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Dynamic susceptibility spectra analysis of ferromagnetic spheres via micromagnetic simulations

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Abstract. Herein, we report the dynamic susceptibility spectra of ferromagnetic spheres with diameters varying from 50 to 100 nm determined via micromagnetic simulations. The dynamic susceptibility spectra were calculated based on magnetization and the external field response in the frequency domain using Fourier transforms. The peak of the imaginary part of the dynamic susceptibility spectra, which indicates the resonance frequency of the ferromagnetic material, is interestingly near Kittel's resonance frequency.

1. Introduction

Understanding the high-frequency response of magnetic systems is important for both fundamental and applied research [1,2]. A previous study explained the relation between high-frequency response and magnetization is characterized using the dynamic susceptibility tensor [3]. Many studies have focused on the microscale dynamic susceptibility spectra in the shaped magnetic systems, such as nanopillars [4,5], rectangular structures [6], nanodots [7], and stripes [8]. However, there has been insufficient research on the microscale spheres of ferromagnetic materials.

This study reports the simulated results of the dynamic susceptibility spectra of ferromagnetic spheres modeled in a public-domain micromagnetics software package. The dynamic susceptibility spectra are calculated based on magnetization and the external field response in the frequency domain. The results show that the peak of imaginary part of the dynamic susceptibility spectra is close to Kittel's resonance frequency. It means that the micromagnetic dynamic susceptibility of ferromagnetic nanosphere materials can be predicted both numerically and analytically.

2. Micromagnetic simulation

Herein, we used the public-domain micromagnetic simulator OOMMF [9] to numerically solve the Landau–Lifshitz–Gilbert (LLG) equation [10]. The diameter of the ferromagnetic spheres modeled herein was varied from 50 to 100 nm. A dynamic exponential magnetic field, $H(t) = 1000\exp(-10^9 t), \quad t \geq 0$ ($H(t)$ in A/m and t in s), was applied along the x-direction of the sphere and perpendicular to the spin configuration (y-direction) [4], as shown in figure 1. The material and parameters are listed in table 1 [11]. The damping factor was α = 0.05, and the cell size was $2.5 \times 2.5 \times 2.5\ \text{nm}^3$. The dynamic susceptibility spectra were calculated based on magnetization and the external field behavior in the frequency domain using Fourier transform.

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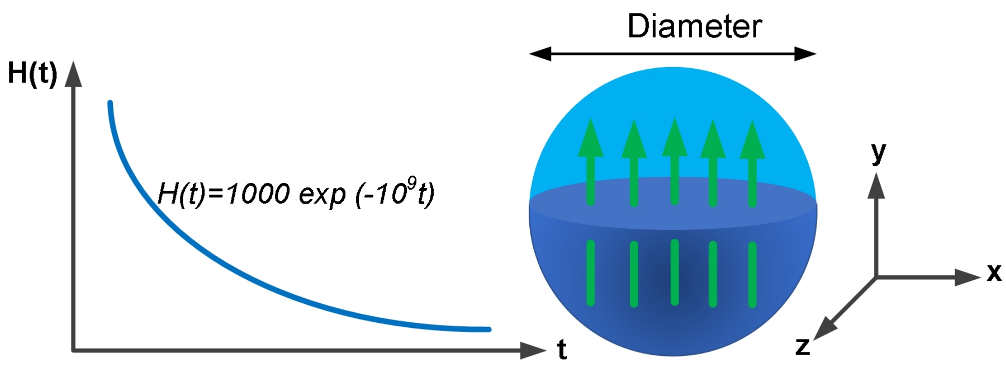

Figure 1. An exponential magnetic field is applied to a ferromagnetic sphere model along the x-direction and perpendicular to the spin configuration (y-direction) in simulations. The sphere diameter is varied from 50 to 100 nm.

Table 1. Material and parameters are used in micromagnetic simulation [11].

Materials	Magnetization saturation M_s (Am^{-1})	Exchange stiffness A (Jm^{-1})	Anisotropy constant K (Jm^{-3})
Co	1400×10^3	14×10^{-12}	53×10^4
Fe	1700×10^3	21×10^{-12}	48×10^3
Ni	490×10^3	9×10^{-12}	-5.7×10^3
Py	860×10^3	13×10^{-12}	0

3. Results and discussion

According to the resonance principle, the dynamic susceptibility of a ferromagnetic sphere model can be calculated from the relation $\chi(\omega) = M(\omega)/H(\omega) = \chi(\omega)' - j\chi(\omega)''$, where $\mathrm{M}(\omega)$ and $H(\omega)$ represent the magnetization and the external field, respectively, in the frequency domain. We used fast Fourier transforms (FFTs) to convert the time series of the magnetization response and external field into the frequency domain. The imaginary part of the dynamic susceptibility spectra $\chi(\omega)''$ is related to resonance frequency behavior [3,4]. The real and imaginary parts of the dynamic susceptibility spectra are plotted in figure 2. In this figure, the dynamic susceptibility spectra are around the GHz range, as expected at the nanometer scale.

