LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–98/033 (P)
8 Ottobre 1998

Numerical study of the frequency and temperature dependence of the ac magnetic susceptibility in presence of a static magnetic field in HTS

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Abstract

The temperature dependence of the harmonics (χ_n) of the ac magnetic susceptibility in HTS have been investigated by numerical solutions of the non linear diffusion equation for the magnetic flux. Within the framework of the collective pinning model, we show that the transition between different regimes for the flux dynamics (taff, creep, flow) is determined by the field frequency for a fixed dc field, or by the dc field for a fixed frequency. As a consequence, a non universal behavior arises for the temperature dependence of χ_n. In particular, in this approach the frequency dependencies of both amplitude and temperature of the peak of the imaginary part of the first harmonic and of the modulus of the third harmonic are discussed.

PACS.: 74.62.Bf
Key words: susceptibility, higher harmonics, numerical analysis, losses

Presented at the
1998 Applied Superconductivity conference September 13–18, 1998, Palm Desert California
and Submitted to
IEEE Transsaction on Applied Superconductivity

1- INTRODUCTION

Dynamic magnetic properties in the mixed state of high T_c superconductors have been investigated by various authors both by transport and magnetic measurements. In particular, the low frequency complex susceptibilities (fundamental and its harmonics: $\chi_n = \chi'_n + i\chi_n''$) are given by the Fourier coefficients of the steady magnetization cycles, which are determined by the dynamics of flux quanta threading into the sample. Such processes can be accounted for only in a first approximation by the critical state description [1–2], which cannot describe the experimentally observed frequency dependence [3–4] of χ_n. Therefore, it is necessary to study the non–linear diffusion–like equation [5] which governs the spatial–temporal evolution of the local magnetic field B. In this case the role of the flux diffusivity is played by the resistivity ρ, which depends on the various regimes of flux dynamics, so that its dependence on temperature (T), local field (B) and local current density (J) is determined by the different pinning mechanisms operating in the material.

Recently, the ac response of thin superconductors has been studied in the flux creep regime by numerically solving the integral equation which describe the flux diffusion in the transverse geometry [6].

Some authors also suggested [7–8] the possibility of an universal behavior described by the single scaling parameter $\delta(\omega,T)$, i.e. the effective penetration length, which is related to a frequency dependent critical current. In this approach the susceptibilities can be written as: $\chi_n = f_n(\delta(\omega,T))$. In absence of dc bias magnetic fields, the temperature and frequency dependence of $\chi_n(T)$ has been calculated by the present authors [9,10] starting from the non–linear magnetic diffusion equation, where the diffusivity has been described in terms of a "parallel resistor model" [11], incorporating both flux creep and flux flow resistivities. Such an approach naturally accounts for changes of the non linear behavior produced by variations of the currents induced in the sample by the driving ac magnetic field. As a consequence, a non–universal behavior appears in the general shape of the temperature dependence of higher harmonics.

Following the same approach of ref.[9] in the present paper we shall focus on the temperature and frequency dependence of $\chi_n(T)$ in presence of dc bias magnetic fields.

2 – THE MAGNETIC FIELD DIFFUSION PROBLEM

The one–dimensional case of an homogeneous infinite slab with thickness 2d (d=100 µm) has been studied in presence of both dc and ac external magnetic fields, $B_{ext}(t) = B_{dc} + b_o \sin(2\pi\nu t)$, applied parallel to the sample surface (b_o=2mT; $0 \le B_{dc} \le 10$T). In such case the non–linear diffusion equation for the local magnetic field B inside the sample is:

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial x}\left[\left(\frac{\rho(B,J)}{\mu_0}\right)\frac{\partial B}{\partial x}\right] \qquad (1)$$

where $\rho(B,J)$ is the resistivity, written as the parallel (ρ_{par}), between the "flux creep" (ρ_{cr}) [12] and the "flux flow" (ρ_{ff}) [13] resistivities:

$$\frac{1}{\rho(B,J)} = \frac{1}{\rho_{par}(B,J)} = \frac{1}{\rho_{cr}} + \frac{1}{\rho_{ff}} \qquad (2)$$

$$\rho_{cr}(J) = 2\rho_c\left(\frac{J_c(t)}{J}\right)e^{-\frac{U_p(T)}{KT}}\sinh\left(\frac{JU_p(t)}{J_c(t)KT}\right) \tag{3}$$

