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Evaluation of uncertainty in the inductive measurement of critical current densities of superconducting films using third-harmonic voltages

H. Yamasaki [a,*], Y. Mawatari [a], Y. Nakagawa [a], H. Yamada [b]

[a] National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
[b] Oshima National College of Maritime Technology, 1091-1 Komatsu SuouOshima-city, Oshima County, Yamaguchi 742-2193, Japan

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ABSTRACT

Several techniques can be used for inductive measurement of the critical current density J_c of large-area superconducting thin films used in microwave devices and fault-current limiters. The most popular of these methods employs the third-harmonic voltages V_3. We have proposed a standard method using V_3 for determining J_c under a criterion of electric field E. Here, the uncertainty in the standard method is evaluated. Since the measured J_c is directly proportional to the magnetic field at the upper surface of the superconducting film, the most significant systematic effect is the deviation of the coil-to-film distance Z_1 from the prescribed value. The principal origins of this deviation of Z_1 are (1) inadequate pressing of the coil onto the film and (2) ice layers occasionally forming between the coil and the protective polyimide film. If these effects are eliminated, uncertainty of J_c originates mainly from (a) uncertainty of the experimental coil coefficient k', which is dominated by uncertainty of the transport J_c, and (b) underestimation of the induced electric field E when using a simple Bean model. For a typical $DyBa_2Cu_3O_7$ film specimen, the relative combined standard uncertainty in the standard method was evaluated as ∼5%. The effect of the film edge on J_c measurements is also described.

1. Introduction

High-temperature superconducting (HTS) microwave filters, which make use of the extremely low surface resistance of HTS thin films, have already been commercialized in cellular telephone base stations [1]. They possess two major advantages over conventional non-superconducting filters, namely low insertion loss (low noise characteristics) and high frequency selectivity (sharp cut) [2]. Large-area HTS thin films have been fabricated for use in microwave devices [3], and they are also used in emerging superconducting power devices, such as resistive-type superconducting fault-current limiters (SFCLs) [4–6] and persistent-current switches used for persistent-current HTS magnets [7,8]. The critical current density J_c is a key parameter describing the quality of HTS films. Nondestructive AC inductive methods are widely used for measuring J_c and its distribution in large-area HTS films [9–12]. Among these methods, a technique that utilizes the third-harmonic voltage $V_3\cos(3\omega t + \theta)$ is the most widely adopted [9,10].

In the V_3 inductive method, an AC magnetic field is generated by an AC current $I_0\cos\omega t$ in a small coil mounted just above the film, and the amplitude of the third-harmonic voltage V_3 generated in the coil is measured as a function of I_0 (inset of Fig. 1). V_3 is zero up to a certain threshold coil current I_{th}, after which it starts to emerge at $I_0 = I_{th}$. By using this threshold coil current I_{th} (at which full penetration of the magnetic field to the film is achieved), J_c can be calculated as $J_c = k'I_{th}/d$, where k' is the experimental coil coefficient and d is the film thickness [13–15]. For an explanation of the experimental coil coefficient and other terms, see the nomenclature below. Since the scaling relation observed between V_3/I_0 and I_0/I_{th}, namely $V_3/I_0 = 2\pi f|G(I_0/I_{th})|/(I_0/I_{th})$, is at the base of this measurement method, I_{th} must be determined by using a constant-inductance ($V_3/fI_0 = 2\pi L_c$) criterion [13–15]. An example demonstrating the determination of I_{th} is shown in Fig. 1. Since the critical current density J_c depends on the electric-field (E) criterion, the threshold current I_{th} also depends on E and consequently on the frequency f. The electric field induced in the superconducting film at $I_0 = I_{th}$, which is proportional to the frequency f of the AC current, can be estimated from a simple Bean model [16] as follows:

$$E_{avg} \approx 2.04\mu_0 f d^2 J_c = 2.04\mu_0 k f d I_{th}, \quad (1)$$

where k is the theoretical coil coefficient. A standard method has been proposed for precisely measuring J_c with an electric-field criterion and obtaining the n-values (indices of the power-law E–J characteristics) by precisely measuring I_{th} at various frequencies [15,17,18]. In this paper, the uncertainties of J_c and n-values in the standard method are evaluated, and the effect of the film edge on J_c measurements is also described.

* Corresponding author. Tel.: +81 29 861 5264; fax: +81 29 861 5726.
E-mail address: h.yamasaki@aist.go.jp (H. Yamasaki).

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Nomenclature

I_{th} experimental threshold coil current at which V_3 starts to emerge. It must be defined by using a constant-inductance criterion, specifically, $V_3/fI_0 = 2\pi L_c$ (see Fig. 1). The criterion L_c should be as small as possible within the range with a sufficiently large S/N ratio, in order to use the simple Eq. (1) for calculating the electric field (see Section 3.3)

k' experimental coil coefficient, which is the parameter used for calculating $J_c = k' I_{th}/d$ from the obtained I_{th} (see Fig. 1). The procedure for obtaining k' has been reported in [15], and it is briefly described in Section 3.2

k theoretical coil coefficient calculated from the maximum parallel magnetic field at the surface of the superconducting film as $k = \max(F(r)) = 2H_{0,max}/I_0$ (Fig. 2a and b) [13]. When the coil current I_0 equals the theoretical threshold current I_{th0}, the highest magnetic field below the coil is $2H_{0,max} = J_c d$, and the magnetic field just fully penetrates the film. Since the theoretical coil coefficient k can be calculated from the coil parameters [13], we can obtain $J_c = kI_{th0}/d$. However, the above theoretical I_{th0} corresponds to the coil current at which infinitesimal V_3 is generated in the coil. As it is impossible to detect $V_3 \approx 0$ to obtain I_{th0}, an alternative approach is needed to obtain an experimental I_{th}, at which detectable V_3 is generated, and the corresponding experimental coil coefficient k' [15]. Generally, k' is about 30% smaller than k, and therefore I_{th} is ~30% larger than I_{th0}, as shown in Fig. 1

