Phase diagrams for the precession states of the nanoparticle magnetization in a rotating magnetic field

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1. Introduction

Due to the well-defined direction of the natural (free) precession of magnetic moments, an applied magnetic field rotating in the plane perpendicular to the easy axes of nanoparticles breaks the degeneracy between the up and down states of the nanoparticle magnetization. As a consequence, this field magnetizes the nanoparticle systems [1], and depending on the direction of its rotation, increases the stability of magnetic moments in one state and decreases it in the other [2]. According to [3], these magnetic moments can perform only two kinds of forced precession, which are characterized by a constant precession angle (periodic or P precession) and by a quasiperiodic dependence of the precession angle on time (Q precession). If the direction of the natural precession of the up/down magnetic moment coincides with the direction of the field rotation then both forms of forced precession can be realized. In contrast, only P precession occurs for the down/up magnetic moment. Because of its practical importance, the switching between the up and down states of the nanoparticle magnetization, induced by a rotating magnetic field, is a subject of current interest (see, e.g., Refs. [2–6]). In this paper, we report on possible scenarios for the switching depending on the characteristics of the rotating and bias magnetic fields.

2. Stability of the P precession

At small amplitudes h of the rotating field $\mathbf{h}(t)$ the nanoparticle magnetic moment $\mathbf{m}=\mathbf{m}(t)$ always performs the P precession [2,3]. Therefore, the instability of this precession is necessary (but not sufficient, see below) condition for the switching of $\mathbf{m}$ under increasing h. For describing the dynamics of the dimensionless nanoparticle magnetization, $\mathbf{u}=\mathbf{m}/m$, we use the Landau–Lifshitz equation

$$\dot{\mathbf{u}} = -\gamma\mathbf{u}\times\mathbf{H}_{\rm eff} - \lambda\gamma\mathbf{u}\times(\mathbf{u}\times\mathbf{H}_{\rm eff}), \tag{1}$$

where the cross denotes the vector product, γ is the gyromagnetic ratio, λ is the dimensionless damping parameter,

$$\mathbf{H}_{\rm eff} = (H_a m_z/m + H)\mathbf{e}_z + \mathbf{h}(t), \tag{2}$$

is the effective magnetic field acting on the magnetic moment, H_a is the anisotropy field, H is the bias field,

$$\mathbf{h}(t) = h\cos(\omega t)\mathbf{e}_x + \rho h\sin(\omega t)\mathbf{e}_y, \tag{3}$$

$\rho=\pm 1$ is the parameter characterizing the direction of rotation of $\mathbf{h}(t)$, ω is the frequency of rotation, and $\mathbf{e}_i$ (i=x, y, z) are the unit vectors along the corresponding axes of the Cartesian coordinate system xyz. In the case of P precession the precession angle θ (i.e., the angle between the magnetic moment $\mathbf{m}$ and the z axis) is constant, and, according to Eq. (1), $u_z=\cos\theta$ satisfies the algebraic equation

$$(1-u_z^2)[(\tilde{H}-\rho\kappa+u_z)^2+(\lambda\kappa u_z)^2]-(\tilde{h}u_z)^2=0, \tag{4}$$

with $\tilde{H}=H/H_a$, $\tilde{h}=h/H_a$, $\kappa=\tilde{\omega}/(1+\lambda^2)$, and $\tilde{\omega}=\omega/\gamma H_a$. Among four solutions of this equation there must be chosen the real one which lies in the interval $[-1,1]$ and is stable. The latter assumes [2] that

$$S(u_z)\equiv\lambda(\tilde{\omega}_1+\tilde{\omega}_4)-{\rm Re}\sqrt{\lambda^2(\tilde{\omega}_4-\tilde{\omega}_1)^2-4\tilde{\omega}_2\tilde{\omega}_3}>0, \tag{5}$$

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where

$$\tilde{\omega}_1 = u_z^2 + [\tilde{H} - \rho\kappa(1-u_z^2)]/u_z, \quad \tilde{\omega}_2 = 1 + [\tilde{H} - \rho\kappa(1+\lambda^2 u_z^2)]/u_z,$$
$$\tilde{\omega}_3 = u_z^2 + [\tilde{H} - \rho\kappa(1+\lambda^2 u_z^2)]/u_z, \quad \tilde{\omega}_4 = 1 + [\tilde{H} - \rho\kappa(1-u_z^2)]/u_z. \tag{6}$$

In accordance with Eq. (4), u_z is a function of the parameters $\tilde{H}$, $\tilde{h}$, $\rho\kappa$, and λ, and so $S(u_z) = S(\tilde{H}, \tilde{h}, \rho\kappa, \lambda)$. The equation $S(\tilde{H}, \tilde{h}, \rho\kappa, \lambda) = 0$ determines in the space of these variables the surfaces on which the P precession becomes instable. Thus, within this theoretical framework, we can find the critical values of the mentioned parameters at which the P precession loses stability. But the questions, what is the steady state of the magnetic moment after instability and what are the scenarios of the switching, remain open. To answer these questions, we solved the Landau–Lifshitz Eq. (1) numerically and calculated in different variables phase diagrams for the precession states of the nanoparticle magnetization.