$$\rho_{ff} = \rho_n(T)\left(\frac{B}{B_{c2}(t)}\right) \tag{4}$$

where $t = T/T_c$ is the reduced temperature, $U_p(t,B)$ is the pinning potential, $J_c(t,B)$ is the critical current density and $B_{c2}(t)$ is the upper critical field written as: $B_{c2} = B_{c2}(0)(1-t^2)/(1+t^2)$. The magnetic field dependence of both variables U_p and J_c is assumed to be of Kim type, $(\propto B_0/(B+B_0))$. The current density J is proportional to the gradient of the local magnetic field (B) and it is induced by the time derivative of B. In eq.3 ρ_c is determined by: $\rho_{cr}(J_c) = \rho_{ff}$. For $x \equiv JU_p/J_c KT << 1$, sinh (x) $\approx$ x, so that the linear "taff" resistivity is recovered $\left(\rho_{taff} \approx (U_p(t)/KT)\exp(-U_p(t)/KT)\right)$.

Equation (1) has been numerically solved by means of NAG Library routines, with $B(x,t=0)=B_{dc}$, as initial conditions, which corresponds to field cooling situation in presence of a strong flux pinning. The algorithm computes the time evolution of the flux profile in presence of boundary conditions given by B_{ext}. The periodic steady magnetization loops have been then calculated starting from the difference between the volume average $\langle B(r,t)\rangle$ of the profile B(r,t) and the instantaneous value of the applied field. The susceptibilities $\chi_n=\chi_n'+i\chi_n''$ were finally calculated by Fourier transforming. The temperature dependence of the susceptibilities are regulated by the temperature dependencies of J_c and U_p which, in turn, depend upon the pinning model. In our case the collective pinning model (14) has been assumed, yielding the following temperature dependencies:

$$U_p(B,t) = U_0\,(1-t^4) \quad \text{5a)}$$

$$J_c(B,t) = J_0\,(1-t^2)^{5/2}\,(1+t^2)^{-1} \quad \text{5b)}$$

with $U_0/K=2\cdot10^4$ K, and $J_0=10^{11}$ A/m^2, which are a reasonable choice for YBCO.

3 - RESULTS AND DISCUSSION

Figure 1 shows the temperature behavior of the imaginary part of the first harmonic, (χ''_1), calculated at ν= 0.8Hz for various applied dc fields; the real part is not shown since it is not particularly relevant for our discussion. The χ''_1 peak temperature (T_p) shifts regularly towards lower temperature as the dc field increases; the peak amplitude first decreases for increasing fields up to $B_{dc} \approx b_o$ and then approaches a value close to 0.417, which pertains to a pure resistivity. Indeed, simulations carried out only using the "taff" resistivity yield a χ''_1 peak of the same amplitude, located at the same T_p of the peak obtained using the parallel resistivity. Thus, the behavior at the largest dc fields can be explained by considering that the time varying ac magnetic field generates electric fields, which induce currents biasing the sample in the "taff" region of the E–J characteristic. On the other hand, the decrease of the peak value found on lowering the dc field towards b_0, can be explained considering that the "taff" resistivity decreases, so that the electric fields induce larger currents. For such a reason the bias point in the E–J characteristics moves towards the non–linear region close to the "critical current bias point". As a consequence, the χ''_1 peak amplitude begin to decrease towards the critical state value (0.21).

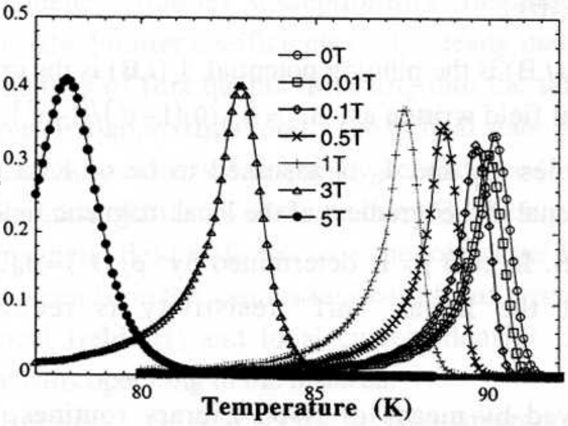

Fig. 1 – Calculated χ''_1 as a function of temperature for ν=0.8Hz and b_0=2mT at different B_{dc} values.

Finally, the peak enhancement at B_{dc}=0T is due to the field dependence of the resistivity (eq.4), which can lead to peak values well above both the critical state and the normal resistance peak value [10].

As a matter of fact, an overall behavior similar to the present finding has been reported in literature for melt–powder–melt grown samples [15].

In order to display the hysteretic contribution to the losses, the third harmonic (both real and imaginary parts) is plotted in fig.2a,b as a function of temperature at various dc fields.

