, y, z, t) / T_c]^2\} \exp(-H_D / H_0). \quad (4b)$$

A slab sample with thickness $2D$ along the y -axis and extending infinitely in the (x, z) plane is considered. An applied magnetic field $H = H_D + H_A \cos 2\pi ft$ is applied in the z -axis, and the electrical field and current are induced in the x -axis. In addition, it is assumed that J_c , ρ_f , and T_c are only dependent on the external DC magnetic

Fig. 1 The schematic of a superconducting bulk running above PMG with a velocity v_0 . The fixed reference is denoted as X, Y, Z and the moving reference frame is denoted as x, y, z . The distribution of the Z -direction component of the magnetic field PMG at the levitation higher $Z = Z_0$ is sketched also in the figure

Fig. 2 The schematic of the E - J curve used for constructing the model. E_0 is the flux creep field which is a good approximation for the E - J curve of high temperature superconductors.

field, H_D , but not dependent on the AC magnetic field. The reduced Maxwell equations and the thermal diffusion equation can be expressed as follows [6-9]:

$$\frac{\partial b(\xi, \tau)}{\partial \xi} = -j_c(\xi, \tau) - \lambda_m \varepsilon(\xi, \tau), \quad (5a)$$

$$\frac{\partial b(\xi, \tau)}{\partial \tau} = -\frac{\partial \varepsilon(\xi, \tau)}{\partial \xi}, \quad (5b)$$

$$\frac{\partial^2 \Omega(\xi, \tau)}{\partial \xi^2} = \lambda_h \left[\frac{\partial \Omega(\xi, \tau)}{\partial \tau} - \beta p(\xi, \tau) \right], \quad (5c)$$

where

$$b = B / \mu_0 H_A, \quad \varepsilon = (E - E_0) / 2\pi\mu_0 f H_A D,$$

$$\Omega = T / T_c, \quad p = (\varepsilon + \varepsilon_0) j,$$

$$\varepsilon_0 = E_0 / 2\pi\mu_0 f H_A D,$$

$$j = \frac{JD}{H_A}, \quad j_c = \frac{J_c D}{H_A}, \quad h = \cos 2\pi f t,$$

$$\xi = y / D, \quad \tau = 2\pi f t,$$

$$\lambda_m = 2\pi\mu_0 f D^2 / \rho_f = f / f_m,$$

here f_m is defined as $f_m = \rho_f / 2\pi\mu_0 D^2$, characterizing the relaxation rate of the flux diffusion in the sample; $\lambda_h = 2\pi f C D^2 / \kappa = f / f_h$, here $f_h = \kappa / 2\pi C D^2$, describing the relaxation rate of thermal diffusion in the sample; $\beta = \mu_0 H_A^2 / C T_c = T_m / T_c$, here $T_m = \beta T_c = \mu_0 H_A^2 / C$ possessing a unit of temperature, which is a measure of temperature fluctuation caused by the AC magnetic field, and C and κ are specific heat and thermal conductivity of the sample, respectively. Taking into account the spatial symmetric and temporal quasi-periodicity, the general solution of Eq. (5) can be expressed as

$$b(\xi, \tau) = h(\tau) + \int_{\xi_1}^1 j_c(\xi', \tau) d\xi' - \lambda_m \int_{\xi}^1 \int_{\xi_1}^{\xi''} \frac{\partial b(\xi', \tau)}{\partial \tau} d\xi' d\xi'', \quad (6a)$$

$$\Omega(\xi, \tau) = \Omega_0 + \lambda_h \int_0^1 [1 - \max(\xi, \xi')] \times \left[\beta p(\xi', \tau) - \frac{\partial \Omega(\xi', \tau)}{\partial \tau} \right] d\xi', \quad (6b)$$

$$J_c(\xi, \tau) = J_0 \left(1 - \frac{2\lambda_h}{1 - \Omega_0^2} \right) \times \int_0^1 [1 - \max(\xi, \xi')] \left[\beta p(\xi', \tau) - \frac{\partial \Omega(\xi', \tau)}{\partial \tau} \right] d\xi', \quad (6c)$$

where ξ_1 is the place at which the current changes sign, and it is a function of time. The physical meaning of ξ_1 is sketched in Fig. 3. $\Omega_0 = T_0 / T_c$, T_0 is the bath temperature, and $J_0 = J_{c0} (1 - \Omega_0^2) \exp(-H_D / H_0)$ is the critical current density at $T = T_0$ and $H = H_D$. Here we have assumed that the superconducting bulk is cooled from the surface with an initial temperature the same as the bath temperature, T_0 . The boundary conditions used for temperature distribution are $T(\pm D) = T_0$ and $dT / dx|_{x=0} = 0$.