3. Phase diagrams

Our results show that the rotating magnetic field facilitates switching of the magnetic moments with $u_z(\tilde{h}=0) = \rho$ and hampers it for the magnetic moments with $u_z(\tilde{h}=0) = -\rho$. Therefore, assuming for definiteness that $\mathbf{h}(t)$ rotates in the counterclockwise direction, i.e., $\rho = 1$, we can restrict our analysis to the magnetic moments which at $\tilde{h}=0$ are in the up state. Moreover, the numerical results presented here for an illustrative purpose are derived for $\lambda = 0.2$.

We first consider the case of zero bias field, $\tilde{H}=0$. The precession states of the nanoparticle magnetization are shown in Fig. 1 in the variables "amplitude-frequency" of the rotating field. These states are detected by numerical solution of the Landau–Lifshitz equation (1) and describe the situation when the amplitude changes at fixed frequencies. The regions 1 (white) and 2 (light-green) correspond to two different P precessions of the nanoparticle magnetization in the up state. Within these regions the precession angle changes with $\tilde{h}$ continuously, but it is discontinuous at the boundary between them. The transition from one form of P precession to the other is reversible. The region 3 (pink) corresponds to the Q precession of the nanoparticle magnetization, and like the previous case, the transitions between this form of precession and P precessions in the up state are reversible. Finally, the region 4 (violet) corresponds to the P precession of the nanoparticle magnetization after switching to the down state. It is important to note that the transition from the Q precession or the P precession in the up state to the P precession in the down state is irreversible. The nanoparticle magnetization remains in the down state for all $\tilde{h}$ and $\tilde{\omega}$. The back transition, i.e., switching of magnetization to the up state, is now possible only if $\mathbf{h}(t)$ rotates in the clockwise direction ($\rho = -1$). For convenience, the reversible and irreversible transitions are depicted by the bidirectional and unidirectional arrows, respectively. The symbols depict the numerical results for the lines of transitions between different precession states, and the black solid lines represent the solution of the equation $S(\tilde{H}, \tilde{h}, \rho\kappa, \lambda) = 0$.

The bias magnetic field with $H<0$ ($|\tilde{H}|<1$) can essentially decrease the critical values of $\tilde{h}$ and $\tilde{\omega}$, which correspond to the transitions between different precession states. This fact illustrates Fig. 2. In Fig. 3 we also show the precession states of the nanoparticle magnetization in the variables $\tilde{h}$ and $\tilde{H}$. For large values of the bias field ($|\tilde{H}|>0.7$), the range of the Q precession becomes invisible on the chosen scales of the axes $\tilde{h}$ and $\tilde{H}$.

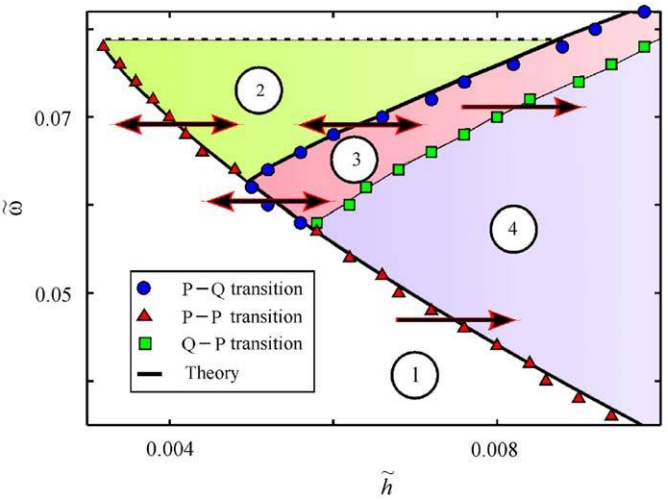

Fig. 2. Precession states of the nanoparticle magnetization that are realized under increasing $\tilde{h}$ at $\tilde{H} = -0.9$.

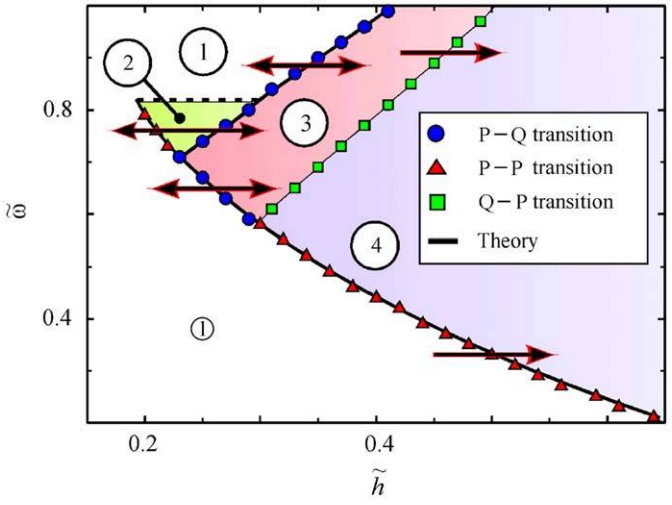

Fig. 1. Precession states of the nanoparticle magnetization that are realized under increasing $\tilde{h}$ at $\tilde{H} = 0$.

