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Virtual additive moments measured by a vibrating sample magnetometer on superconducting thin films

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Abstract. Virtual additive magnetic moment was observed on a series of YBaCuO thin films in an external field perpendicular to the film plane: magnetic hysteresis loops measured by a PAR 155 vibrating sample magnetometer up to fields of ± 2 T were symmetrical at high field sweep rates, whereas at low sweep rates they exhibited a large additive offset of the reversible magnetic moment. This effect increased particularly at high fields and it was especially noticeable at intermediate temperatures, typically between 40 and 65 K. We identified this phenomenon as an artefact originating from vibrations of a sample possessing a high differential susceptibility in a slightly inhomogeneous bias field. This undesirable effect is quite general and it can be generated in any type of VSM with even very slight inhomogeneity of magnetic field. It can however, be found only on laterally large, thin samples with a high differential susceptibility (typically thin films). Experimental results are consistently explained by the proposed model. We present expressions which enable us to estimate this effect from the differential susceptibility of the sample and known inhomogeneity of the bias magnetic field.

1. Introduction

Measurement of induced magnetic moment in superconductors is a widely used method for the study of critical currents [1]. Magnetic measurements are very frequently performed on vibrating sample magnetometers (VSM) which enable rapid measurement of magnetic moment in the regimes of both constant and sweeping field [2–5]. In the study of superconductors the former regime corresponds to the conventional relaxation experiment, the latter one to measurements of magnetic hysteresis loops (MHL). The amplitude of sample vibrations is small (typically a few tenths of a millimetre) and the effect of sample translations during the measurement can usually be neglected.

The finite height of the MHL ($m^+ - m^-$), where m^+ and m^- are the moment values on the descending and ascending field branch, respectively, of the MHL, is a result of an equilibrium between induction of critical currents by a change of external magnetic field and the simultaneous relaxation of the induced current due to thermal activation. Therefore, shape of the MHL strongly depends on the value of the field sweep rate R [6–9]. MHL is narrow at low R and wide at high R. In most superconducting thin films the reversible magnetic moment defined as $m_r = (m^+ + m^-)/2$ is negligible and MHL is, therefore, nearly symmetrical with respect to the field axis, irrespective of the field sweep rate.

MHL measured on several thin $YBa_2Cu_3O_{7-\delta}$ films at low sweep rates were not only narrower, but they also exhibited anomalous additive reversible moment, i.e. they were shifted at high positive fields towards positive moment values and at high negative fields towards negative moment values [10]. Measurements at larger sweep rates did not exhibit such an offset. This peculiar behaviour was particularly evident at intermediate temperatures (40–65 K). If we assume that the 'real' reversible moment in our thin films is negligible and the observed shift of MHL recorded by VSM is due to some additive virtual moment m_{vir} we have to start to distinguish strictly between the real moment existing in the sample and that obtained as output from the magnetometer. Throughout all this paper we will denote the former as m and the latter as m_m.

It is interesting to note that some spurious signals due to inhomogeneity of bias magnetic fields during the sample scan have also been observed during measurements of induced magnetic moments of superconductors performed on SQUID magnetometers with a moving sample (for example the Quantum Design MPMS [11]). These effects have been discussed in detail in [12, 13].

The aim of this paper is detailed experimental description and theoretical explanation of the virtual additive moment $m_{vir} = (m_m^+ + m_m^-)/2$ recorded by VSM and formulation of the criteria when this virtual additive moment appears.

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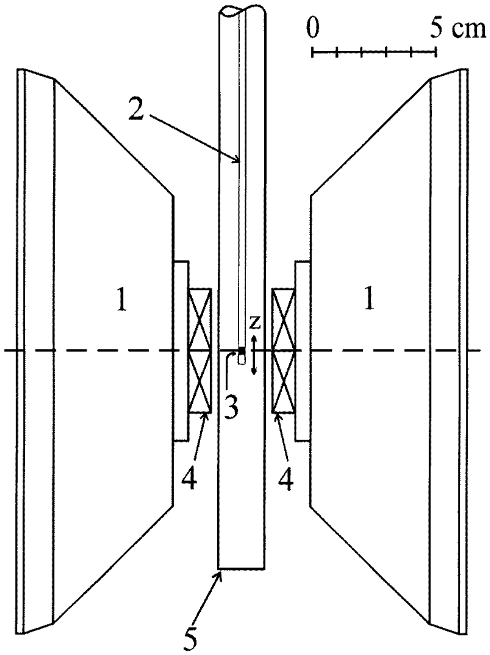

Figure 1. Schematic view of the 11″ magnet pole tips (1) with the sample (3) centred between pick-up coils (4). The sample holder (2) with the sample vibrates with frequency $\omega_v/2\pi$ = 82 Hz and with amplitude $a_v \approx 0.2$ mm inside a helium cryostat (5). The sample position is characterized by the coordinate z along the sample holder. The optimum sample position is in the geometrical centre of the pick-up coils which should be also identical with the geometrical centre of the magnet poles. The range of the investigated sample positions from the centre of the pick-up coils is marked by arrows. All dimensions are scaled as indicated at the upper part of the figure.

