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Detection of the flux creep regime in the AC susceptibility curves by using higher harmonic response

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Abstract

In order to investigate the dynamic properties of the flux line lattice, the temperature dependencies of the basic and higher harmonic complex AC susceptibilities have been analysed. In particular, the first (i.e., fundamental) and the third harmonic $\chi_{1,3}(T) = \chi'_{1,3}(T) + i\chi''_{1,3}(T)$, have been measured at different frequencies, and the measurements have been compared with both analytical and numerical results. In this way, by using a combined analysis of the first and the third harmonics, it is possible to affirm that the experimental behaviour of the $\chi'_3(T)$ curves is due only to flux creep and flux flow dynamical processes for each temperature T lower than the temperature T^* close to the peak temperature of the first harmonic imaginary part, $T_p(\chi''_1)$. In fact, in this temperature region, the $\chi'_3(T)$ Bean critical state prediction does not agree with the experimentally detected magnetic response. Moreover, the experimental curves show that, when the frequency is increased, the flux dynamics always gets more relevant as compared to the critical state. Finally, the superposition of a DC field, H_{DC}, much higher than the AC field amplitude, allows to evidence the contribution which is due only to flux creep events in the harmonic response. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The investigation of different regimes in the dynamics of the flux-line lattice is often performed by using an AC susceptibility technique. In fact, changes in the vortex dynamics can be induced by changes of the magnitude of the external parameters, such as the AC field amplitude and frequency, the DC field intensity, the angle between the crystallographic axes and the applied fields, and the temperature [1–3]. Nevertheless, the interpretation of the experimental results requires the use of theoretical models, which relate the AC magnetic response to the electrical transport properties. For this purpose, the non-linear diffusion equation for the internal magnetic field B, in its one-dimensional form, has been integrated numerically by some authors [4–7]. In particular, the diffusion processes related to dissipative phenomena (flux creep, thermally activated flux flow or TAFF, and flux flow) have been simulated for a slab, by using different pinning models [6]. The higher sensitivity of the third harmonics of the AC susceptibility to the different flux dynamic regimes [6,8], together with the availability of χ'_3 and χ''_3 curves simulated by considering Flow, TAFF and Creep processes

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[6,7], allows us to select in the experimental curves the contribution due to the different vortex regimes. In this work, the AC harmonic susceptibility data have been interpreted with the help of analytical results and numerical simulations, and a temperature region has been identified, in which the $\chi_3(T)$ behaviour is uniquely governed by the dynamical regime.

2. Experimental results and discussion

The temperature dependencies of both the first and the third harmonics of the AC susceptibility, have been measured on a YBCO melt-textured sample, at different AC field amplitudes and frequencies, both with and without an applied DC field. The dimensions of the sample are $1.8 \times 3.2 \times 5$ mm, its