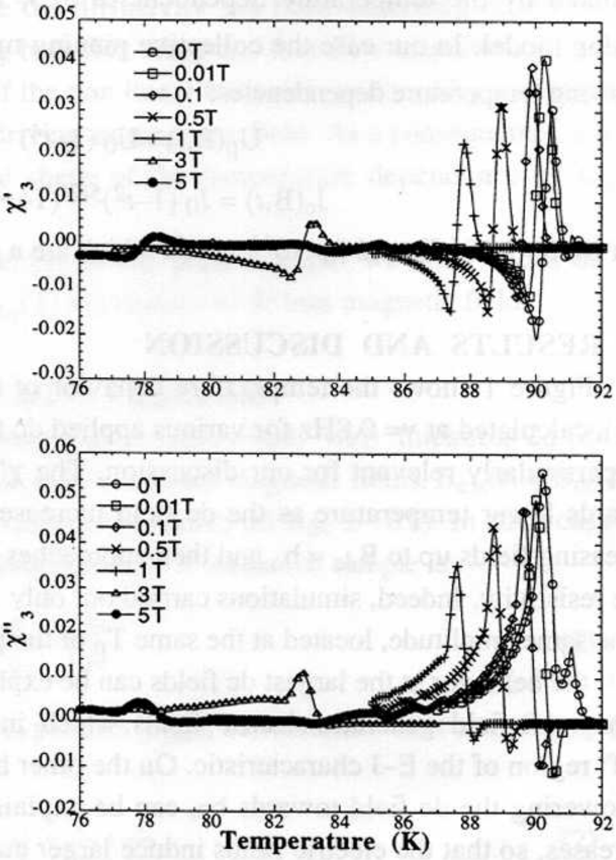

Fig. 2 – χ'_3 (a) and χ''_3 (b) as a function of temperature for ν=0.8Hz and b_0=2mT at different B_{dc} values.

As far as the temperature dependence of χ'_3 is concerned, the critical state predicts the presence of a bell shaped positive peak (similar to χ''_1) with a peak value of$\approx$0.05. On the contrary, the numerical results show an oscillation between positive and negative values, being the positive peak always located at temperature higher than the negative one. Such feature is the signature of thermally activated creep phenomena.

Concerning the temperature behavior of χ''_3 for dc fields larger than 0.01T, the general shape is similar to the critical state prediction, with an oscillatory behavior with a negative peak at temperatures higher than the positive peak. In the absence of dc fields, both the real and the imaginary part display a more complex temperature dependence due to the interplay between the ac and the dc fields.

The decrease of the peak temperatures with the increase of the dc field is a common feature of the first and the third harmonic, which is related to the field dependence of the critical current density. By the way, the presence of χ_3 is related to the occurrence of non–linear processes (like "flux creep"). Therefore, as the dc field increases, the decrease of the χ_3 amplitude is determined by a reduction of the non–linear behavior of the material, due to a larger relevance of the taff phenomenon. This result gives a further support to the correctness of the analysis given for χ''_1.

Similar features of a transition between different regimes of the flux diffusion appears also with the increase of the frequency of the ac field. Indeed, concerning the frequency dependence of the temperature and amplitude of the χ''_1 peak, fig. 3 shows the numerical results obtained at different dc fields. As discussed by some authors [3], the logarithmic frequency dependence of T_p results from the thermally activated flux motion over effective energy barriers (U). These processes [3] lead to a reduction of the measured critical current density (J_c) below its value in the absence of thermal activation: $J_c=J_{c0}(1-(KT/U)\ln(\nu_o/\nu))$. In such flux–creep–based picture, the effective activation energy at fixed temperature and field is inferred from the slope of the $1/T_p$ vs $\ln \nu$ plot. However, our diffusion based numerical calculations yield values of χ''_1 peak amplitude in the range 0.32–0.42 well above the critical state prediction (0.24). For this reason, for the frequencies and dc fields investigated, the flux creep picture is clearly ruled out in describing the peak occurrence for B_{dc} >0.1T.

Therefore the derivation of the effective activation energy from the slope of the empirical "linear" behavior cannot be regarded as a routine procedure.

In such a context, even the analysis of the third harmonic has to be necessarily carried out carefully. In Figs.4a,b the frequency dependencies of the peak temperature and the peak value of the modulus of the third harmonic are reported at different dc fields.

Despite the similar frequency and dc field dependencies of $1/T_p$ shared by χ''_1 and $|\chi_3|$ (Fig.3a and 4a respectively), it should be noted that, at fixed dc field for increasing frequency, their amplitudes display an opposite behavior. Indeed, as shown in Figs.3b and 4b, the χ''_1 amplitude decreases, whilst the opposite occurs for the peak of $|\chi_3|$. The same behavior is found on decreasing the dc field.

