

Power Loss of the Nanoparticle Magnetic Moment in Alternating Fields

T.V. Lyutyi^{1,*}, S.I. Denisov¹, A.Yu. Polyakov¹, C. Binns²

¹ Sumy State University, 2, Rymsky Korsakov Str., 40007 Sumy, Ukraine

² University of Leicester, Leicester, LE1, 7RH, UK

(Received 13 August 2012; revised manuscript received 25 August 2012; published online 27 August 2012)

Using the Landau-Lifshitz equation, the dependencies of the power loss of the nanoparticle magnetic moment on the amplitude and frequency of alternating magnetic fields are calculated numerically. A special attention is paid to the different precessional modes of the magnetic moment and their influence on power loss value. The results for the circularly and linearly polarized fields are compared in order to choose the optimal one with respect to the power loss.

Keywords: Magnetic moment, Power loss, Landau-Lifshitz equation, Circularly polarized field, Linearly polarized field.

PACS numbers: 75.50.Tt, 76.20.+q, 05.40.-a

1. INTRODUCTION

Energy transformation during an interaction of ferromagnetic fine particles with external magnetic fields is an important problem. It is related, for example, to microwave absorbers [1], that is interesting with respect to security and military application, or microwave-assisted magnetic switching [2], that is very promising magnetic recording technique. But one of the most famous and attractive applications based on the absorption of an alternating field energy by the fine particle magnetic moment is the magnetic fluid hyperthermia (MFH) [3].

According to Rosensweig [4], three mechanisms of energy absorption are possible. The first mechanism is the eddy current generation. It is applicable to conductive nanoparticles only and is negligible if they are small enough. The second one, the so-called Brownian relaxation mechanism, is related to the mechanical rotation of a particle in a liquid media. Within this mechanism the energy dissipation occurs via viscous friction. Finally, nanoparticle can absorb the energy of an alternating magnetic field due to the damping of the magnetic moment. Usually, this mechanism is associated with the Néel relaxation at low frequencies. At the same time, the resonant behavior of the magnetic energy loss, which takes place for the high frequencies, has not been considered in [4].

Despite the mechanical rotation is considered as the main source of heating during the MFH, recently, special attention was also paid to the energy absorption that occurs via rotation of the magnetic moment in a fixed nanoparticle [5, 6]. Moreover, the MFH techniques were proposed [7], where the high frequencies can be used. Therefore, the investigation of the energy loss processes in magnetic nanoparticles driven by high-frequency magnetic fields is demanded.

A simple analysis of the power loss caused by the damping of the nanoparticle magnetic moment was performed for both isotropic [8] and anisotropic [9] nanoparticles. However, because these studies were restricted by low frequencies, the role of different precessional states

of the magnetic moment, which are generated by alternating magnetic fields, has not been clarified. In particular, in contrast to the low-frequency case, at high frequencies there exist quasiperiodic (in the circularly polarized field) and chaotic (in the linearly polarized field) precessional modes of the magnetic moment. In this paper we study in detail the power loss of the magnetic moment driven by either circularly or linearly polarized magnetic field. Particular attention is paid to the effects caused by each precessional mode and transitions between them.

2. MODEL AND MAIN EQUATIONS

We consider the single-domain nanosized particle with uniaxial anisotropy that is characterized by the anisotropy field H_a and the magnetic moment $\mathbf{m} = \mathbf{m}(t)$ of a constant magnitude $|\mathbf{m}| = m$. The z axis of the Cartesian coordinate system xyz is chosen to be directed along the particle easy axis. It is also assumed that the nanoparticle is under the action of the alternating magnetic field

$$\mathbf{h} t = \mathbf{e}_x h \cos \omega t + \mathbf{e}_y \rho h \sin \omega t, \quad (1)$$

where $\mathbf{e}_{x,y}$ are the unit vectors along the corresponding coordinate axes, $h(>0)$ and $\omega(>0)$ are the field amplitude and frequency, respectively, $\rho = \pm 1$ for the circularly polarized field, and $\rho = 0$ for the linearly polarized one. The magnetic energy of such a particle is given by

$$W(t) = -\frac{H_a}{2m} m_z^2 - \mathbf{m} \cdot \mathbf{h} t \quad (2)$$

and the dynamics of the magnetic moment \mathbf{m} is described by the Landau-Lifshitz equation