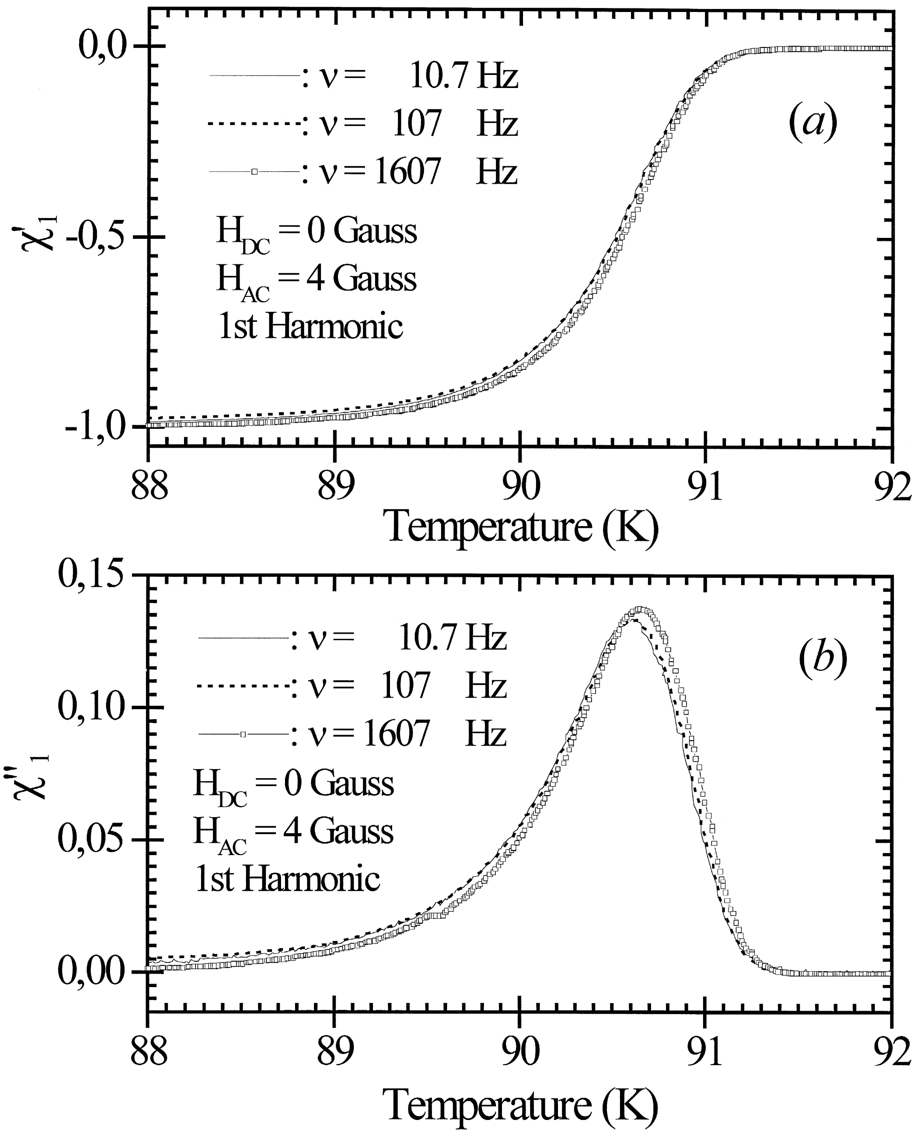

Fig. 1. Temperature dependence of (a) the real and (b) the imaginary part of the first harmonic, measured at $H_{AC} = 4$ G, $H_{DC} = 0$ and $\nu = 10.7$, 107, 1607 Hz.

critical temperature is $T_c = 91.3$ K, and its critical current density at $T = 77$ K is $J_c(77\ \mathrm{K}) = 8.7 \times 10^7$ $\mathrm{A/m^2}$. In Fig. 1, we report the $\chi_1'(T)$ and $\chi_1''(T)$ curves, measured at different frequencies ($\nu = 10.7$, 107, 1607 Hz), at fixed AC amplitude ($H_{AC} = 4$ G) and without a DC field ($H_{DC} = 0$). From the curves in Fig. 1, it is possible to notice that the first harmonic of the AC susceptibility is just slightly dependent on the frequency, at least in the range 10.7–1607 Hz. On the contrary, the dependence on the frequency is much more pronounced in the $\chi_3'(T)$ and $\chi_3''(T)$ measurements, as it is shown in Fig. 2. In fact, even the shape of the $\chi_3(T)$ curves is clearly modified if the frequency is changed in the same range as the $\chi_1(T)$ reported in Fig. 1. If the strong dependence of $\chi_3(T)$ on the AC field amplitude [8] is also considered, we can affirm that the third harmonic is more sensitive than the first one to the variation of external parameters and, then, it represents a very sensitive instrument to investigate the flux dynamics.

To analyse the meaning of these experimental curves, it is necessary to consider the models reported in the literature.

