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Bulk high-T_c magnetometer

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Abstract. We report a study of a bulk YBCO magnetometer based on the detection of harmonics during nonlinear magnetization. For a low-DC field, the amplitude of the even harmonic appearing at the pickup coil depends linearly on the DC field intensity. The performance of the magnetometer depends on the quality of the sample, and the intensity and frequency of the AC field excitation. At higher H_{ac}, the fourth harmonic becomes more sensitive than the second harmonic. The hysteresis in the magnetometer for DC field measurement has been reported.

Keywords. Harmonic generation; YBCO; magnetometer.

1. Introduction

A bulk YBCO magnetometer based on the RF SQUID effect, with noise sensitivity $\approx 10^{-10}\mathrm{T/(Hz)^{1/2}}$, was reported earlier (Pegrum *et al* 1987). It utilizes the internal superconducting loops connecting internal weak links. However, the presence of many loops of varying area and critical current introduces an ambiguity in flux locking and thus limits the applicability of the bulk magnetometer. Eventually more controllable two-hole devices were constructed which showed more sensitive performance (Harrop *et al* 1988; Poulshkin and Vaisiliev 1989; Khare *et al* 1991). Recently observations of harmonic generation in bulk YBCO have been reported by many workers (Ji *et al* 1989; Muller 1989; Ishida and Goldfarb 1990; Buckley *et al* 1991; Kumar *et al* 1993; Gilbricht and Domre 1994; Karthikeyan *et al* 1994; Revenaz and Dumas 1994). This is an outcome of the nonlinear magnetization behaviour of the material. A bulk high-T_c magnetometer based on this nonlinear phenomenon was demonstrated by Gallop *et al* (1988) and had noise sensitivity $\approx 10^{-10}\mathrm{T/(Hz)^{1/2}}$. Such a device is sometimes called a 'superconducting flux gate magnetometer' because of its mode of operation. Buckley *et al* (1991) have demonstrated the applicability of this magnetometer to nondestructive evaluation of steel plates.

In this paper we report on a detailed study of the dependence of the sensitivity factor of the bulk YBCO magnetometer on operating conditions and on the quality of sample. A comparison of the sensitivity of the magnetometer using second and fourth harmonics has been made.

2. Background to the experiment

Consider a specimen on which a uniform AC magnetic field ($H(t) = H_{ac}\sin\omega t$) is applied.

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The magnetization $M(t)$ as a function of t is given by

$$M(t) = H_{ac} \sum_{n=1}^{\infty} [\chi'_n \sin(n\omega t) - \chi''_n \cos(n\omega t)], \tag{1}$$

where $\chi_n = \chi'_n - i\chi''_n (n = 1, 2, 3, \ldots)$. The quantities χ'_n and χ''_n can be calculated by

$$\chi'_n = 1/\pi H_{ac} \int_0^{2\pi} M(t) \sin(n\omega t) \, d(\omega t), \tag{2}$$

and

$$\chi''_n = -1/\pi H_{ac} \int_0^{2\pi} M(t) \cos(n\omega t) \, d(\omega t). \tag{3}$$

When a pickup coil is wound over the specimen, the voltage induced in it is proportional to the time derivative of $M(t)$,

$$V(t) = dM(t)/dt = H_{ac} \sum_{n=1}^{\infty} n\omega [\chi'_n \cos(n\omega t) + \chi''_n \sin(n\omega t)]. \tag{4}$$

It is usual to use a spectrum analyser to display the Fourier transform of $V(t)$ directly, so that the amplitudes, V_n, of higher-harmonic terms can be directly observed. Here V_n is directly proportional to $\omega H_{ac} \chi_n$. When the DC field is also present then $H(t) = H_{ac} \sin(\omega t) + H_{dc}$, while the form of (1) remains the same.

Measurements of the AC susceptibility of YBCO superconducting materials have shown that the materials have a highly nonlinear magnetization which is strongly dependent on both H_{dc} and H_{ac} even at low fields (Buckley 1991). The application of the critical state model, in which the critical current density J_c flowing at any point in the sample is solely a function of the local field intensity H_1 at that point, has been used by many workers (Ji *et al* 1989; Ishida and Goldfarb 1990; Buckley *et al* 1991) to explain the nonlinear magnetization and the appearance of even and odd harmonics. Even harmonics are found to be odd functions and odd harmonics to be even functions of DC field.

3. Experimental

Three types of bulk samples were used in the present study: dense, less dense and foam types, which had 34%, 64% and 88% porosity respectively. In each case a bulk sample of YBCO was cut into rectangular blocks of dimensions 10 mm × 4 mm × 2 mm. A 10-turn copper coil wound on the YBCO rectangular block formed the pickup coil. The block was mounted on the axis of a solenoid. A signal generator (HP 3325A) provided the excitation and the spectrum of the signal in the pickup coil was measured using a spectrum analyser (HP 3561A at low frequencies and HP 8590 for excitation frequencies above 25 kHz).

