An Extended Thin Approximation Method to Simulate Screening Current Induced in REBCO Coils

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Superconducting magnets wound with second-generation high-temperature superconductors, i.e. $REBa_2Cu_3O_{7-x}$ (REBCO, RE = Rare Earth) tapes, are desired to apply high magnetic field NMR, MRI, and accelerators. However, a major problem for practical application is an undesirable irregular magnetic field caused by screening currents induced in REBCO tapes. To investigate the screening current-induced magnetic field, a few simulation methods have been proposed. One of effective simulation methods employs a finite element method with a thin approximation method. Although the thin approximation method was developed to simulate eddy currents in magnetic steel sheets, it is not applicable to REBCO tapes carrying a transport current. Therefore, the thin approximation method is extended to simulate screening currents in REBCO tapes taking into account a carrying transport current. To show the validity of the proposed extended thin approximation method, the screening currents of a REBCO magnet are computed, the results are compared with the measurement and the simulation results of the conventional thin approximation method. The more accurate solution are available by using the proposed methods.

***Index Terms*—HTS magnet, REBCO tape, screening current, thin approximation method.**

I. Introduction

ULTRA-HIGH-FIELD NMR magnets wound with $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = Rare Earth) tapes have been developed [**?**]. Since REBCO tapes are very flat (the thickness and width of REBCO layer are 1-5 μm and 4-10 mm, respectively), a large amount of screening currents are induced in REBCO layers during charging a REBCO magnet (Fig. **??**). A crucial problem to develop such an NMR/MRI magnet is an irregular magnetic field generated by screening currents. A screening current-induced magnetic field (SCMF) was measured in experiments [**?**], [**?**], and the behaviors of screening currents were confirmed in simulations [**?**], [**?**]. A nonuniform current distribution generates an irregular magnetic field, however NMR/MRI systems require magnetic field homogeneity less than a few ppm. It is important to accurately evaluate the SCMF by simulations, when designing NMR/MRI magnet.

In the simulation [**?**], a thin approximation method [**?**], [**?**] was used, because it is difficult to make a 3-D mesh due to the flat shape of REBCO tape. The thin approximation method was proposed to compute eddy currents induced in thin magnetic steel sheets [**?**]. Then, Hashizume *et al.* applied it to a simulation of shielding currents in high-temperature superconducting bulks [**?**]. In these simulations, the thin approximation method required three assumptions: (1) very thin simulated materials, (2) phenomenon uniform in the thickness direction, and (3) no transport current in the materials. In recent years, the thin approximation method was employed in screening current simulations [**?**], [**?**]. However, the assumption of no transport current was not satisfied. Although the simulation results agreed with measurements well, the simulated screening current phenomenon was not accurate. Therefore, we have tried to developed a new thin approximation considering a transport current to accurately simulate screening currents in REBCO tapes.

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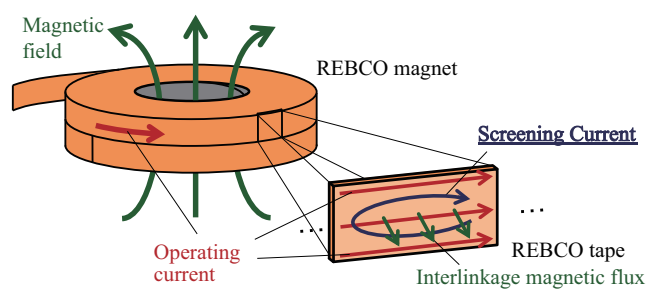


Fig. 1. Screening current is induced in REBCO tape during charging REBCO coil, because the magnetic fluxes penetrate into REBCO tape.

II. Extended Thin Approximation Method to Consider Transport Current

To evaluate a SCMF in detail, a current distribution, including an operating current and screening currents, is simulated using 2-D FEM with quadrangle mesh coupled with a new thin approximation.