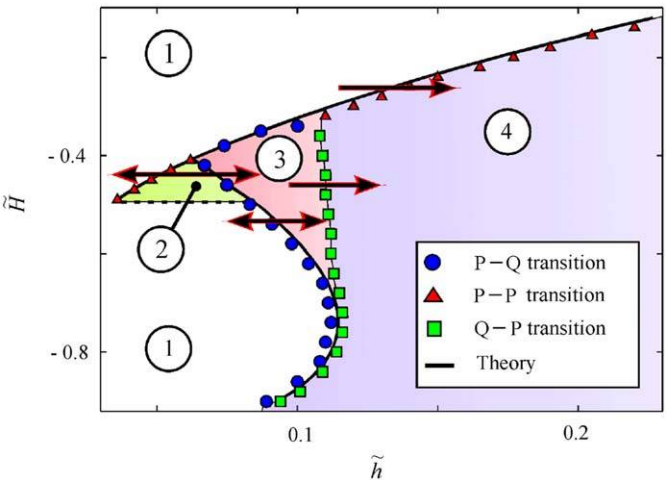

Fig. 3. Precession states of the nanoparticle magnetization that are realized under increasing $\tilde{h}$ at $\tilde{\omega} = 0.4$.

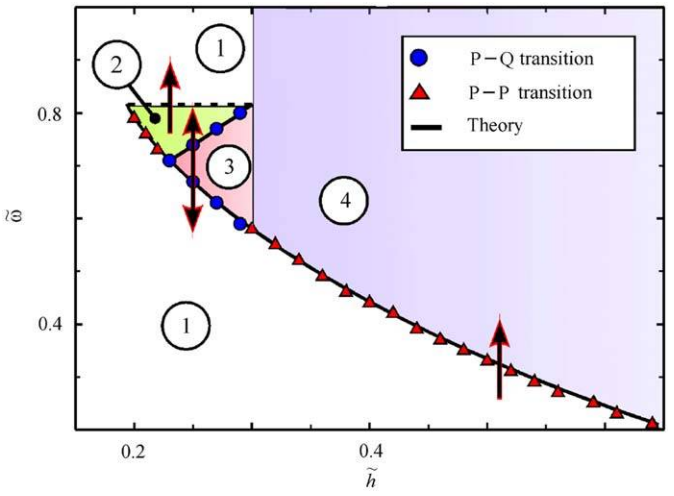

Fig. 4. Precession states of the nanoparticle magnetization that are realized under increasing $\tilde{\omega}$ at $\tilde{H} = 0$.

As is clear from Figs. 1–3, there exist three different scenarios for the switching of the nanoparticle magnetization under increasing amplitude of the rotating magnetic field: (i) direct switching from the P precession in the up state to the P precession in the down state, the so-called P–P switching, (ii) compound switching through the Q precession, the so-called P–Q–P switching, and (iii) compound switching through the P and Q precessions, the so-called P–P–Q–P switching. In principle, any other control parameter can also be used for the switching. If, for example, the rotating field frequency increases at fixed amplitudes, then, as seen from Fig. 4, the P–P switching takes place if the rotating field amplitude exceeds a threshold value. Otherwise, no switching occurs for all frequencies.

Thus, by calculating phase diagrams, we have classified the precession states of the nanoparticle magnetization which appear under increasing amplitude and frequency of the rotating magnetic field. We have shown that the switching of the nanoparticle magnetization can occur via three scenarios, viz., P–P, P–Q–P, and P–P–Q–P switching. While the transition to the P precession of the nanoparticle magnetization in the switched state is irreversible, all others are reversible. By applying the bias field, the switching amplitudes and frequencies of the rotating field can by essentially reduced. Our analytical and numerical results are in excellent agreement.

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References

[1] S.I. Denisov, T.V. Lyutyy, P. Hänggi, Phys. Rev. Lett. 97 (2006) 227202.
[2] S.I. Denisov, T.V. Lyutyy, P. Hänggi, K.N. Trohidou, Phys. Rev. B 74 (2006) 104406.
[3] G. Bertotti, C. Serpico, I.D. Mayergoyz, Phys. Rev. Lett. 86 (2001) 724.
[4] A. Magni, G. Bertotti, C. Serpico, I.D. Mayergoyz, J Appl. Phys. 89 (2001) 7451.
[5] Z.Z. Sun, X.R. Wang, Phys. Rev. B 74 (2006) 132401.
[6] C. Thirion, W. Wernsdorfer, D. Mailly, Nat. Mater. 2 (2003) 524.