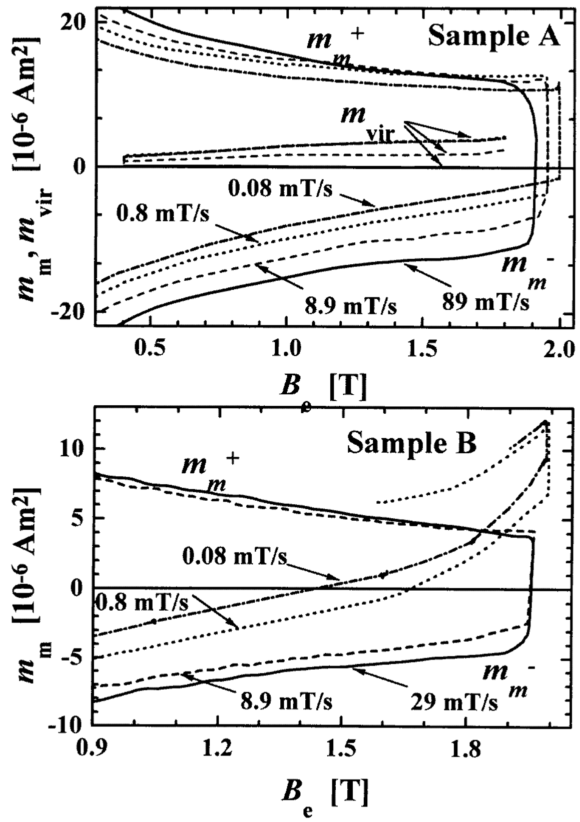

Figure 2. Magnetic moment value m_m recorded by the magnetometer in a sweeping external magnetic field B_e (i.e. the magnetic hysteresis loops (MHL)) measured on sample A at 60 K at various rates of field sweep between 89 and 0.08 mT s^{-1}. B_e was perpendicular to the film plane. Besides the upper (m_m^+) and lower (m_m^-) branch of the MHL the values of $m_{vir} = (m_m^+ + m_m^-)/2$ are also indicated. MHL recorded with high sweep rates ($>$ 30 mT s^{-1}) are nearly symmetrical with respect to the field axis at all temperatures; MHL at slow sweep rates ($<$ 1 mT s^{-1}) are shifted to the positive moment values. This effect considerably increases in high fields. Similar MHLs measured on sample B at 65 K exhibit even more pronounced positive offset at slow sweep rates.

2. Experiment

Magnetic hysteresis loops analysed in this paper were measured on two samples of $YBa_2Cu_3O_{7-\delta}$ thin films prepared by magnetron sputtering on yttrium-stabilized ZrO_2 with (100) orientation (sample A) and on $SrTiO_3$ with (100) orientation (sample B). The thickness of both samples was 200–300 nm, and the lateral dimensions 5 × 5 mm^2. All measurements were done with the external magnetic field perpendicular to the film plane (i.e. along the c-axis).

We used a Princeton Applied Research VSM, model 155, with sample vibration frequency $\omega_v/2\pi$ = 82 Hz and amplitude $a_v \approx 0.2$ mm [5]. Four signal pick-up coils are geometrically centred between magnet pole faces (see figure 1) to record the magnetic moment in the direction perpendicular to the sample vibrations. The distance between them is 25.4 mm. The optimum sample position is in the geometrical centre of the signal pick-up coils (the saddle point); these are mounted in such a position as to be symmetrically centred with the magnet poles. The d.c. voltage output from the original VSM electronics (the lock-in amplifier) is recorded by a Keithley 2001 multimeter and processed by a PC 486 computer. The magnetic field is produced by a conventional Newport Instruments 11″ electromagnet with the magnet power supply C904 operating up to ±2 T. The power supply is controlled by a non-commercial sweep unit using a temperature-stabilized calibrated Hall sensor in a field regulation circuit which allows measurements at constant field sweep rates ranging from 90 mT s^{-1} to 60 μT s^{-1}.

Magnetic moment values m_m recorded by the magnetometer in sweeping external magnetic field B_e (i.e. the MHLs) measured with high sweep rates (typically $R > 30$ mT s^{-1}) were symmetrical with respect to the field axis ($m_m^+ + m_m^- \approx 0$). However, the MHLs measured at slow sweep rates ($R < 1$ mT s^{-1}) were at intermediate temperatures (typically between 40 and 65 K) at high positive fields considerably shifted to positive moment values ($m_m^+ + m_m^- \gg 0$, see figure 2). To recognize the mechanism responsible for the additive moment we performed a series of experiments under different conditions.