The description of the magnetic and thermal dynamics of the superconducting bulks in the high- T_c superconducting Maglev system shown in Fig. 1 is here expressed with Eqs. (5) and (6), which in principle are the same as those to describe the AC losses of superconductors in an alternative field [6-9].

Fig. 3 The schematic of the physical meaning of ξ_1 , which changes with time.

3. Results and discussion

Using the calculation method developed previously [6-9], an asymptotic solution of magnetic and electric fields is obtained and described as below:

$$b(\xi, \tau) = \begin{cases} 1 - j_0(1 - \xi), & (\xi_0 \leq \xi \leq \xi_1, \text{ or } 0 \leq \tau \leq \tau_1), \\ h + j_0(1 - \xi) + \frac{\lambda_h}{24} \frac{\beta}{1 - \Omega_0} \frac{dh}{d\tau} j_0^2 (1 - \xi)^2 [(1 - \xi)^2 + 2\phi(3\phi - 2 + 2\xi)] - \\ \lambda_m \frac{dh}{d\tau} (1 - \xi) \left(\phi - \frac{1 - \xi}{2}\right), & (\xi_1 \leq \xi \leq 1, \text{ and } \tau_1 < \tau \leq \pi), \\ h + j_0(1 - \xi) + \frac{\lambda_h}{24} \frac{\beta}{1 - \Omega_0} \frac{dh}{d\tau} j_0^2 (1 - \xi)^2 [(1 - \xi)^2 + 2] - \\ \lambda_m \frac{dh}{d\tau} (1 - \xi) \left(1 - \frac{1 - \xi}{2}\right), & (0 \leq \xi \leq 1, \tau > \tau_p), \end{cases} \quad (7)$$

$$\varepsilon(\xi, \tau) = \begin{cases} 0, & (\xi_0 \leq \xi \leq \xi_1, \text{ or } 0 \leq \tau \leq \tau_1), \\ -\frac{dh}{d\tau} (\xi - 1 + \phi) + \frac{\lambda_h \beta}{120(1 - \Omega_0)} j_0^2 \frac{d^2 h}{d\tau^2} (\xi - 1 + \phi) [(\xi - 1 + \phi)^4 + 5\phi^3(2 - 2\xi + \phi)] + \\ \frac{\lambda_h \beta}{48(1 - \Omega_0)} j_0 \left(\frac{dh}{d\tau}\right)^2 [6\phi^4 + (1 - \xi)^4 - 4\phi(1 - \xi)^3] - \frac{\lambda_m}{4j_0} \left(\frac{dh}{d\tau}\right)^2 [2\phi^2 - (1 - \xi)^2] + \\ \frac{\lambda_m}{6} \frac{d^2 h}{d\tau^2} (\xi - 1 + \phi) [3\phi^2 - (\xi - 1 + \phi)^2], & (\xi_1 < \xi \leq 1, \text{ and } \tau_1 < \tau \leq \pi), \\ -\frac{dh}{d\tau} \xi + \frac{\lambda_h \beta}{120(1 - \Omega_0)} j_0^2 \frac{d^2 h}{d\tau^2} \xi (\xi^4 - 10\xi + 15) + \frac{\lambda_h \beta}{48(1 - \Omega_0)} j_0 \left(\frac{dh}{d\tau}\right)^2 \xi (6\xi - \xi^3 - 8) - \\ \frac{\lambda_m}{4j_c} \left(\frac{dh}{d\tau}\right)^2 [1 - (1 - \xi)^2] + \frac{\lambda_m}{2} \frac{d^2 h}{d\tau^2} \xi [1 - \xi^2 / 3], & (0 < \xi \leq 1, \text{ and } \tau_p < \tau \leq \pi), \end{cases} \quad (8)$$

where j_0 is the value of j_c at $\Omega = \Omega_0$, $\xi_p = 1 - 1/j_0$ is the normalized macro-penetration depth determined by Bean model, $\phi = (1 - h)/2j_0$, τ_1 is the time corresponding to $\xi = \xi_1$, τ_p is the value of τ_1 at $\xi = 0$, called penetration time. τ_1 and ξ_1 are given as:

$$\tau_1 = \arccos \{ 1 - 2j_0(1 - \xi) - [\lambda_m(1 - \xi)^2 - \frac{\lambda_h \beta}{4(1 - \Omega_0)} j_0^2 (1 - \xi)^4] \sqrt{j_0(1 - \xi)[1 - j_0(1 - \xi)]} \}, \quad (9)$$

$$\xi_1 = 1 - \phi - \frac{\lambda_m}{4j_0} \frac{dh}{d\tau} \phi^2 + \frac{\lambda_h}{16} \frac{\beta}{1 - \Omega_0} j_0 \frac{dh}{d\tau} \phi^4, \quad (10)$$

where $w(\tau) = (4 \cos \tau + 3) / \sin \tau$. In solving Eqs. (6), a continuity of temperature at $\xi = \xi_1$ is applied.

When the superconducting bulk is exposed to an alternative field, the magnetic field will penetrate into the superconducting bulk through a diffusion way. The generated heat by the diffusion of the magnetic field will transport from the inner part to the surface of the superconducting bulk. τ_m and τ_h are two characteristic times describing magnetic and thermal diffusion in the material, respectively, and can be expressed as [10]

$$\tau_m \sim \frac{(2D)^2}{\rho_f / \mu_0}, \quad (11a)$$

$$\tau_h \sim \frac{(2D)^2}{\kappa / C}. \quad (11b)$$

When $f \ll 1/\tau_m$, the critical state can be well defined and Bean model can be used to describe the magnetic behavior of the materials. When $f \ll 1/\tau_h$, the heat generated by AC loss can be transferred to the thermal bath rapidly and the temperature inside the superconductor is uniform and almost the same as the thermal bath temperature, T_0 . However, for superconducting bulks, for example, an YBCO bulk superconductor with $D=30$ mm, $1/\tau_h$ is around 10 Hz to 10 kHz, comparable to the frequency of the applied ac field. In this case, the self-heat effect [11] cannot be negligible.

Compared with the solutions of the magnetic and electric fields obtained previously, the current new results contain the effects of both the magnetic and thermal diffusion. The effects of magnetic and thermal diffusion can be clearly reflected:

$$\Delta b(\tau, \xi) = b(\tau, \xi) - b_0(\tau, \xi),$$

where $b_0(\tau, \xi)$ is the magnetic field without the effects of magnetic and thermal diffusion. It is evident that both magnetic diffusion (reflected by $\lambda_m > 0$) and thermal diffusion (reflected by $\lambda_h > 0$) have modified the time-evolution of $b(\tau, \xi)$ with changing $\Delta b(\tau, \xi)$ more dras-

tically by λ_m (see Figs. 4(a) and 4(b)). In addition, it is observed that the transient modification of $b(\tau, \xi)$ may reach about 14% inside the superconducting bulk ($\xi=0.6$, see Fig.4(a)), but only 4.7% near the surface of the bulk ($\xi=0.9$, see Fig. 4(b)). Although Fig. 4 shows only the situation of incomplete penetration of the AC

field since $j_0 = 1.2 > 1$, the main features of the field evolution are the same in the complete penetration state (for the sake of limited space of text, the results are not shown here).

The spatial distribution of the $b(\tau, \xi)$ in the incomplete field penetration is shown in Fig. 5.

Fig. 4 Time evolution of magnetic field when the AC field penetrates incompletely into the superconductor: (a) In the inner part of the superconductor (at $\xi=0.6$); (b) near the surface of the superconductor (at $\xi=0.9$). The main panels show the net contributions of flux flow and heat diffusion, $\Delta b(\tau, \xi)$. The insets show the behaviour of $b_0(\tau, \xi)$ in the case of no effects of flux flow and heat diffusion existing.

Fig. 5 Spatial distribution of the magnetic field inside the superconducting bulk at different time: (a) $\tau=0$; (b) $\tau=0.25\pi$; (c) $\tau=0.5\pi$; (d) $\tau=0.75\pi$; (e) $\tau=\pi$.

The field distribution at the initial stage ($0 \leq \tau \leq 0.25\pi$) is the same as that of $b_0(\tau, \xi)$, no significant effects of magnetic field and heat diffusion have been observed. However, a significant retardation of the magnetic field diffusion is observed with time evolution. This retardation mainly occurs in the inner part of the bulk material, and gradually reduces toward the surface area, which is in consistence with the phenomenon shown in Fig. 4.

