Influences of Geometrical Configuration on AC Loss Measurement with Pickup-Coil Method

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Abstract — We usually measure AC losses of superconducting wires and cables exposed to a transverse AC magnetic field by a pickup-coil method. In this case, a main pickup coil is coaxially located around the sample wire wound as a solenoidal coil. An additional pickup coil (a cancelling coil) is also placed inside or outside the sample coil. This method is advantageous to obtain detailed electromagnetic properties of the sample. In the present study, we discussed the effect of the geometrical configurations of the sample and pickup coils on AC losses measured by the pickup-coil method for three types of arrangements of the cancelling coils. We analytically calculated interlinkage magnetic flux into the pickup coils due to magnetic moments induced in the sample wire, and formulated the geometrical errors in the pickup-coil method. We also prepared some sets of sample and pickup coils, and compared observed AC losses with the theoretical predictions.

I. INTRODUCTION

In the present, international programs toward a standardization for AC loss measurement of NbTi multifilamentary wires are in progress [1]–[4]. In these works, two methods to measure AC losses in NbTi superconducting wires exposed to a transverse AC magnetic field are discussed. One is a method to measure DC magnetization using VSM (Vibrating Sample Magnetometer) or SQUID (Superconducting Quantum Interference Device) and to obtain AC losses by integrating the magnetization curves [1], [3]. The other is a method to measure AC magnetization using two pickup coils in relatively high frequencies [2], [4]. In this paper, the latter is called “a pickup-coil method.”

In the pickup-coil method, the superconducting wire is wound as a solenoidal coil, and a main pickup coil is coaxially located outside it to detect a signal of its magnetization. On the other hand, an additional pickup coil (a cancelling coil) is also placed coaxially inside the sample coil or symmetrically with respect to the main pickup coil in an excitation magnet to cancel out a component induced by the external magnetic field from a terminal voltage of the main pickup coil [2], [4]–[13]. In this paper, these are called “a coaxial arrangement” and “a symmetrical one,” respectively. We theoretically considered the influence of the geometrical relation of the sample and pickup coils on the AC losses observed by the pickup-coil method with two types of arrangements [14]. It is pointed out in this work that we take into account the interlinkage magnetic flux into the cancelling coil due to magnetic moments induced in the sample coil in addition to the main pickup coil. However, the geometrical errors in the AC losses measured by the pickup-coil method have not been experimentally estimated yet.

In this paper, in order to check the theoretical expression of the geometrical error factor, we measured the transverse-field losses in a NbTi multifilamentary wire under various geometrical conditions and obtained the geometrical errors. We also compared them with the theoretical predictions.

II. THEORY

Fig. 1 shows the configurations of sample and pickup coils in the pickup-coil method. Fig. 1(a) represents the configuration in the coaxial arrangement, and Fig. 1(b), (c) are those in the symmetrical one. We assume that the sample coil of $R$ in radius and $2h_s$ in height can be simplified as a very thin cylinder magnetized uniformly. In this case, an apparent AC loss $W$ per unit volume per a cycle of the external magnetic field $H_e$ measured by this method is predicted by estimating interlinkage flux into the pickup coils due to magnetic dipole of the sample coil [14]. The theoretical expression is given by

$$W = -\mu_0 G (\phi) M dH_e,$$

(1)

where $\mu_0$ is the permeability of vacuum and $M$ is the magnetization of the sample defined as a magnetic dipole moment per unit volume. The coefficient $G$ in (1) is represented as [14]

$$G = \frac{1}{8\pi R h_s} \left[ \int_0^{2\pi} g(R+a,\phi) \int_0^{2\pi} g(R+a,\phi) \right] d\phi,$$

(2a)

$$G = \frac{1}{8\pi R h_s} \left[ \int_0^{2\pi} g(R+a,\phi) \int_0^{2\pi} g(R+a,\phi) \right] d\phi,$$

(2b)

$$G = \frac{1}{8\pi R h_s} \left[ \int_0^{2\pi} g(R+a,\phi) \int_0^{2\pi} g(R+a,\phi) \right] d\phi,$$

(2c)

in the cases shown in Fig. 1(a), (b) and (c), with

$$h = \begin{cases} h_{pc} : h_s \geq h_{pc} \\ h_s : h_s < h_{pc} \end{cases},$$

(3)

$$g(r,\phi) = \left[ f(r,\phi,\varepsilon,\zeta_0) \right]_{\zeta=\varepsilon=b_{pc}}^{\zeta=b_{pc}} \left[ f(r,\phi,\varepsilon,\zeta_0) \right]_{\zeta=\varepsilon=-h_s},$$