The typical sweep rate dependence of $m_{vir} = (m_m^+ + m_m^-)/2$ measured on sample A at three different

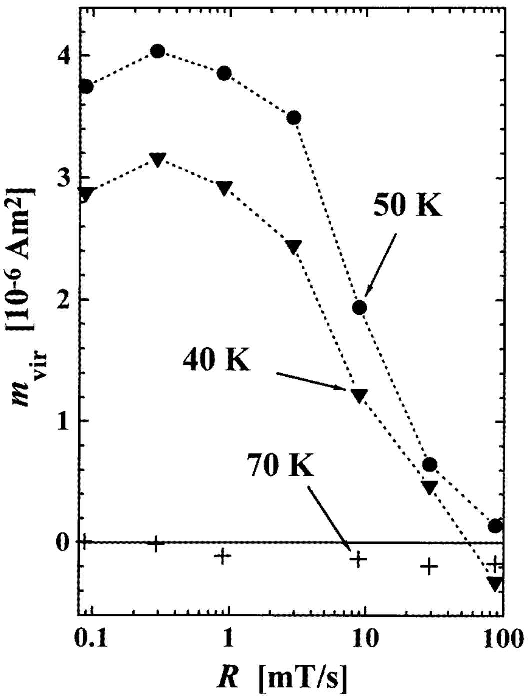

Figure 3. The dependence of $m_{vir} = (m_m^+ + m_m^-)/2$ on the field sweep rate $R = \partial B_e/\partial t$ measured on sample A at three different temperatures. m_m^+ and m_m^- are magnetic moment values at B_e = 1.8 T obtained from the upper and lower branches of MHLs measured by VSM with various R. m_{vir} increases considerably with decreasing R at temperatures of 40 and 50 K but it stays close to zero at 70 K for any value of R.

temperatures and evaluated in the external field $B_e = 1.8$ T is presented in figure 3. We can see that m_{vir} is close to zero at sweep rates higher than about 30 mT s^{-1} but increases considerably with decreasing R. At about $R < 1$ mT s^{-1} the dependence $m_{vir}(R)$ nearly saturates at a maximum value. Figure 3 also shows that $m_{vir}(R)$ stays at $T = 70$ K close to zero (MHL is symmetrical) for any measured value of R. It illustrates the effect of temperature. Increase of temperature to about 70 K and higher leads to a rapid reduction of the additive apparent moment.

To specify the effect of the sample position we have measured sets of MHLs at different vertical distances of the sample from the centre of the signal pick-up coil set (parallel to the vibration direction). The sample was moved within a 12 mm range around the geometrical centre of the pick-up coils fixed at the geometrical axis of magnet poles. This distance is about half of the distance between the pick-up coils. The $m_{vir}(z)$ values for sample B plotted as a function of the sample position z are presented in figure 4. These measurements were performed at $T = 60$ K and the sweep rate $R = 0.88$ mT s^{-1}, i.e. at conditions under which m_{vir} can be clearly observed. We present our results in such a coordinate system that the position $z = 0$ corresponds to the saddle point (the geometrical centre of the pick-up coils). We can see a strong (approximately parabolic) dependence of m_{vir} on z. The lowest value of m_{vir} is for different external fields at about $z \simeq -2.7$ mm. Even this value of m_{vir} is, however, non-zero. At positions

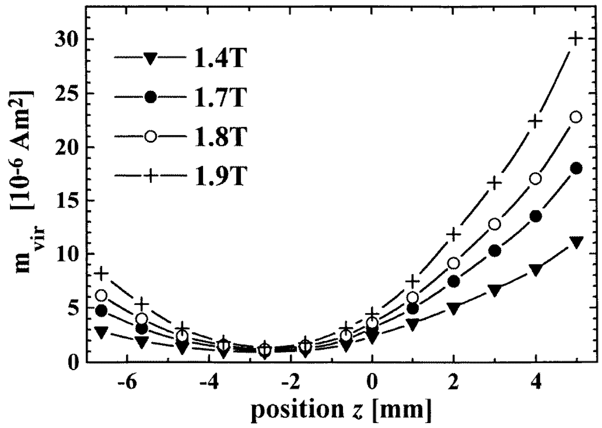

Figure 4. The virtual magnetic moment $m_{vir} = (m_m^+ + m_m^-)/2$ of sample B plotted as a function of the sample position z with respect to the magnet pole axis and the signal pick-up coils (see also figure 1). m_{vir} was evaluated at different bias fields from MHLs measured with the sweep rate $R = 0.88$ mT s^{-1} at $T = 60$ K.

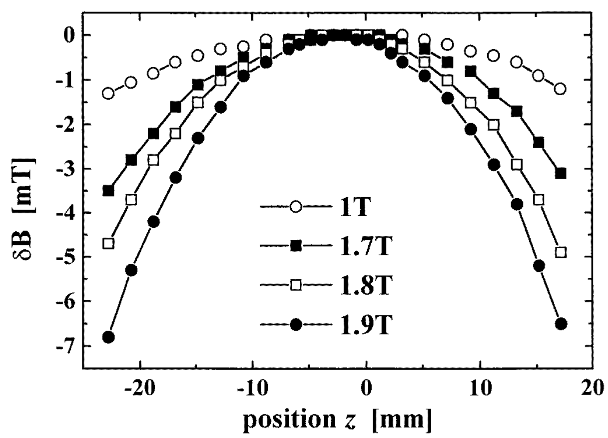

Figure 5. Difference of the local and maximum external magnetic field $\partial B = B_e(z) - B_e(z_0)$ as a function of z for different maximum external fields $B_e(z_0)$ = 1–1.9 T.

away from this magnetic centre it considerably increases with increasing bias field. This points to the importance of field inhomogeneity in the investigated effect.