A. Ordinary Thin Approximation

The current density in REBCO tapes is obtained from the following governing equation:

$$\nabla \times (\rho \nabla \times \boldsymbol{T}) = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

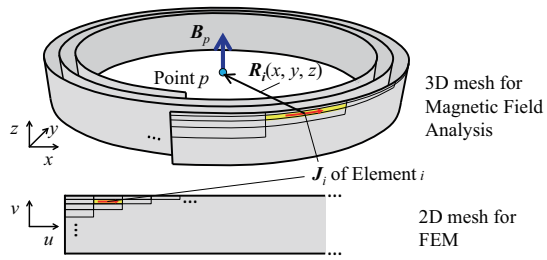


Fig. 2. The 2-D quadrangle mesh allocated for magnetic field analysis in the Cartesian (xyz) coordinate (upper), and the 2-D quadrangle mesh of the unwound REBCO tape in the local (uv) coordinate (lower). The current distributions computed in 2-D space, and the magnetic field on every element is computed according to the Biot-Savart law in 3-D space.

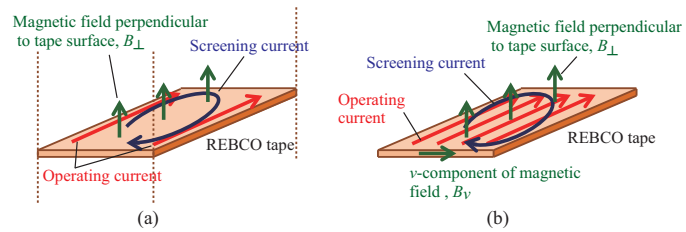


Fig. 3. (a) Considering only the magnetic field perpendicular to tape surface, the operating current flows along both the edges of tape. The operating current behaves like infinite-thickness phenomenon. (b) Considering the v-component of magnetic field as well as perpendicular component, the operating current flow entirely inside of tape.

where $\boldsymbol{T}$, $\boldsymbol{B}$, and ρ are the current vector potential, the magnetic field, and the electrical resistivity, respectively. A REBCO tape is too thin to make a 3-D mesh in the Cartesian (xyz) coordinates, hence the current distribution in the REBCO tape is considered as the 2-D phenomenon in the uv space. Applying the thin approximation method for eddy current simulation [**?**], [**?**], (**??**) yields

$$\rho\left(\frac{\partial^2 T}{\partial u^2}+\frac{\partial^2 T}{\partial v^2}\right) -\frac{\mu_0 d}{4\pi}\frac{\partial}{\partial t}\int_S \frac{(\nabla T^{(s)}\times \boldsymbol{i})\times \boldsymbol{R}(x,y,z)}{R(x,y,z)^3}\cdot \boldsymbol{i}\mathrm{d}S = \frac{\partial B_\perp}{\partial t} \quad (2)$$

where T, μ_0, d, $T^{(s)}$, $\boldsymbol{R}(x,y,z)$, $\boldsymbol{i}$, and $B_\perp$ are the current vector potential in the uv system, the permeability of free space, the thickness of REBCO tape, the current vector potential at the source point, the distance vector toward the field point from the source point in the xyz system, the unit vector perpendicular to the REBCO tape surface, and the external magnetic field perpendicular to the REBCO tape surface, as shown in Fig. **??**, respectively. The third term in left side of (**??**) represents the self-field generated by the coil itself. This term is computed from the interlinkage magnetic field perpendicular to the REBCO tape element, contributed from the currents of every element based on the Biot-Savart law.

The perpendicular magnetic field $B_\perp$ is considered in the ordinary thin approximation method. Using (**??**), the simulated operating current flows along the edges of REBCO tape as well as the screening currents, because not considering the v-component of magnetic field. Its phenomenon looks like that inside material of infinite thickness (Fig. **??**(a)). However, the operating current carries entirely inside the REBCO tape due to the v-component of magnetic field [**?**] (Fig. **??**(b)). Therefore, the ordinary thin approximation must be extended to consider the change of the v-component of magnetic field.

B. Extended Thin Approximation Method

In the simulation results obtained from the above ordinary thin approximation, an operating current flows along the edges of REBCO tape. However, due to the magnetic field parallel to the wide surface of REBCO tape, a slight mount of operating current carries in the middle part of REBCO tape. Although 3-D simulation is effective in such a problem, it is hard to make a 3-D mesh of REBCO magnet because of very thin REBCO tape. Therefore, the parallel component of magnetic field must be taken into account in the 2-D simulation, improving the ordinary thin approximation method.