2. Experimental

To measure J_c by detecting V_3 we employed an electric circuit similar to that described by Yamasaki et al. [16], in which a cancel coil with the same specifications as the sample coil was used for noise cancelation. Three different coils were used in the experiments, and their specifications (inner winding diameter D_1; outer diameter D_2; height h; and number of turns), coil coefficients and inductance criteria used to determine I_{th} for these coils are shown in Table 1. Each coil was mounted at a distance of $Z_1 = 0.2$ mm from a superconducting film, and V_3 measurements were performed with the film specimen and the coils immersed in liquid nitrogen. To obtain the E–J characteristics, we plotted V_3–I_0 curves from data obtained at frequencies from 200 Hz to 20 kHz. We also measured the DC magnetization using an Oxford vibrating sample magnetometer on rectangular film specimens (~3 mm × ~11 mm), and obtained the E–J characteristics from the dependence of the magnetization on the magnetic field sweep rate [19].

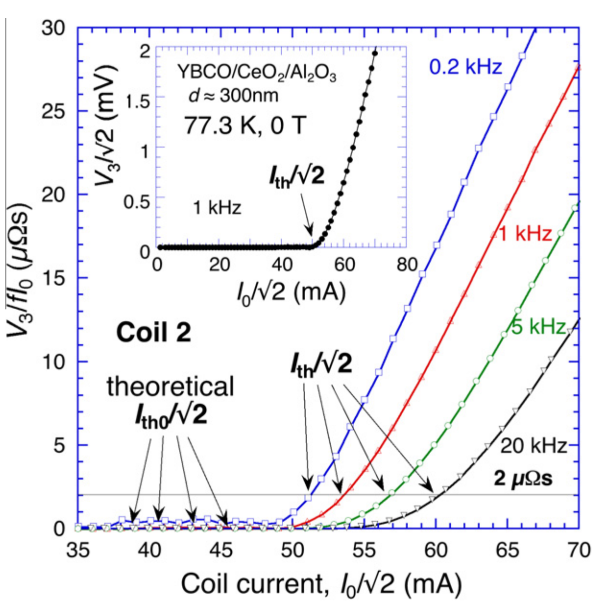

Fig. 1. Example V_3/fI_0 values measured at various frequencies using coil 2 in Table 1. The difference between experimental and theoretical values of I_{th} is clearly seen, where the latter was calculated from the ratio between k' and k. The inset shows the curve for V_3 vs. I_0 plotted from data measured at $f = 1$ kHz.

3. Results and discussion

3.1. Systematic effects that affect the measurement

The most significant systematic effect on the V_3 measurement is the deviation of the coil-to-film distance Z_1 from its prescribed value. Because $J_c d$ values measured by this standard technique are directly proportional to the magnetic field $2H_0$ at the upper surface of the superconducting film, the deviation of Z_1 directly affects

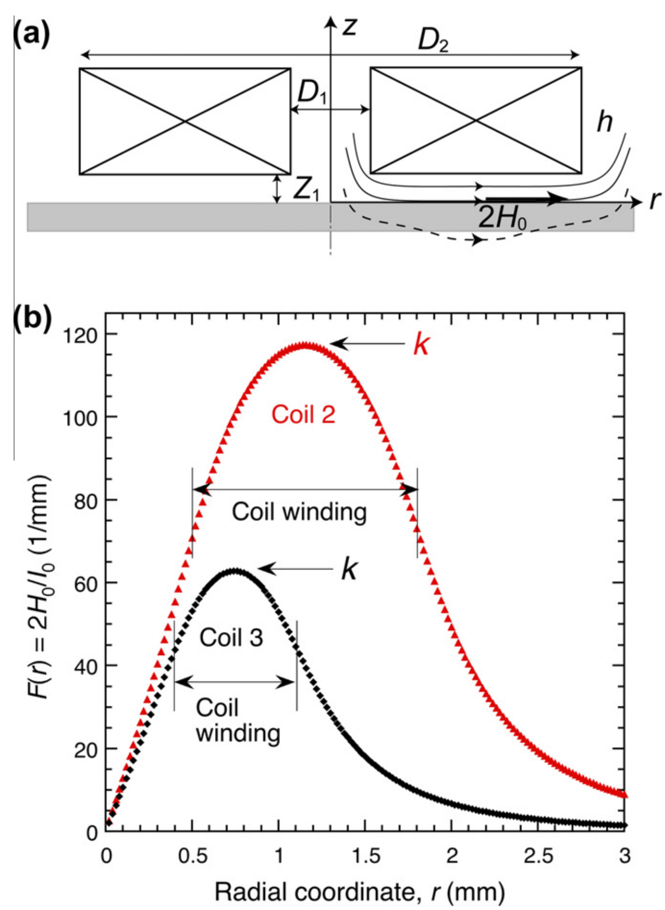

Fig. 2. (a) Schematics of a coil and its associated magnetic field during measurements. (b) Coil-factor function $F(r) = 2H_0/I_0$, which represents the radial component of the magnetic field divided by the coil current at a position 0.2 mm below the coil windings.