Such behaviors are related to the enhancement of non linearity of the magnetic response of the material, as long as the frequency increases or the dc field decreases, due to gradual crossover from the "taff" to "flux creep" regime. Such an enhancement leads to a decrease of the first harmonic and an increase of the third one.

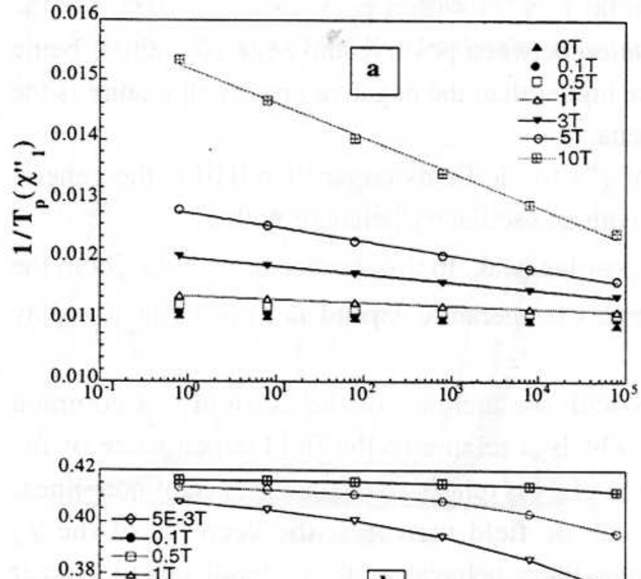

Fig. 3 – $1/T_p$ (a) and peak amplitude (b) of the imaginary part of first harmonic as a function of frequency at different B_{dc} values.

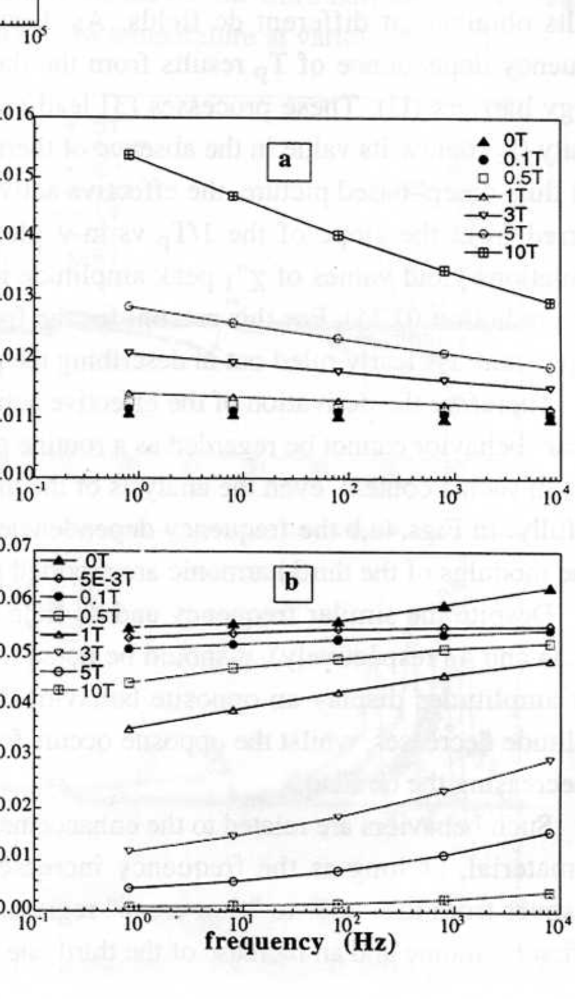

Fig. 4 – $1/Tp$ (a) and peak amplitude (b) of the third harmonic modules as a function of frequency at different B_{dc} values.

4 - CONCLUSIONS

In this paper the first and third harmonic of the ac susceptibility have been calculated in presence of dc fields, starting from the numerical solution of non–linear diffusion–like equation for the magnetic flux. In particular, the diffusivity has been described in terms of a "parallel resistor model" incorporating both flux creep and flux flow resistivities. By varying the dc field or the frequency of the driving magnetic field, it is possible to bias the sample at different regions of its E–J characteristic, which shows a different degree of non linearity. As a consequence, the susceptibilities χ_n does not show an universal behavior.

For the frequency and dc fields used in the simulations a crossover from taff to flux creep regime has been observed. In presence of such a crossover we have found that an analysis based only on the linearity in the $1/T_p(\chi"_1)$ vs log f plot does not allow, even for the third harmonic, to distinguish the different regimes of flux dynamics. On the contrary, the unfolding of the single contributions can be carried out only by a simultaneous inspection of the frequency dependencies of both $1/T_p(\chi"_1)$ and the amplitude of the harmonics.

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