The local bias field value as a function of the vertical position z was measured using a small Hall probe. The relative variations of the local magnetic field in a 1 cm^3 volume around the centre of the signal pick-up coil set obtained from these measurements are 0.65, 1, 1.4, and 2.2×10^{-4} for $B_e(z = 0) = 1$, 1.7, 1.8 and 1.9 T, respectively.

The dependence $B_e(z)$ is illustrated in figure 5 for two values of the nominal magnetic field $B_e(z = 0) = 1$ and 1.9 T. Due to enhanced stray fields the local magnetic field is considerably less homogeneous at high field values than at low ones. One can also see that the highest homogeneity of the bias magnetic field is also at the position $z = z_0 \simeq -2.7$ mm. In other words, the bias field axis is shifted from the geometrical axis of the magnet poles by about 2.7 mm.

Comparison of figures 4 and 5 indicates that the additive offset of m_{vir} is related to the magnetic field inhomogeneity: (i) the lowest m_{vir} is at the place of the highest homogeneity of the bias magnetic field; (ii) the changes of m_{vir} are larger at higher fields where magnetic field is less uniform; and (iii) the $m_{vir}(z)$ dependence is qualitatively similar to $\delta B(z) = B_e(z) - B_e(z_0)$.

The distance $z \simeq -2.7$ mm is very small compared with dimensions of the 11″ electromagnet core but, in spite of that, we show in this paper that it may cause, under special conditions, a measurable spurious additive moment.

3. Model and discussion

In magnetic measurements of superconducting samples magnetic moment m is induced by a change of the external magnetic field. Sensitivity of the magnetic moment to changes of magnetic field B_e is usually characterized by the differential susceptibility χ_0 defined as $\chi_0 = \mu_0(\Delta m/(B_e)$ in the regime of small reversible changes of m. The value of χ_0 is determined by the volume screened by induced currents in the sample which is approximately given by the sphere with a diameter equal to the effective lateral dimension of the sample. It means that χ_0 is a geometrical factor and it will not depend (at least in the first approximation) on field and temperature. Its value is practically identical with the initial (virgin) susceptibility in small fields [6, 7].

In *bulk superconductors* with all outer dimensions comparable, the screened volume is typically not very different from the sample volume. Consequently, the induced magnetic moment m of the sample (proportional to the sample volume) is relatively large, the penetration field (proportional to the moment) is also large and, therefore, the magnetic field change δB_e necessary for the full reversal of the induced magnetic moment is also large.

In *thin films* magnetized along the c-axis (normal to the film plane) the screened volume is approximately given by the sphere with a diameter equal to the effective lateral dimension of the thin film sample. Such a volume is several orders of magnitude higher than the sample volume (for our purpose 'thin film' means that one sample dimension is much smaller than other two dimensions). The induced magnetic moment is relatively low as is the penetration field. On the other hand, differential susceptibility is high and even a slight change of magnetic field can cause a full reversal of the induced magnetic moment. Differential susceptibility for our samples was determined experimentally in both cases to be $|\chi_0| \approx 65$ mm^3 while the volume of the samples is typically four orders of magnitude smaller. A magnetic field change even smaller than 1 mT is often large enough to reverse the induced currents in a large part of the thin film. This fact is essential to explain the observed properties of the additional magnetic moment m_{vir}.

According to figure 3, m_{vir} saturates at the field sweep rate R lower than about 1 mT s^{-1}. This saturation value of m_{vir} can be recorded even at constant B_e. We will first discuss the case of constant B_e, i.e. $R = 0$, and deduce the relation between m_{vir} and non-uniformity of local magnetic field.

The instantaneous position of a small (point-like) sample characterized by the co-ordinate z along the sample vibrations changes with time as

$$z(t) = \langle z\rangle + a_v \cos(\omega_v t) \qquad (1)$$

where $\langle z\rangle$ is the sample position averaged over the vibration cycle, a_v and ω_v are the (small) amplitude and frequency of vibrations respectively, and t is time. In our VSM $a_v \approx 0.2$ mm and $\omega_v = 515$ s^{-1} so that the maximum sample velocity during vibrations is about 0.1 m s^{-1}.

