Energy dissipation of superparamagnetic suspensions in correlation with their nonlinear response of dynamic magnetization

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Nonlinear dependence of magnetization incorporated within superparamagnetic system upon magnetic field strength is basically found as the consequence of its saturation with respect to either the alignment of magnetic moments or the coexisting interparticles interactions. A mathematical approach of this nonlinearity is well described by Langevin function which takes the in-between dominance of Zeeman energy and thermal energy into account. Owing to this phenomenon, it has been huge interest to explore the capability of such superparamagnetic suspensions in biomedical fields along with the utilization of sinusoidal magnetic field to induce magnetization responses of the suspended particles. In this manner, a few amount of external field energy is dissipated during relaxation processes of the particles in which its value corresponds to the imaginary part of magnetic susceptibility. This mechanism of energy dissipation is mainly used as fundamental concept in developing magnetic hyperthermia, a temporary local heating of cancer at 43°C[1]. Meanwhile, translation of Langevin function into polynomial form leads to a term of harmonic magnetization of which the contribution cannot be omitted in order to obtain high resolution of magnetic particle imaging while applying high field strength of alternating magnetic field.

The change of hyperthermic efficiency (of energy dissipation in form of temperature increase) related to nonlinear magnetization is supposed to have a correlation with excitation of harmonic magnetization within nonlinear region of Langevin function. To verify this hypothesis, we experimentally measured and evaluated complex magnetic susceptibility of superparamagnetic suspensions containing iron oxides nanoparticles, with respect to the dependence of particles behavior upon magnetic field strength H_0 at fundamental frequency f. The measurements were done at 0.3 kHz, 3 kHz, 30 kHz, and 300 kHz in frequency with amplitude ranging from 6.5 to 65 Oe-rms. The equilibrium susceptibility at fundamental frequency χ_1 was then calculated toward estimation of efficiency of harmonic excitation regarding nonlinearity of magnetization response observed in the respective specimens. From Fig. 1 showing the evolutional deviation of magnetization from its linear response represented by $d\chi_1/dH_0$ in the function of frequency, the excitation of harmonic magnetization can be said to be generally significant at low frequency. Here, higher value of the negative gradient simply means that the decrease of magnetization becomes greater when field strength increases. Otherwise, the magnetization response becomes linear as the gradient reaches to zero value at higher frequency. The nonlinearity at low frequency itself can be addressed to relaxation dynamics of the particles causing such saturation of rotational motions, based on further evaluation of imaginary part of magnetization. We can also see in Fig. 1 that a weakly interacting particles system of Specimen 1 shows more linear behavior compared to a clustered particles system of Specimen 2. Furthermore, in accordance with these results, we will numerically discuss the contribution of nonlinear response of dynamic magnetization in attenuating the hyperthermic efficiency as a compensation of harmonic excitation.

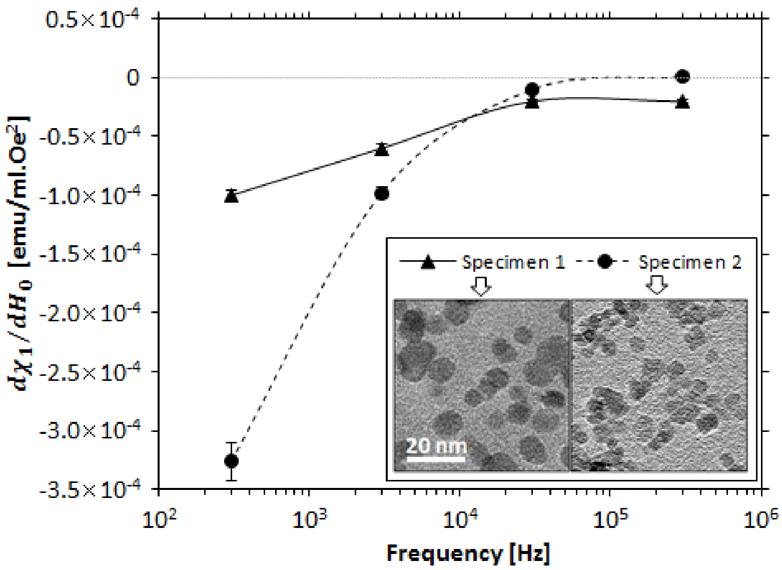

Fig. 1 Gradient of equilibrium susceptibility at fundamental frequency

Reference

1) R. E. Rosensweig, J. Magn. Magn. Mater., **252** (2002) 370–374.