For comparison, we also calculated the resonance frequency of a ferromagnetic sphere model using the Kittel's formula $\omega_r = \gamma\sqrt{[H_0 + H_k + (N_y - N_x)M_s][H_0 + H_k + (N_z - N_x)M_s]}/(2\pi)$ [12], where γ is the gyromagnetic ratio $2.21\times10^5\ mA^{-1}s^{-1}$ [13], H_0 is the static magnetic field, and $H_k = 2K/(\mu_0 M_s)$ is the anisotropy field. In the sphere model, the demagnetizing factors $N_x = N_y = N_z$ and $N_x + N_y + N_z = 1$, so Kittel's resonance frequency is $\omega_r = \gamma(\mathrm{H}_0 + H_k)/(2\pi)$ [4]. Figure 3 plots the resonance frequency predicted from Kittel's formula and the frequency peak of the imaginary part of the simulated dynamic susceptibility spectra for Co, Fe, Ni, and Py. Interestingly, the frequency peaks of the imaginary dynamic susceptibility spectra are close to Kittel's resonance frequency: Co was 42 GHz, Fe was 29.5 GHz, Ni was 28.2 GHz, and Py was 27.9 GHz. The resonance frequency varied with the diameter of the nanospheres, as predicted by Kittel's formula, which is expected from the geometry of the demagnetizing factors. The small differences between the micromagnetic simulations and Kittel's formula originated from the discretization of the cubic model in micromagnetic calculations [14]. Further, the resonance frequency originated from dipolar interactions [4,15].

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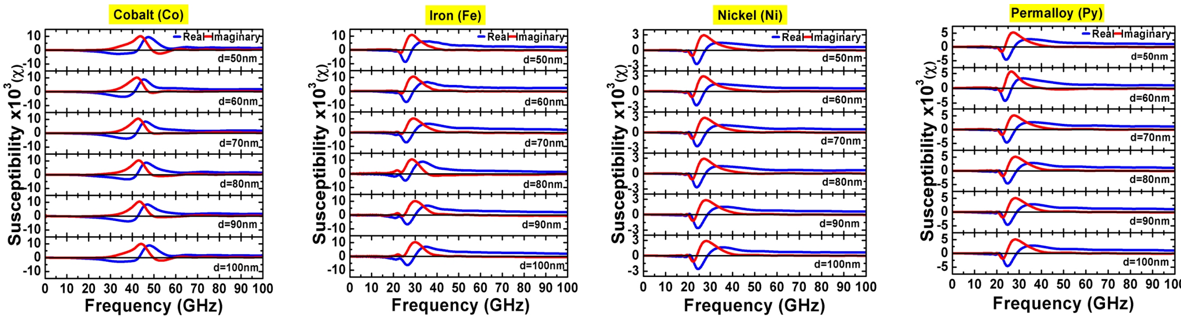

(a) (b) (c) (d)

Figure 2. The dynamic susceptibility of ferromagnetic sphere model profiles for (a) Co, (b) Fe, (c) Ni, and (d) Py for diameter ranging from 50 to 100 nm. Blue lines indicate the real part, and red lines indicate the imaginary part.

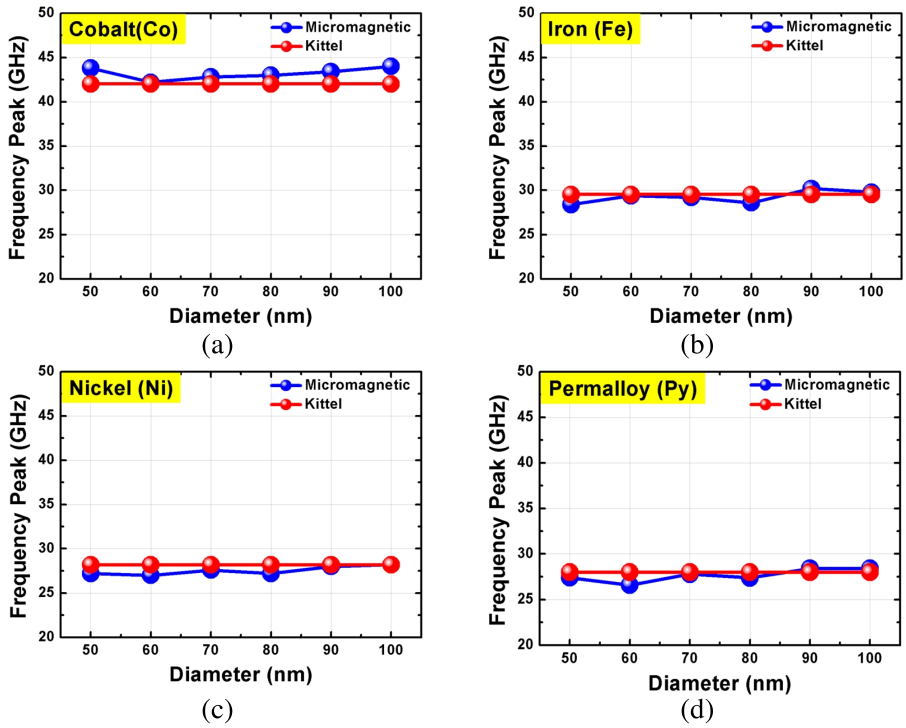

Figure 3. Frequency peak in the imaginary part of the dynamic susceptibility spectra (blue line) and Kittel's equation predictions (red line) for (a) Co, (b) Fe, (c) Ni, and (d) Py spheres with diameters from 50 to 100 nm.

4. Conclusions

Our findings help in understanding the resonance frequency behavior of nanoscale ferromagnetic spheres via micromagnetic simulations, which yielded the dynamic susceptibility spectra. We found that the imaginary part of the frequency peak in the dynamic susceptibility agrees well with analytical solutions for the resonance frequency of the ferromagnetic nanospheres. Engineers can therefore use Kittel's equation or magnetic simulation to effectively predict resonance responses when designing magnetic devices with microscale ferromagnetic spheres.

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