Here, the u-component of the magnetic field is regarded as 0 because of axisymmetric coil's shape. It is also assumed that the vector potential T linearly varies in the thickness direction:

$$T=\tilde{T}+\triangle T\frac{w}{d} \quad (3)$$

where $\tilde{T}$, $\triangle T$, and w are the current vector potential on one REBCO tape surface, the difference of the current vector potential between the tape surfaces, and the position in the tape thickness direction.

From the governing equation (**??**), the following equation is obtained:

$$\rho\frac{\partial^2 T}{\partial v\partial w}=-\frac{\partial B_v}{\partial t}. \quad (4)$$

Here, the u- and v-components of current vector potential are assumed to be constant, because the REBCO layer is very thin. Integrating (**??**) with respect to the thickness, the following equation is yielded:

$$\rho\frac{\partial \triangle T}{\partial v}=-d\frac{\partial B_v}{\partial t}. \quad (5)$$

Considering the interlinkage magnetic fields of elements each other like the ordinary thin approximation, (**??**) is extended to

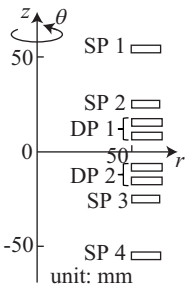
$$\rho\frac{\partial \triangle T}{\partial v}+\frac{\mu_0 d^2}{4\pi}\frac{\partial}{\partial t}\int_S \frac{(\nabla T^{(s)}\times \boldsymbol{i})\times \boldsymbol{R}(x,y,z)}{R(x,y,z)^3}\cdot \boldsymbol{i}_v\mathrm{d}S = -d\frac{\partial B_{ex,v}}{\partial t} \quad (6)$$

where $\boldsymbol{i}_v$ and $B_{ex,v}$ are the v-directional unit vector and the v-component of external magnetic field, respectively.

Finally, the above two equations (**??**) and (**??**) are discretized by the 2-D FEM in the proposed thin approximation method. A transport current is given as a boundary condition.

III. Applications

To confirm the validity of the extended thin approximation method, the screening current of REBCO magnet are simulated, and then the results are compared with the results of the ordinary thin approximation method.



Coil specifications

	SP 1	SP 2	SP 3	SP 4	DP 1	DP 2
Tape width (mm)	5.0	5.0	5.0	5.0	5.0	5.0
Tape thickness (mm)	0.122	0.120	0.120	0.122	0.122	0.123
Inner diameter (mm)	100	100	100	100	100	100
Outer diameter (mm)	131	129	129	131	132	132
Height (mm)	9.3	9.3	9.3	9.3	16.6	16.6
Number of turns	100	100	100	100	109	109
I_c (A)	94.3	108.4	108.7	95.4	95.3	96.7
n-value	26.2	30.9	30.6	26.4	29.2	30.5

Fig. 4. Simulated magnet consisting of 4-SP and 2-DP coils, and coil specifications.

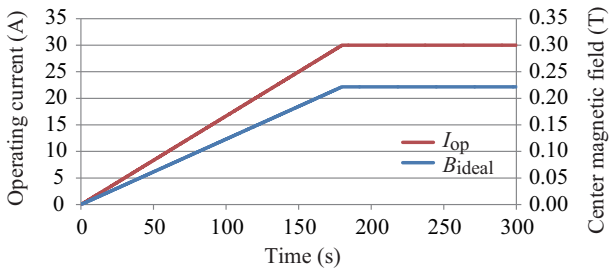


Fig. 5. Operating current I_{op} and on-axis magnetic field B_{ideal} when the operating current uniformly flows inside REBCO layer without screening current.

A. Magnet Model

A simulated REBCO magnet consists of 4 single pancake (SP) and 2 double pancake (DP) coils [**?**], as shown in Fig. **??**. The DP coil consists of 2 SP coils connecting at the innermost turns each other. The operating current I_{op} linearly increases up to 30 A with 10 A/min., and hold at 30 A for 2 min, as shown in Fig. **??**. The n-power law model, where n-value of each coil are shown in Fig. **??**, is taken into account as a non-linear E–J characteristic [**?**].