(4)

$$g'_e (r,\phi) = \left[ f'(r,\phi,\varepsilon,\zeta_0) \right]_{\zeta=\varepsilon=-h_s}^{\zeta=\varepsilon=-h_s} \left[ f'(r,\phi,\varepsilon,\zeta_0) \right]_{\zeta=\varepsilon=-h_s},$$

(5)

$$f = \left[ \left( 2R^2 + r^2 - 3Rr \cos \varphi \right) / \left( R^2 + r^2 - 2Rr \cos \varphi \right) \right] \ln \left( \ell + (z-z_0) \right) \cos \varphi,$$

(6)

$$\ell = \sqrt{R^2 + r^2 + (z-z_0)^2 - 2Rr \cos \varphi}.$$
Here $a$ is the difference between the mean radii of the sample coil and each concentric pickup coil, $2h_p$ is a height of the pickup coils, and $d$ is a distance between the centers of two pickup coils in the case shown in Fig. 1(b). It is assumed that the cancelling coil doesn’t detect the interlinkage flux from the magnetization of the sample coil in the case shown in Fig. 1(c). The coefficient $G$ is dependent only on geometrical parameters of $R$, $a$, $h_s$, $h_p$, and/or $d$. As known from (1), $G$ gives an error factor in the AC loss measurements with the pickup-coil method. We can measure asymptotically accurate AC losses when the factor $G$ approaches to unity.

III. Experiments

The specification of sample is listed in Table I. The sample is a NbTi multifilamentary wire of 0.365 mm in diameter, and has 925 filaments of 7.9 $\mu$m in diameter surrounded by a matrix of Cu-10Ni. The twisting pitch of filaments is 10.8 mm. We fabricated various configurations of the sample and pickup coils. Table II shows their characteristics. The sample was closely wound in a layer. The mean radius of the sample coil is 23 or 8.6 mm, and the height is 10, 20, 40, 50 or 100 mm. The height of the pickup coils is 10, 20 or 50 mm, and the mean distance from the sample coil is 1.5 mm.

We measured the transverse-field losses in combined DC magnetic field of 3 T and sinusoidal AC magnetic fields whose maximum amplitude and frequency are 0.1 T and 1 Hz, respectively. The measuring temperature was 4.2 K. The field homogeneity over the sample and pickup coils was within 1%. An experimental circuit is shown in Fig. 2. $V_c$ and $V_p - kV_c$ are converted into digital signals and stored in a memory of computer, where $V_p$ and $V_c$ are the terminal voltages of the main pickup and cancelling coils, and $k$ is the ratio of output signal to input signal in the resistive voltage divider shown in Fig. 2. We can obtain external magnetic fields $H_e$ by numerically integrating $V_c$ because the magnetic field generated by the magnetization of the sample coil is much smaller than $H_e$. Thus, the AC loss $W$ per unit volume per a cycle of $H_e$ can be numerically calculated by the equation

$$W = -\frac{1}{v_s n_p} \int_0^T (V_p - kV_c) H_e dt,$$

where $v_s$ is the sample volume surrounded by the main pickup coil, $n_p$ is the turn number per unit length of the main pickup coil, and $T$ is the period of $H_e$.

In the pickup-coil method, errors other than the geometrical one may be caused by a magnetization of the superconducting magnet for excitation, eddy currents in the pickup coils and structure materials of metal, a phase difference between the signals $V_p$ and $V_c$, and so on. We obtained a net AC loss by subtracting the error estimated under a condition without the sample inside the main pickup coil from the measured AC loss.

Fig. 3 shows an example of the dependence of measured AC loss densities on the amplitude of AC magnetic field. In this figure, we plotted the AC losses for the sample coil height of 10 to 100 mm in a case of the sample coil radius of 23 mm and the pickup coil height of 20 mm in the coaxial arrangement. In this

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**TABLE I**

<table>
<thead>
<tr>
<th>SPECIFICATION OF A SUPERCONDUCTING WIRE</th>
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<tbody>
<tr>
<td>diameter of wire</td>
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<tr>
<td>diameter of filaments</td>
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<tr>
<td>number of filaments</td>
</tr>
<tr>
<td>twisting pitch</td>
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<tr>
<td>matrix ratio, Cu-10Ni / NbTi</td>
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<td>critical current at 3 T</td>
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**TABLE II**

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF SAMPLE AND PICKUP COILS</th>
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<tbody>
<tr>
<td>sample coil: mean radius, $R$</td>
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<tr>
<td>height, $h_s$, 10, 20, 40, 50, 100 mm</td>
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<tr>
<td>number of layers</td>
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<tr>
<td>pickup coils: height, $2h_p$</td>
</tr>
<tr>
<td>mean distance from sample coil, $a$</td>
</tr>
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<td>mean distance between each other, $d$</td>
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case, the theoretical prediction of geometrical coefficient $G$ in $2h_t = 100$ mm is 1.0017 and approximately equal to unity. Therefore, we can obtain geometrical coefficients in the other sample coil heights on the basis of the AC losses measured in the case of $2h_t = 100$ mm.

