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RAPID COMMUNICATION

High-frequency-band resonance in magnetic fluids

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Abstract. Measurement of the complex susceptibility has been carried out on two magnetic fluids containing magnetic particles of median diameters 7.7 nm and 6.1 nm. It was observed that the real part of the complex relative magnetic susceptibility becomes negative above a critical frequency in the MHz range. This behaviour is suggestive of ferroresonance at frequencies which are well below the values predicted by theory.

The maximum frequency of the split-toroid technique [1] for the measurement of low-field, complex, frequency-dependent magnetic susceptibility, $\chi(\omega)=\chi'(\omega)-i\chi''(\omega)$, has been extended to 450 MHz. An apparent resonance has been observed in a number of magnetic colloids in which for the first time $\chi'(\omega)$ has been observed *to change sign* at a particular frequency and $\chi''(\omega)$ shows a maximum at a somewhat lower frequency, $f_r(\omega_r/2\pi)$.

Ferromagnetic resonance in a uniaxial particle is characterized by the precession of the magnetic moment, m_p, about its axis of easy magnetization with an angular frequency

$$\omega_0=\gamma\,\mathrm{H_A}\mu_0 \tag{1}$$

and relaxation time

$$\tau_0=(\alpha\omega_0)^{-1} \tag{2}$$

where H_A is the internal field of the particle, γ is the magneto-mechanical ratio and α is a damping constant. The internal field H_A is given by

$$H_A=\frac{2K}{M_s} \tag{3}$$

where M_s is the saturation magnetization per unit volume and K is the effective anisotropy constant. The resonant frequency ω_r, at which $\chi''(\omega)$ is a maximum, is given by [2]

$$\omega_r=\omega_0\ \alpha/\sigma \tag{4}$$

where $\sigma=KV/kT$ is the ratio of the anisotropy energy to the thermal energy, kT, and V is the volume of the particle.

Calculations by Raikher and Shliomis [2] for the case of a single particle have shown that, for $\sigma\equiv0.5$, $\chi'(\omega)$ has a broad resonance, whilst for $\sigma\equiv0.1$ $\chi'(\omega)$ displays little or no resonant behaviour.

A typical example of our experimental results is shown in figure 1 for colloidal suspensions (samples 1 and 2) of partially oxidized magnetite particles (Fe_3O_4/γFe_2O_3) with a log–normal volume distribution of median diameters 7.7 nm and 6.1 nm respectively and standard deviation 0.4 and 0.3 respectively. The particles were coated with a perfluoro surfactant and dispersed in a perfluoro carrier. Values of K were determined by the method of El-Hilo and O'Grady [3] from low-temperature measurements. Because the particles are small the effect of Brownian motion is considered to be negligible and hence what we observe is the net effect of internal Neel relaxation [4] and an apparent resonance. It will be seen that for both samples $\chi'(\omega)$ initially shows a gradual increase with an increase in frequency

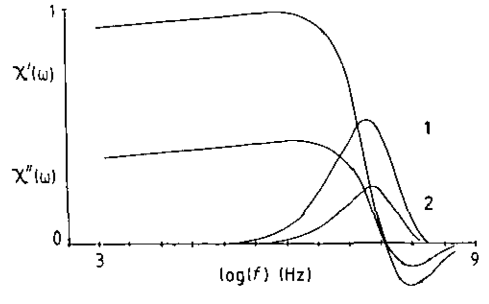

Figure 1. Normalized plots of $\chi'(\omega)$ and $\chi''(\omega)$ against log(f) Hz for samples 1 and 2.

followed by a sharp decrease and a change in sign at a frequency of approximately 40 MHz (slightly higher for sample 2). Similarly, $\chi''(\omega)$ has a maximum value at a frequency of approximately 20 MHz for sample 1 and 25 MHz for sample 2.

The values of σ for samples 1 and 2 were calculated as being 0.95 and 0.47 respectively. Accordingly [2] these values place the samples in that region where both Neel and resonance behaviour is to be expected, with a resonant frequency, f_r, of about 500 MHz, assuming a gyromagnetic frequency of 1 GHz.

The literature contains little on the topic of resonance in magnetic colloids. Anderson and Donovan [5] reported in 1960 on the observation of resonance in a colloidal sample of magnetite. They found the resonant frequency at 30 °C to be 230 MHz, which is lower than the theoretical estimate but higher than that reported here, and the difference in results is something that we cannot readily explain. The variation of $\chi'(\omega)$ and $\chi''(\omega)$ with ω which we have observed, is qualitatively similar to that described by the equation proposed by Landau and Lifshitz [6] for an assembly of identical signal domain particles. However it is certain that in our experiments there was a particle-size distribution. Furthermore the theoretical calculation of the gyromagnetic frequency is based on an estimate of the effective anisotropy field of about 52 kA m^{-1}. It may be that this estimate requires substantial revision. We are about to complete a study on a range of colloidal samples and also on magnetic tapes where we have observed the same phenomena, and we will be reporting on these measurements in the near future.

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