The mesh is subdivided to 29 in the tape-width direction and 8 per one turn in the circumferential direction, respectively.

B. Screening Current Distribution Map

Fig. **??** (a) and (b) show the current density distributions, consisting of the operating and screening currents, on the cross section of SPs 1 and 2 and DP 1 at $t = 180$ s, using the ordinary and extended thin approximation methods, respectively. The distributions on SP 1 are not greatly different, but those on SP 2 and DP 1 are completely different. These differences produce the difference of SCMF. Since the SP 2 and DP 1 are closer to the magnet center than SP 1, the screening current distribution of SP 2 and DP 1 largely affects the generated magnetic field.

Next, the current density on the unwound REBCO tape of DP 1 is depicted in Fig. **??**. The difference between two distributions is obvious, and the width of the low current density on the proposed method is wider than that of the ordinary method.

The operation current is likely to flow along the tape edges in the ordinary method (as shown in the upper left of Fig. **??**), and the net current distribution on the bottom left of Fig. **??** are obtained superimposing the screening current like the middle left of Fig. **??**. Meanwhile, the operation current flows entirely inside of the REBCO tape in the proposed method, by considering the z-component of the magnetic field (the upper right of Fig. **??**). Accordingly, the net current distribution must be like the bottom right of Fig. **??**. The widths of low current density region, d_{ord} and d_{new} shown in Fig. **??**, in the results of the ordinary and the extended thin approximation method are different. The large SCMF is generated in the result of the extended thin approximation method because $d_{\mathrm{ord}} < d_{\mathrm{new}}$.

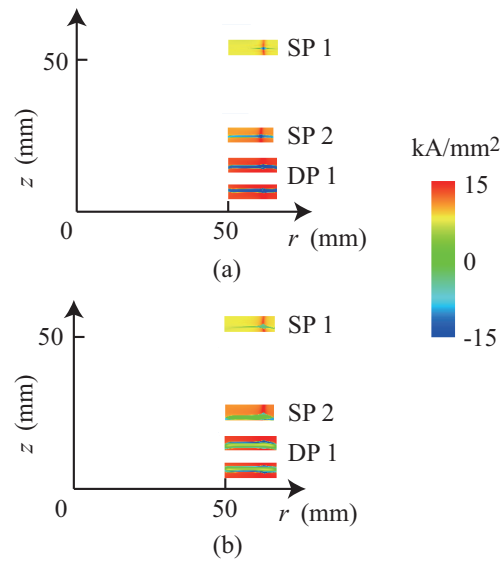


Fig. 6. Current distribution map at $t = 180$ s. (a) the ordinary thin approximation method and (b) the proposed extended thin approximation method.

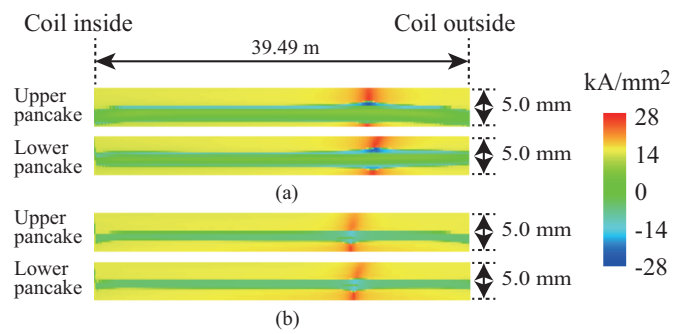


Fig. 7. Current distribution map on unwound REBCO tape of DP 1: (a) the ordinary thin approximation method and (b) the proposed extend thin approximation method. (Not to scale)

C. Screening Current-Induced Magnetic Field

Here, the SCMF B_{S} is defined as follows:

$$B_{\mathrm{S}} = B_0 - B_{\mathrm{ideal}} \tag{7}$$

where B_0 and B_{ideal} are the measured or simulated magnetic field and the magnetic field when the operating current homogeneously flows inside REBCO layer, respectively. Fig. **??** shows B_{ideal} at the magnet center, however the actual magnetic field (B_0) is generated by the inhomogeneous current in the