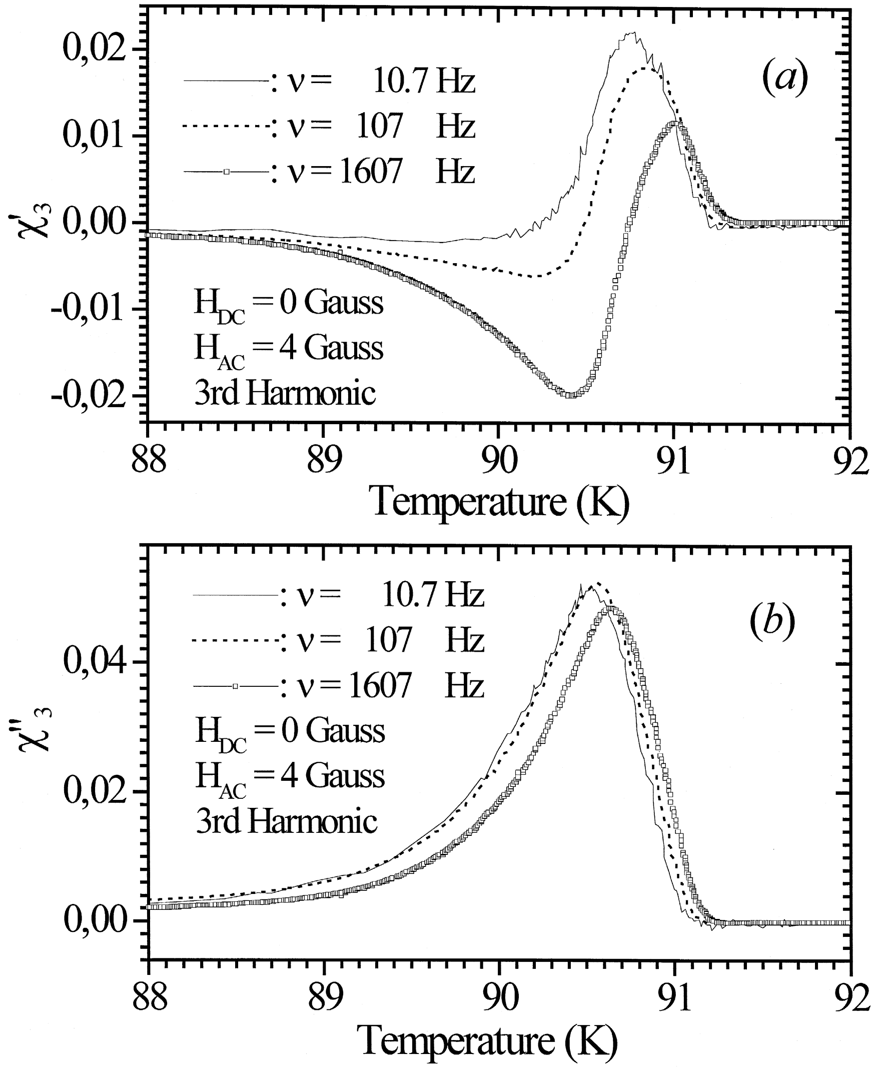

Fig. 2. Temperature dependence of (a) χ_3' and (b) χ_3'' measured at $H_{AC} = 4$ G, $H_{DC} = 0$ G and $\nu = 10.7$, 107, 1607 Hz.

The simplest and the most used model is the Bean model [9], which is independent of the frequency. The Bean results for the temperature dependence of the third harmonics, in the framework of the collective pinning [10], are plotted in Fig. 3 as function of the reduced temperature $t = T/T_c$. A comparison with the experimental data shows that this model is not suitable because of two principal reasons.

First, by a combined analysis of both the first and the third harmonics, we note that in the Bean model and its subsequent extensions [11], the real part of the odd higher order harmonics (in particular the real part of χ_3) is zero if the AC amplitude H_{AC} is lower than the full penetration field H^*, i.e., if $\delta(T) = H_{AC}/H^*(T)$ is lower than one [11]. Moreover, the temperature T^* determined by $\delta(T^*) = 1$ is close to the temperature of the peak in χ_1'', namely, $T_p(\chi_1'')$ [12,13]. As shown in Fig. 4, the experimental $\chi_3'(T)$ has non-zero values in the temperature region $T < T_p(\chi_1'') \approx T^*$, and then the data in this region cannot be interpreted by using only the Bean model.

Second, the weak frequency dependence of our measured χ_1 could suggest the use of only the Bean model to interpret the data. On the contrary ,the strong frequency induced shape modifications of χ_3, reported in Fig. 2, suggests that the dynamic effects must be seriously considered. These modifications cannot be justified within a critical state description by considering only a frequency dependent critical current $J_c(\omega)$ [5], since this dependence only produces a shift of the whole $|\chi_3(T)|$ curve when the frequency is changed.

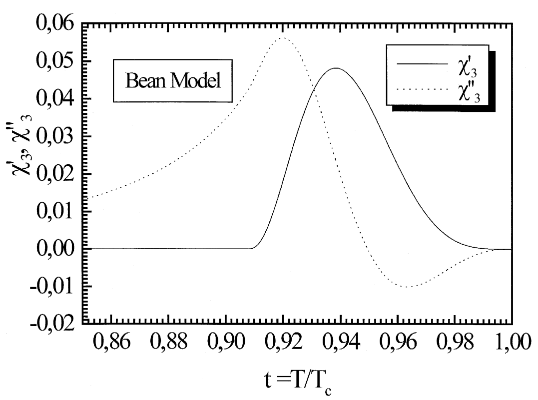

Fig. 3. χ_3' and χ_3'' as function of the reduced temperature t, obtained from the Bean model for a slab geometry.

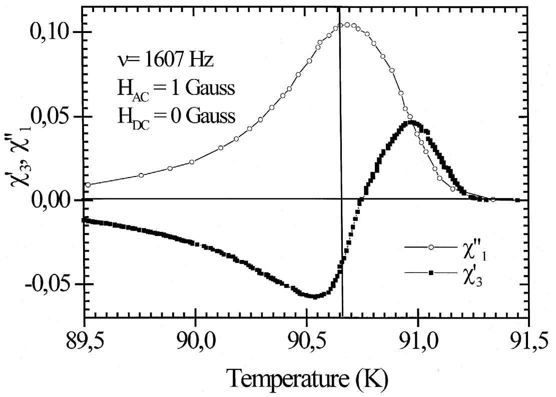

Fig. 4. The imaginary part of the first harmonic is compared with the real part of the third one, measured at $\nu = 1607$ Hz, $H_{AC} = 1$ G and $H_{DC} = 0$ G. We can observe that $\chi_3'(T) \neq 0$ for $T < T_p(\chi_1'')$.