The magnetic flux Φ generated in the pick-up coils by the magnetic moment m of the sample depends on m and on the actual sample position z. We assume well compensated pick-up coils with $\Phi = 0$ for a sample at $z = 0$. The sample position at $z = 0$ is the saddle point [5] which is close to but not necessarily identical with the magnetic axis of the magnet poles. If the pick-up coils are far enough from the vibrating sample (the present case) we can simply express the magnetic flux in them using the first two non-zero terms of the Taylor expansion as

$$\Phi(m, z) = mG_1(z - g_1 z^3) \qquad (2)$$

where G_1 and g_1 are constants depending on the geometry of the signal pick-up coils and z is given by (1). The magnetic moment m_m recorded by VSM is proportional to the harmonic component $\mathrm{d}\Phi_\omega/\mathrm{d}t$ with frequency ω_v and a proper phase of the voltage $\mathrm{d}\Phi/\mathrm{d}t$ induced in the pick-up coils. The time-independent component of the flux Φ and other components changing with frequencies other than ω_v do not contribute to the signal detected by the VSM.

The highest value of $\mathrm{d}\Phi/\mathrm{d}t$ is for a sample vibrating in the geometrical centre of the pick-up coils (the saddle point). Assuming first that the magnetic moment of a sample does not change during sample vibrations, $m = m_0$, (the typical case is for a saturated ferromagnetic sample) we get from (2) that the moment reading m_m of the magnetometer depends on the mean position $\langle z\rangle$ as $m_m(\langle z\rangle) = m_0(1 - 3g_1\langle z\rangle^2)$, where $\langle x\rangle = 0$ is the position of the saddle point where the VSM output is properly calibrated to the known standard moment $m_m = m_0$ (of an Ni sphere). The parameter g_1 characterizes the geometry of the pick-up coils. The value $g_1 = 0.0016$ mm^{-2} characterizing our VSM was obtained from a fit of the (nearly parabolic) experimental dependence $m_m(\langle z\rangle)$ (see figure 6) measured using a small spherical Ni sample made from a rod of pure nickel provided by the VSM manufacturer.

In superconductors a magnetic moment m is due to currents induced by a change of external field. Due to the high differential susceptibility of superconductors, in particular of superconducting films, the moment m is very sensitive to even small variations of local magnetic field with time and therefore it is also in general *not constant* during vibrations in a VSM. The induced magnetic moment m of a superconducting sample consists of two parts: one practically time-independent moment m_0 resulting from the constant sweep of the (homogeneous) bias field and the

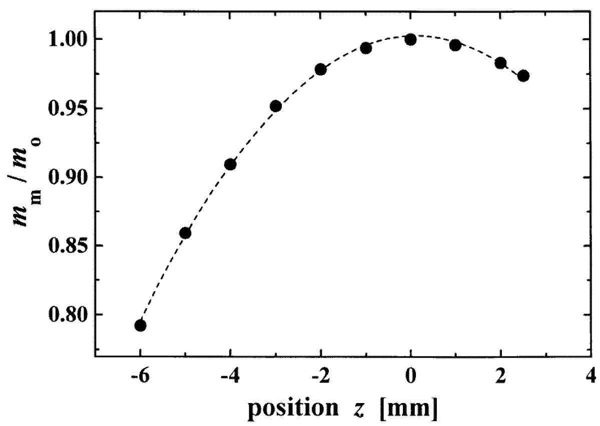

Figure 6. The variation of the normalized VSM output m_m/m_0 obtained with a ferromagnetic sample (Ni) placed at different distances z from the centre of the signal pick-up coils. The best quadratic fit (broken curve) corresponds to $g_1 = 0.0016$ mm^{-2} according to equation (5).

a.c. component due to vibrations around position $\langle z\rangle$ in a slightly non-uniform magnetic field

$$m = m_0 + \frac{\chi_0}{\mu_0}\frac{\partial B_e(z)}{\partial z}(z(t) - \langle z\rangle) \tag{3}$$

where χ_0 is the differential susceptibility discussed above. Using equations (1), (2) and (3) we get the time-dependent flux Φ_ω in the pick-up coils changing with frequency ω_v as

$$\Phi_\omega(t) = G_1 a_v \cos(\omega_v t) \times \left(m_0(1 - 3g_1\langle z\rangle^2) + \frac{\chi_0}{\mu_0}\frac{\partial Be(z)}{\partial z}\langle z\rangle(1 - g_1\langle z\rangle^2)\right). \tag{4}$$

The moment value m_m recorded by the VSM reads

$$m_m(\langle z\rangle) = m_0(1 - 3g_1\langle z\rangle^2) + m_{vir}(\langle z\rangle) \tag{5}$$

where

$$m_{vir}(\langle z\rangle) = \frac{\chi_0}{\mu_0}\frac{\partial B_e(z)}{\partial z}\langle z\rangle(1 - g_1\langle z\rangle^2). \tag{6}$$

m_{vir} is the component of m_m which is proportional to the field gradient, i.e. it is equal to zero if the sample vibrates in a perfectly homogeneous field, $\partial B_e(z)/\partial z = 0$. It is an artefact of the magnetometer. For small g_1 we can write simply $m_{vir} \approx (\chi_0/\mu_0)(\partial Be(z)/\partial z)\langle z\rangle$. The virtual additive moment m_{vir} does not depend on m_0 but is proportional χ_0. This means that m_{vir} may become considerable only for samples with relatively high χ_0. This is typically the case of thin films in a magnetic field perpendicular to the film plane where the sample volume is several orders of magnitude smaller (low m_0) than the screened volume (large χ_0). In ceramic and bulk single-crystalline superconductors the sample volume and the volume screened by the induced currents flowing in the sample are usually comparable; χ_0 is *relatively* small and m_{vir} is, therefore, negligible.