The time evolution of the electric field in the state corresponding to that of Fig. 4 is shown in Fig. 6, in which the effect of thermal diffusion is shown in Fig. 6 (a) and the effect of magnetic diffusion Fig. 6(b). Compared to the behavior of the magnetic field evolution in the superconducting bulk, a distinguishing feature of behavior of the electric field from that of the magnetic one is that the electric field near the superconducting bulk surface is stronger than in the inner part, which is due to a more rapid change of magnetic field near the surface of the superconducting bulk. In addition, in order to emphasize the influence of the thermal diffusion on the behavior of electric field, we have examined the situation where the external driving frequency lower that the magnetic field diffusion rate, but significantly higher than the thermal diffusion rate. In this case, we can see that the thermal diffusion also has significant effect on the behavior of the electric field, but with a different way from that by magnetic diffusion. Further, it is observed here that the effect of the magnetic diffusion on the behavior of the electric field is getting stronger in the final stage of a period (i.e. near $\tau = \pi$), which is quite different from the effect of the thermal diffusion.

The spatial distribution of the electric field is shown in Fig. 7, corresponding to the states shown in Fig. 5. It is evident that the effect of the magnetic field diffusion on the spatial distribution of the electric field appears later than that on the magnetic field. This may be due to that the electric field is mainly induced by the changes of magnetic field in this system.

More important is the energy dissipation in the system. The energy flow density $p(\xi, \tau)$ is given by [10]

$$p(\xi, \tau) = \varepsilon(\xi, \tau)j(\xi, \tau) + \frac{1}{2} \frac{\partial}{\partial \tau} b(\xi, \tau)^2 = \varepsilon(\xi, \tau) \frac{\partial}{\partial \xi} b(\xi, \tau) + \frac{1}{2} \frac{\partial}{\partial \tau} b(\xi, \tau)^2. \quad (12)$$

As shown in Fig. 8, the behavior of the energy flow density in the superconducting bulk is significantly affected by both the thermal and magnetic diffusion. Both of these diffusion effects have enhanced the energy dissipation since. Usually, most of the previous models only consider the hysteresis loss which is the most important source for the energy dissipation of AC losses of superconductors; however, besides that, magnetic flow and thermal diffusion also contribute significantly to the energy dissipation. These are the unique features that the high- T_c superconducting bulks distinguishing themselves from others being used in the Maglev train system. As a consequence of the modification in magnetic and electric fields, the temperature and critical current density may also be modified significantly. These will be carried out in our future studies.

Fig. 6 Time evolution of electric field in the incomplete penetration state: (a) in the case that only thermal diffusion is taken into account ($\lambda_m=0$, $\lambda_h>0$) near the surface of the superconductor (at $\xi=0.9$) and inner part ($\xi=0.6$); (b) in the case that only magnetic diffusion is taken into account ($\lambda_m>0$, $\lambda_h=0$) near the surface of the superconductor (at $\xi=0.9$) and inner part ($\xi=0.6$).

Fig. 7 Spatial distribution of the electric field inside the superconducting bulk at different time

Fig. 8 Time evolution of the energy flow density in the incomplete penetration state: (a) in the case that only thermal diffusion is taken into account ($\lambda_m=0, \lambda_h > 0$) near the surface of the superconductor (at $\xi=0.9$ and 1.0) and in the inner part ($\xi=0.6$); (b) in the case that only magnetic diffusion is taken into account ($\lambda_m > 0, \lambda_h = 0$) near the surface of the superconductor (at $\xi=0.9$ and 1.0) and inner part ($\xi=0.6$).

4. Conclusion

In this work, we have studied the behavior of a high- T_c superconducting bulk in a high- T_c superconducting Maglev train, and proposed a model to describe the dynamics of electromagnetic and thermal properties of the superconducting bulks. As the first stage of this study, the behavior of magnetic and electric fields, as well as the distribution energy flow density in the superconducting bulk, is analyzed. The results reveal that the flux flow and thermal diffusion affect the behaviors of the electromagnetic field in the high- T_c superconducting bulks in a different way; however, both of them contribute significantly to the energy dissipation of the superconducting bulks when they are used in the Maglev train.

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