The only way to interpret these results is to analyse in detail the presence of dynamical regimes (TAFF, flux creep, and flux flow) governing the magnetic response.

As it has been reported in a previously published paper [8], the $\chi_3(T)$ measurements on a YBCO sample are in qualitative agreement with the results obtained by numerical simulations [6] of diffusion processes in the framework of the collective pinning model [10]. In the numerical curves obtained by using this pinning model, if different resistivities are assumed in the calculations, the general shape of χ_1' and χ_1'' does not change, whereas the χ_3' and χ_3'' curves change drastically. In particular, for $T < T_p(\chi_1'')$ one has $\chi_3'(T) \approx 0$ if the TAFF resistivity is inserted into the diffusion equation, whereas $\chi_3'(T) \neq 0$ if the creep or flow resistivities are considered [6].

The simulations also show that modifications in the shape of the curves can be induced by changing the AC field frequency, as it is found in the experimental curves of Fig. 2. In particular, we can observe that when the frequency is increased, the absolute values of $\chi_3'(T)$ for $T < T_p(\chi_1'')$ grow. These features show that the flux creep and the flux flow processes are becoming more and more relevant.

To split the contribution due to these different dynamic regimes, one may consider that the TAFF and flow resistivities are independent of J, but they depend on the magnetic field. For this reason, when

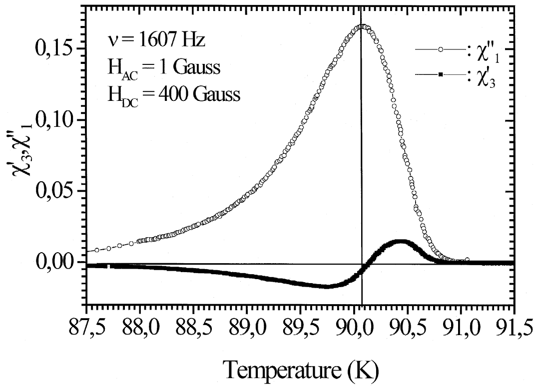

Fig. 5. The comparison between the imaginary part of the first harmonic and the real part of the third one, measured at $\nu = 1607$ Hz, $H_{AC} = 1$ G and $H_{DC} = 400$ G. In this experimental situation, the flux flow is a linear regime.

an AC field is applied, the diffusion equation becomes non-linear. Nevertheless, the application of an external DC field $H_{DC} > H_{AC}$ allows to neglect this non-linearity and then the higher harmonics related to the TAFF and to the flux flow become negligible. Therefore, if higher order harmonic signals are present, they can be due only to the creep regime, which is non-linear, and to hysteretic phenomena. In Fig. 5, the comparison between $\chi'_3(T)$ and $\chi''_1(T)$, in the presence of a DC field ($H_{DC} = 400$ G $\gg H_{AC} = 1$ G) is shown. From Fig. 5, we can see that the general behaviour of the $\chi'_3(T)$ curve for $T > T_p(\chi''_1)$ is similar to what the Bean model predicts. On the contrary, the $\chi'_3(T) \neq 0$ values in the temperature region $T < T_p(\chi''_1)$, do not agree with the Bean model, and they can only be justified in terms of the flux creep. This result is also confirmed by the good agreement between our $\chi'_3(T)$ data shown in Fig. 5, and by the numerical simulations performed by Qin and Ong [7] using a frequency and an H_{DC}/H_{AC} ratio similar to our external parameters, in order to evidence the flux creep.

3. Conclusions

In this work, we have measured the frequency dependencies of the AC susceptibilities χ_1 and χ_3, and we have compared them with both analytical and numerical results. In particular, to explain the experimental results, a new type of analysis, based on a combined study of the first and the third harmonics, has been used. The comparison between the experimental curves and the predictions of the Bean model has suggested that, for $T < T^* \approx T_p(\chi''_1)$, the $\chi'_3(T) \neq 0$ values can only be due to the presence of dynamic processes. By using the numerical results reported in the literature and the evidence of a frequency dependence in the experimental curves, it has been possible to attribute these values to the magnetic response governed by the flux creep and the flux flow regimes. Finally, the application of a DC field much higher than the AC field amplitude has allowed us to distinguish the contribution of the flux creep events in the harmonic response. The good agreement between our experimental results and the most recently published numerical simulations of magnetic diffusion processes confirms our conclusions.

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