Recording of m_{vir} by a vibrating sample magnetometer is a natural consequence of vibrations of the superconducting sample having a high differential susceptibility in an inhomogeneous magnetic field. The differential susceptibility χ_0 is always negative and the gradient $\partial B_e(z)/\partial z$ of the local external field generated by the conventional magnet has an opposite sign from the field. Therefore m_{vir} in our set-up is always of the same sign as the external field.

If we know (from independent measurements) the value of the field gradient $\partial B_e(z)/\partial z$, m_{vir} calculated according to (6) can be compared with the experimental data. As an example, $\partial B_e(z)/\partial z = -0.20$ mT mm^{-1} for $B_e(z_0) = 1.9$ T at $z = +5$ mm (see figure 5). Using (6) we obtain $m_{vir} = 4.9 \times 10^{-5}$ A m^2 while the experimental value evaluated from hysteresis loops is 3.0×10^{-5} A m^2. This value is in good agreement with it considering that the calculation was done under the assumption of the point-like sample.

The sample placed out of the geometrical centre of the pick-up coils ($z \neq 0$) induces a lower signal $\mathrm{d}\Phi/\mathrm{d}t$ because less stray flux from the sample crosses the windings of the pick-up coils. The slight non-uniformity of the bias magnetic field along the z direction can be approximated by a quadratic dependence (see figure 5) as

$$B_e(z) \cong B_e(z_0) - \gamma(z - z_0)^2 \tag{7}$$

where γ is a constant characterizing the field inhomogeneity. In electromagnets γ increases considerably with increasing magnetic field $B_e(z_0)$ and has the same sign with it. Assuming only a small oscillation amplitude a_v the field gradient $\partial B_e(z)/\partial z$ can be approximated as

$$\partial B_e(\langle z\rangle)/\partial z \approx -2\gamma(\langle z\rangle - z_0). \tag{8}$$

By substituting (8) into (6) we can express the spatial dependence of m_{vir} in the form

$$m_{vir}(\langle z\rangle) = 2\gamma(-\chi_0/\mu_0)\langle z\rangle(\langle z\rangle - z_0)(1 - g_1\langle z\rangle^2). \tag{9}$$

Equation (9) includes implicitly the dependence of the virtual additive moment on bias field: m_{vir} is proportional to γ which is of the same sign as $B_e(z_0)$ and increases considerably with increasing value of $B_e(z_0)$. Therefore, $|m_{vir}|$ increases considerably with $|B_e(z_0)|$, too. According to (9) m_{vir} depends parabolically on $\langle z\rangle$ and is always positive in positive fields except for very narrow range of $\langle z\rangle$ between 0 and z_0, where, however, m_{vir} is close to zero. For small enough g_1 and z_0 we can write simply $m_{vir} \approx 2\gamma(-\chi_0/\mu_0)\langle z\rangle^2$.

As shown in figure 5, $z_0 \approx -2.7$ mm, i.e. that the maximum homogeneity of the field is shifted by 2.7 mm out of the geometrical axis of magnet poles. This difference is small compared with the dimensions of the 11″ electromagnet core, but even such a small shift may under appropriate conditions cause a measurable spurious additive moment signal.

Using (9) we can estimate m_{vir} (see figure 4) from the actual non-uniformity of magnetic field in the magnet (see figure 5). The experimental dependences of $\delta B(z)$ fitted by (8) give the values of γ equal to 7.06 and 14.50 T m^2 for $B_e(z_0)$ equal to 1.7 and 1.9 T, respectively. Using $\chi_0 = -65$ mm^3 we obtain for the same $B_e(z_0)$ the values of the coefficient $2\gamma(\chi_0/\mu_0)$ in (9) equal to 0.73 and 1.50 A

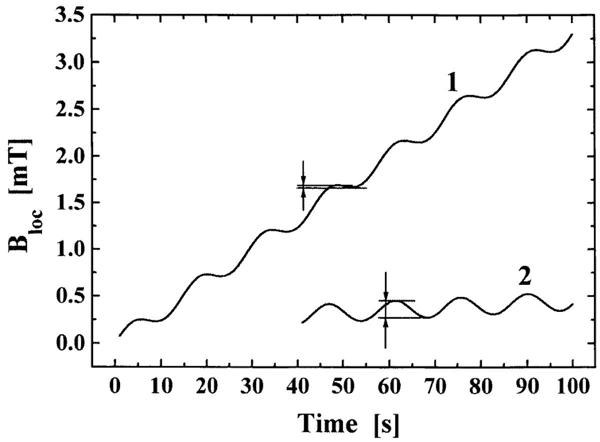

Figure 7. Schematic time dependence of local magnetic field experienced by the sample vibrating in a slightly non-uniform field sweeping with low (2) and high (1) field sweep rate R. In the sweeping field the magnetic moment changes extensively according to $\Delta m/\Delta B_e = \chi_0/\mu_0$ only due to (small) field reversals. However, magnitude of such field reversals depends on the field sweep rate R. At high R the local field experienced by the vibrating sample changes monotonically and the moment is nearly constant while at low R the local field exhibits considerable field reversals and the moment recorded by VSM exhibits the additional component m_{vir} given by equations (6) and (9).