To determine the sensitivity of the device as a magnetometer a second solenoid, coaxial with the first, was used to apply DC fields on the specimen. The size of the even harmonics was measured by the spectrum analyser.

4. Results and discussion

The presence of a DC field causes the appearance of even harmonics. For small variations of the DC field, the changes in the amplitude of the even harmonics are linear. Thus measuring the voltage corresponding to even harmonics can give an estimate of the DC field. The magnitude of this voltage has been found to depend on the quality of the sample, on the intensity and frequency of the AC drive, and also on which even harmonics was considered. For comparing various results a sensitivity figure α_n, indicating the smallest field change which could be detected using the nth harmonic, was defined as

$$\alpha_n = \delta V/(\delta V_n/\delta H_{dc}), \tag{5}$$

where $\delta V_n/\delta H_{dc}$ is the rate of change of voltage corresponding to even harmonic with DC field for linear region of V_n–H_{dc} characteristic. δV is the uncertainty in measurement for a particular operating condition at a fixed DC field (H_0), and is due to the combined noise present in the sample and measuring system.

4.1 *Dependence of DC field sensitivity on H_{ac}*

Figure 1 shows the variation of the sensitivity, α_2, with H_{ac} for three YBCO samples of varying porosities (sample A 34%, sample B 64%, sample C 88% 'foam type'). For samples B and C, α_2 increases as H_{ac} increases, whereas for sample A α_2 decreases at first before increasing at $H_{ac} \sim 3{\cdot}4$ mT. The second-harmonic amplitude depends upon the pinning force density of the material, which in turn depends upon the number of pinning sites per unit volume (n_p) and the pinning force of the sites. The critical current of the sample governs the depth to which magnetic field penetrates. In samples B and C, n_p was less than in sample A and furthermore because of weak flux pinning, the field penetrated the sample fully even at $H_{ac} \sim 0{\cdot}9$ mT. As H_{ac} was increased the intergranular critical current decreased according to the Kim model, and hence $\delta V_n/\delta H_{dc}$ decreases leading to an increase in α_2. In sample A, the stronger pinning and larger value of n_p caused the increase in $\delta V_n/\delta H_{dc}$ (α_2 decreases) with increase in H_{ac}. As the flux penetration increased, more and more pinning sites

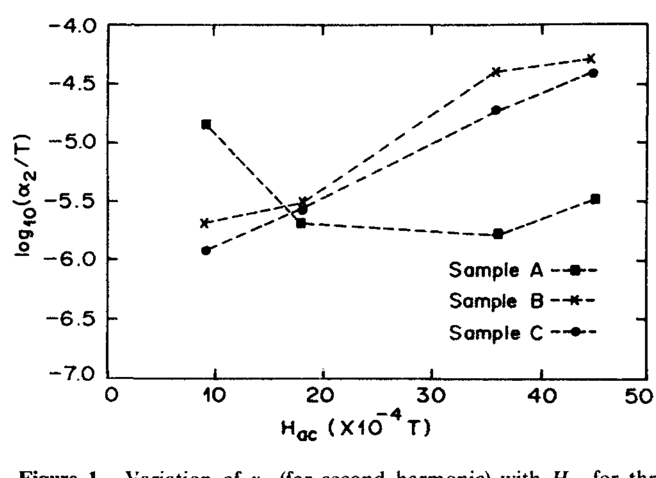

Figure 1. Variation of α_2 (for second harmonic) with H_{ac} for three samples of YBCO of varying porosities (sample A 34%, sample B 64%, sample C 88%).

contributed to magnetization. α_2 reached a minimum when AC field fully penetrated the sample. As AC field was increased to 3·4 mT, α_2 started increasing in a manner similar to samples B and C.

4.2 *Second versus fourth harmonic*

Measurements of α_n for second (α_2) and fourth (α_4) harmonics revealed an interesting result. Figures 2a and 2b show the variation of α_n for second and fourth harmonics with H_{ac} for samples A and B. For the dense sample, α_2 was greater than α_4 at small values of H_{ac}. However for $H_{ac} > 28$ Oe the fourth harmonic became smaller. For the less dense sample B, this crossover point was observed to occur at lower $H_{ac} \approx 10$ Oe. This feature is predicted in Kim's critical state model. The crossover point depends on the critical current density of the sample. If J_c is small (for less dense sample) then the crossover point is expected to occur at a lower value of AC field.