Experimental results of geometrical coefficients obtained using similar procedures are shown in Figs. 4–7. In these figures, the theoretical curves are also drawn by solid lines. One can see that the experimental results almost agree with the theoretical predictions in wide ranges of geometrical parameters of $R$, $h_s$, and $h_{pc}$. Thus, we can almost exactly discuss the geometrical errors with the theoretical expression shown in (2).

IV. DISCUSSION

In AC loss measurements with the pickup-coil method, many researchers are using the symmetrical arrangement [2], [8]–[13] because they can set up their experimental equipment without a resistive voltage divider for cancellation shown in Fig. 2. That is, they can easily remove a component induced by the external magnetic field from the terminal voltage of the main pickup coil when it is connected in series opposite with the cancelling coil having an identical specification. However, one can see from Figs. 4–7 that the geometrical errors in the symmetrical arrangement are larger than those in the coaxial one. This is because a Poynting's vector through an arbitrary cylindrical surface inside the sample coil can't be detected in the symmetrical arrangement. In general, we can estimate the AC loss in a superconducting wire by integrating Poynting's vector $\mathbf{E} \times \mathbf{H}$ on a closed surface surrounding the wire over a cycle of the external magnetic field, where $\mathbf{E}$ and $\mathbf{H}$ are the electric field and the magnetic field on the surface, respectively. In the coaxial arrangement, most of Poynting's vector coming in and out through a closed surface surrounding the sample can be detected because the surfaces formed by two pickup coils can be approximately regarded as a closed one. In the symmetrical arrangement, on the other hand, only a part of Poynting's vector can be detected with the main pickup coil. In this case, the surface formed by the main pickup coil is approximately considered as a closed one when its height is much longer than that of the sample coil. As a result, we may need much larger excitation magnet and power supply in order to realize a huge space with an uniform magnetic field when we measure asymptotically accurate AC losses in the symmetrical arrangement.

V. CONCLUSION

We experimentally estimated the geometrical errors within the transverse-field losses measured by the pickup-coil method with different arrangements of the pickup coils. The obtained results were almost reproduced by the theoretical expression. From both the theoretical predictions and the experimental results, it is concluded that the usable range in geometrical configuration of the coaxial arrangement, in which two pickup coils are located inside and outside the sample coil, is much wider than that of the symmetrical one, in which they are symmetrically placed in an excitation magnet. When we use the latter as

![Experimental circuit to measure transverse-field loss for pickup-coil method.](image)

Fig. 2. Experimental circuit to measure transverse-field loss for pickup-coil method.

![Dependence of transverse-field losses on amplitude of external magnetic field in case of $R = 23$ mm and $2h_{pc} = 20$ mm.](image)

Fig. 3. Dependence of transverse-field losses on amplitude of external magnetic field in case of $R = 23$ mm and $2h_{pc} = 20$ mm.

![Geometrical coefficient $G$ versus ratio of heights $h_s/h_{pc}$ in case of $R = 23$ mm in coaxial arrangement shown in Fig. 1(a).](image)

Fig. 4. Geometrical coefficient $G$ versus ratio of heights $h_s/h_{pc}$ in case of $R = 23$ mm in coaxial arrangement shown in Fig. 1(a). Symbols are experimental results, and solid lines are theoretical curves calculated by (2a).
Fig. 5. Geometrical coefficient $G$ versus ratio of heights $h_s/h_{pc}$ in case of $R = 8.6$ mm in coaxial arrangement shown in Fig. 1(a). Symbols are experimental results, and solid lines are theoretical curves calculated by (2a).

Fig. 6. Geometrical coefficient $G$ versus ratio of heights $h_s/h_{pc}$ in case of $R = 23$ mm in symmetrical arrangement shown in Fig. 1(b). Symbols are experimental results, and solid lines are theoretical curves calculated by (2b).

Fig. 7. Geometrical coefficient $G$ versus ratio of heights $h_s/h_{pc}$ in case of $R = 8.6$ mm in symmetrical arrangement shown in Fig. 1(c). Symbols are experimental results, and solid lines are theoretical curves calculated by (2c).

the method to measure the transverse-field losses, we must pay more attention to calibrate the obtained results taking into account its geometrical error.

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REFERENCES