respectively. By fitting the $m_{vir}(z)$ dependences in figure 4 by parabolic dependence we get $2\gamma(\chi_0/\mu_0)$ equal to 0.25 and 0.46 A for the same magnetic fields $B_e(z_0)$. The experimental values are reasonably close to the calculated ones considering that finite sample dimensions were not taken into account.

According to equation (9) the additive virtual moment should be zero when the sample vibrates around the position with the highest field homogeneity, i.e. around $z = z_0$. However, the value of $m_{vir} \approx (m_m^+ + m_m^-)/2$ measured on MHL is slightly non-zero even at $z = z_0$ (see figure 4). This can be explained by finite dimensions of the sample: up to now we considered a point-like sample. However, the experimental results presented in this paper were obtained on thin films with dimensions 5×5 mm. Such a sample size is reasonably small with respect to dimensions of the pick-up coils [5] but it is large enough to experience a measurable difference in local field at the outer parts of the sample even when centre of the sample is exactly at $z = z_0$. We can therefore expect for the sample with large lateral dimensions a finite value of m_{vir} even when the sample is centred properly at $z = z_0$.

All considerations has been made so far without taking into account effect of the field sweep rate, i.e. for $R = 0$. Experiments show, however, that m_{vir} is a strong function of R: m_{vir} decreases to zero with increasing R (see figure 3). Explanation follows from the schematic diagram in figure 7: there are two time-dependent components of the magnetic field experienced by the sample vibrating in the sweeping, slightly non-uniform field: (i) the bias field changing linearly with time with the sweep rate R; and (ii) the field component caused by sample vibrations in the non-uniform field. Figure 7 shows the difference between situations when the (slightly non-uniform) field is swept slowly and rapidly.

In the case of a *slowly sweeping field* (the curve labelled as 2 in figure 7) the magnitude of the variations of the local field experienced by the sample B_{loc} caused by sample vibrations in the non-uniform field is large compared with the field sweep rate. Consequent small field reversals cause (due to high differential susceptibility χ_0) considerable variations of induced moment with frequency of sample vibrations ω_v and appearance of the additive moment described by the equations (6) and (9).

In contrast to that, at high field sweep rates reversals of the local magnetic field B_{loc} are suppressed by fast ramp of B_e (the curve labelled as 1 in figure 7) and the magnetic field B_{loc} experienced by the sample is (nearly) monotonic with time. Therefore, magnetic moment practically does not change during sample vibrations and, consequently, the additive virtual moment is not observed.

We will estimate the threshold value of the field sweep rate R for which the field reversals due to sample vibrations are just completely suppressed. The rate of change of the local magnetic field $\partial B_{loc}(z)/\partial t$ experienced by a vibrating sample is

$$\frac{\partial B_{loc}(z)}{\partial t} = R + \frac{\partial z}{\partial t}\frac{\partial B_e(z)}{\partial z} = R + a_v\omega_v \sin(\omega_v t)\frac{\partial B_e(z)}{\partial z}. \tag{10}$$

The harmonic part of the expression becomes negligible if $|R| > a_v\omega_v|\partial B_e(z)/\partial z|$. When $\partial B_{loc}(z)/\partial t$ does not change sign, the sample does not feel any field reversals, and magnetic moment practically does not change during field sweep. Consequently, no additional moment m_{vir} is observed. Taking into account quadratic dependence $B_e(z)$ (equation (7)), the range of sample positions $\langle z\rangle$ for which m_{vir} is negligible for the given field sweep rate R can be estimated as

$$|R| > 2|\gamma|a_v\omega_v|\langle z\rangle - z_0|. \tag{11}$$

Equation (11) implies that m_{vir} is equal to zero for any R when a point-like sample is exactly at the position z_0. However, for a sample with finite dimensions this condition has to be applied to all parts of the sample. Therefore, the samples larger than $|R|/(|\gamma|a_v\omega_v)$, we observe an additional moment m_{vir} even when the sample is centred precisely at $\langle z\rangle = z_0$.

In our case $a_v\omega_v \approx 0.1$ m s^{-1}, sample size is 5 mm and $\gamma = 2.59$ and 14.5 T m^2 for $B_e(z_0) = 1$ and 1.9 T respectively. For $B_e(z_0) = 1$ and 1.9 T the virtual additive moment is significant for $|R| < 1.3$ and 7.25 mT s^{-1}, respectively, which is in reasonable agreement with our experiment.