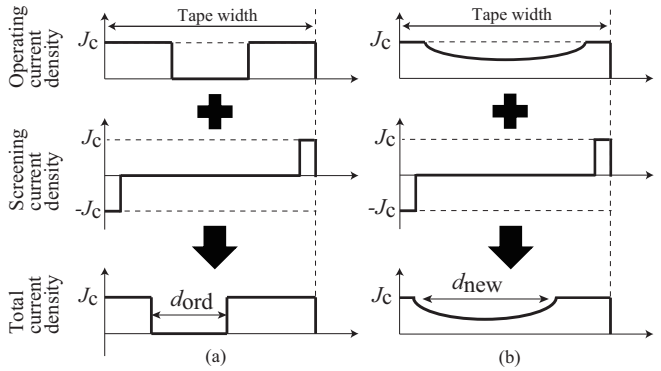


Fig. 8. Current distribution in the tape-transverse direction, superimposing the operating and the screening current: (a) the ordinary and (b) the proposed thin approximation method.

REBCO layer as well as contains the magnetic field induced by the screening currents.

Fig. **??**(a) shows the SCMF at the magnet center, comparing with the ordinary and the proposed simulation methods and the measurement. Obviously, the result of the proposed method is more accurate than the ordinary method. Fig. **??**(b) and (c) show the SCMF generated by each pancake coil of the proposed and ordinary methods, respectively. The SCMFs of each coil are lower than those of the proposed method, because $d_{\mathrm{ord}} < d_{\mathrm{new}}$.

IV. Conclusion

The extended thin approximation method is proposed to more accurately simulate the screening current-induced magnetic field taking into account the carrying operating current inside of REBCO layer. The current distribution obtained by the proposed method is completely different from that using the ordinary thin approximation method. Eventually, the screening current-induced magnetic field is obtained close to the measurements.

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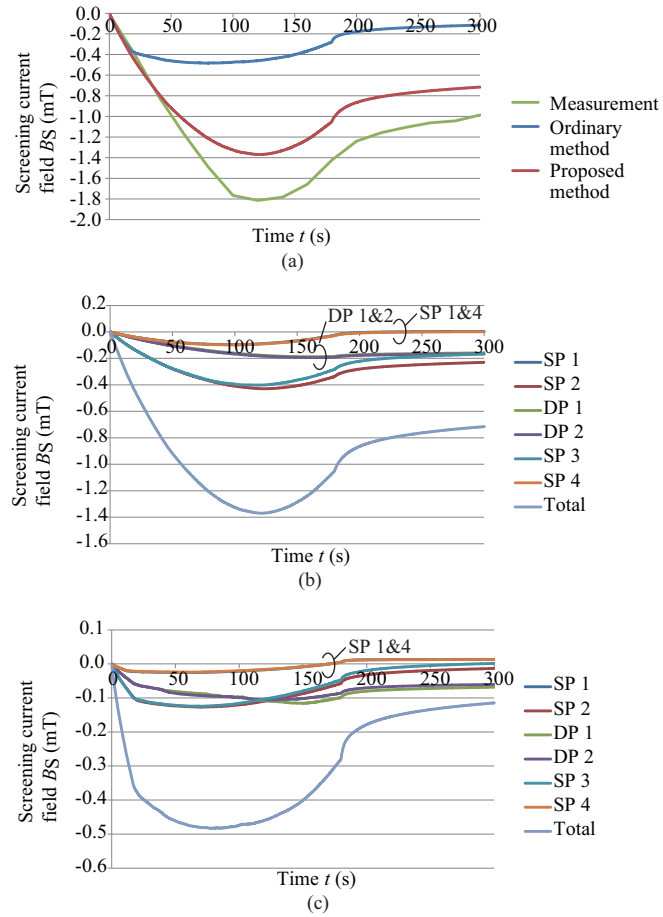

Fig. 9. Screening current-induced magnetic field: (a) the proposed and the ordinary method and the measurement, (b) the proposed and (c) the ordinary method results of each pancake coil.

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