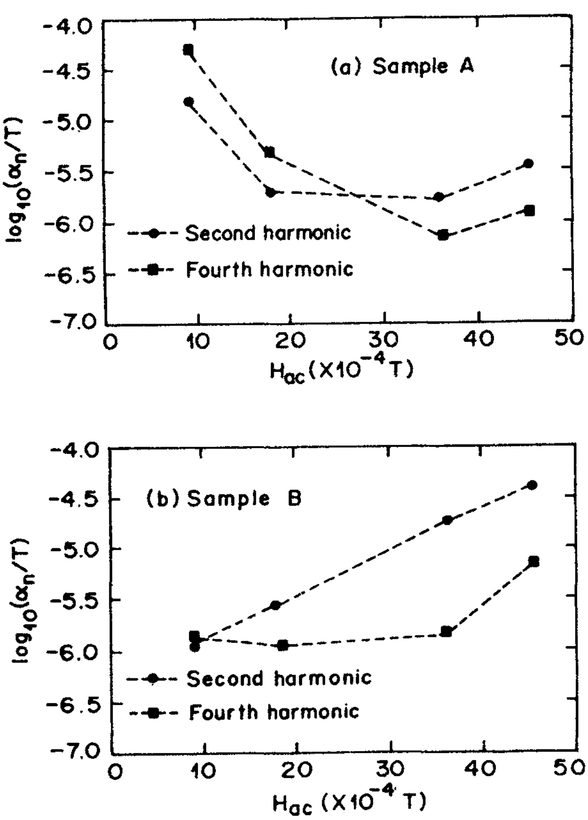

Figure 2. Variation of α_n with H_{ac} corresponding to second and fourth harmonics for sample A (dense) and sample B (less dense).

4.3 *Dependence of DC field sensitivity on frequency of AC drive field*

Figure 3 shows the variation of α_n with the frequency of AC drive field. The AC field intensity was kept constant to 3·6 mT p^k–p^k during the whole measurement. α_n was found to decrease with the frequency. The signal at the pickup coil is the time derivative of the magnetization, M. Thus it is expected to be proportional to f. The inset in figure 3 shows a plot of $(V_2/f)_n$ against f which is proportional to α_2. $(V_2/f)_n$ represents the normalized value of V_2/f at 1 kHz. It shows a decrease with an increase in frequency. The critical state model for granular high-T_c superconductors does not predict the frequency dependence of the intergranular and intragranular critical state profiles (Muller 1989). However, the addition of thermally activated flux creep to the current density term in the critical state equation can explain the frequency dependence behaviour (Muller 1990). With the increase in frequency due to flux creep effect, the effective penetration decreases and hence χ_2 is expected to decrease as observed experimentally. Thus the operation of the magnetometer at very high frequencies will not yield any improvement in its performance.

4.4 *Hysteresis in bulk YBCO magnetometer*

An essential criterion for a practical magnetometer is that it should show negligible hysteresis in its output between increasing and decreasing fields. To investigate this we measured a hysteresis parameter h which was defined as:

$$h = (V_1 - V_2)/(\delta V_n/\delta H),$$

where V_1 was the magnetometer output voltage at a field $H_0(= 10^{-5}\,\mathrm{T})$ when the field was increasing to H_{max} and V_2 was the output voltage at H_0 when the field was decreasing from H_{max}. These measurements were taken by ramping the field from zero to H_{max} and then back to zero. $\delta V_n/\delta H$ was the slope of V_n–H characteristic corresponding

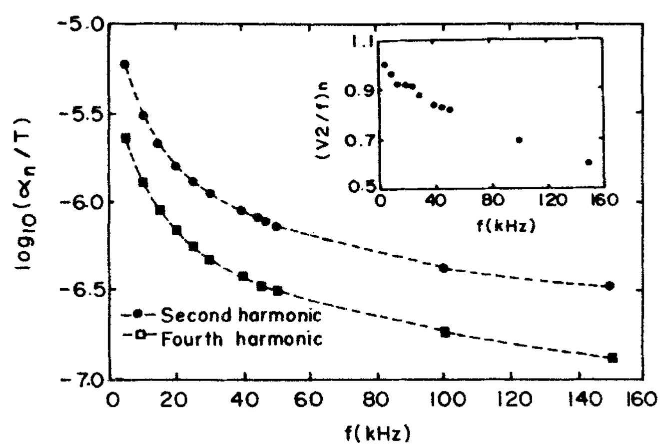

Figure 3. Variation of α_n with frequency of AC drive field. Inset shows variation of $(V_2/f)_n$ with f, V_2 being amplitude of the second harmonic.

to second harmonic. For DC field measurement, when H_{max} was less than 0·2 mT h was equal to α_2, but when $H_{max} > 0{\cdot}2$ mT h increased. This measurement indicates the limitation of the present bulk YBCO magnetometer for DC field measurement when the variation in the field is large.

5. Conclusion

The performance of the bulk YBCO magnetometer has been found to depend on the quality of YBCO sensor, intensity and frequency of the exciting AC field. At higher AC fields, the fourth harmonic was more sensitive than the second harmonic. Use of the dense sample as a sensor gave a better performance. Increasing the operating frequency improves magnetometer sensitivity but due to flux creep effect χ_2 decreases, and so there is no improvement if the magnetometer is operated above 150 kHz.

Hysteresis measurements revealed that the magnetometer for DC field measurement could work well if the variation in the DC field is less than 0·2 mT. Field sensitivities of $\sim 10^{-7}$ T were achieved in the present experiment by optimizing the operating conditions. However, no averaging of the observations and no optimization in pickup coil designing and sample size was done. Inclusion of these will improve the sensitivity further.

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