In figure 3 we can see a significant change of m_{vir} with temperature. This dependence does not follow directly from the above considerations, but it can be explained by decrease of the differential susceptibility close to T_c. All considerations have been made so far assuming large vortex pinning so that all field variations due to sample vibrations are much smaller than the penetration field [1]. It is valid in a wide temperature range except close to T_c. At low temperatures the size of MHL (i.e. the magnitude of m_0) is large due to large vortex pinning. The effect of finite m_{vir} (given by equations (6) and (9)) on the shape of large MHL is *relatively* small (compare with equation (5)). In the medium range of temperatures (typically 50–65 K) size of MHL becomes comparable with the magnitude of m_{vir} and large qualitative changes in the shape of MHL (see figure 2) can be therefore observed.

The magnitude of the virtual additive moment decreases considerably when the temperature approaches T_c (see for example, figure 3). We believe that this is caused by enhanced thermal activation of vortices which leads to weak vortex pinning, vortices move in the sample much more freely and the superconductor is capable of carrying only small currents. Therefore, the value of differential susceptibility χ_0 at temperatures close to T_c is significantly reduced and the response to small variations of local magnetic field is considerably smaller than at lower temperatures. Consequently, according to equation (6), we can also expect at higher temperatures much smaller m_{vir}, as was also observed experimentally.

The above model accounts for the appearance of the additive positive moment m_{vir} observed only on the VSM [5] measuring magnetic moment in the direction perpendicular to the sample vibrations. However, all our model considerations are quite general and apply after minor modifications for another types of VSM as well, for example using the geometry of the signal pick-up coils with their axis along the sample oscillations (mainly used in superconducting magnets). The authors believe that similar spurious effects might affect measurements of magnetic moment on any VSM with a magnetic moment measured in the direction as perpendicular as well as parallel to the sample oscillations. The magnitude of such an effect can also be estimated using equations (6), (9), (10) and (11).

We note that the virtual additive moment described above is to some extent similar to the paramagnetic Meissner effect (PME) observed recently at low magnetic fields on some ceramic superconductors BiSrCaCuO [13–15] and other materials [16, 17]. When the magnetic moment of a thin film is measured under conditions similar to conditions discussed in this paper at a constant external magnetic field while temperature is decreasing, a positive moment appears below T_c similar to the typical PME experiments. The only apparent difference is that the ‘real’ PME is only observed at very small magnetic fields while the virtual additive magnetic moment discussed in this paper is even more positive at higher fields.

The ‘real’ PME is usually explained by spontaneous currents in loops with Josephson π-junctions or by persistence of the giant vortex state with the fixed orbital quantum number [18]. However, the virtual additive moment discussed in this paper is caused only by specific experimental conditions and has nothing to do with physical properties of the studied material itself.

4. Conclusions

The main features of the experimentally observed additive moment m_{vir} can be summarized as:

(i) The MHLs recorded on thin superconducting films sometimes exhibit in the intermediate temperature range an additional virtual moment m_{vir} which shifts the reversible moment $m^+ + m^-)/2$ to positive values in positive external fields and to negative values in negative external fields. Under special circumstances the magnitude of m_{vir} is comparable with even larger than the size of MHL.

(ii) The lowest m_{vir} is obtained when the sample is centred at the place with the highest field homogeneity. The value of m_{vir} considerably increases in high magnetic fields where the conventional electromagnet used in the experiment is close to saturation and the magnetic field becomes more non-uniform.

(iii) m_{vir} is close to zero for large sweep rates (typically $|R| > 30$ mT s^{-1}) and saturates to a constant value at the field sweep rates as slow as $|R| \approx 1$ mT s^{-1}. This value of m_{vir} can also be recorded at constant B_e.

(iv) m_{vir} decreases considerably when the temperature approaches T_c.

We propose the following explanation of the above experimental findings:

(i) The value of the signal recorded by VSM on superconducting samples consists of two components: (i) the magnetic moment m_0 induced by sweep of the bias field, modified only by the position of the vibrating sample with respect to the signal pick-up coils according to (5), and (ii) the spurious additional virtual moment m_{vir} given by (6) and (9) caused by vibrations of a superconducting sample in an inhomogeneous magnetic field.

(ii) The magnitude of the virtual moment m_{vir} is proportional to the differential susceptibility χ_0 and the inhomogeneity of the local magnetic field $\partial B_e(z)/\partial z$, but it does not depend directly on the magnitude of the magnetic moment m_0.

(iii) m_{vir} decreases with increasing field sweep rate and is negligible at the sweep rates $|R| > a_v\omega_v|\partial B_e(z)/\partial z|$.

(iv) The discussed spurious effect and its explanation are quite general and apply to measurements of laterally large superconducting samples on any VSM equipped with pick-up coils parallel as well as perpendicular to the direction of sample oscillations.

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