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} - \frac{\lambda \gamma}{m} \mathbf{m} \times \dot{\mathbf{m}} \times \mathbf{m} \times \mathbf{H}_{\text{eff}}. \quad (3)$$

Here, $\gamma(>0)$ is the gyromagnetic ratio, $\lambda(>0)$ is the damping parameter, $\mathbf{H}_{\text{eff}} = -\partial W / \partial \mathbf{m}$ is the effective magnetic field acting on \mathbf{m} , and the dot and cross denote the scalar and vector product, respectively. Finally, in accordance with Ref. [10], the reduced power loss of

* lyutyi@oeph.sumdu.edu.ua

the magnetic moment can be defined as

$$E = \lim_{\tau \rightarrow \infty} \frac{1}{\tau} \int_0^\tau dt \mathbf{H}_{\text{eff}} \cdot \frac{d\mathbf{u}}{dt}, \quad (4)$$

where $\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{eff}} H_a$, $\mathbf{u} = \mathbf{m}/m$, $t = \omega_r t$, $\omega_r = \gamma H_a$.

3. RESULTS AND DISCUSSION

As follows from the definition of E , the power loss strongly depends on the dynamics of \mathbf{m} . The features of the steady-state modes of the magnetic moment driven by the circularly polarized magnetic field whose plane of polarization is perpendicular to the easy axis were discussed in detail in [11,12]. It has been shown (see also Ref. [13]) that in this case two precessional modes, periodic and quasiperiodic, can exist. The first one is characterized by a constant precession angle θ , which can be determined analytically [13,14]. If the magnetic field rotates in the direction opposite to the direction of natural precession of the magnetic moment, then the corresponding periodic mode is stable for all h and ω . In contrast, if these directions are the same, then the periodic mode is stable only in some region of these variables. At the boundary of this region the periodic mode becomes unstable and, depending on the concrete values of h and ω , the magnetic moment switches to a new periodic mode or to quasiperiodic mode. The latter is characterized by the time-dependent precession angle whose period differs from the period of the circularly polarized magnet field. This mode can also be unstable that results in switching of the magnetic moment to the state with a stable periodic mode.

In Fig. 1, we show the power loss as a function of the reduced amplitude $h = h/H_a$ for different values of the reduced frequency $\omega = \omega/\omega_r$ of circularly polarized magnetic field. The character of the function $E(h)$ is changed in the vicinity of the points where the periodic and quasiperiodic modes become unstable. At small frequencies (see the representative curve with $\omega = 0.4$) the power loss monotonically grows with h up to a critical value $h \approx 0.31$, where the transition from one periodic mode (in the up state of the magnetic moment when

$m_z > 0$) to the other (in the down state of the magnetic moment when $m_z < 0$) occurs. At larger frequencies ($\omega = 0.6; 0.7$) the character of $E(h)$ is changed twice. The reason is that in this case the increase of h leads to two transitions, namely, from periodic (in the up state) to quasiperiodic mode and then from quasiperiodic to periodic (in the down state) mode. The curve with $\omega = 0.8$ represents the situation [11,12] in which two periodic modes with different precession angles exist in the up state. Finally, in the case of large frequencies (see the curve with $\omega = 0.9$) the situation with two transitions is again realized.

When the nanoparticle is under the action of linearly polarized magnetic field ($\rho = 0$), the dynamics of \mathbf{m} becomes quite different from that described above. In particular, the magnetic moment can exhibit chaotic motion for some field amplitudes and frequencies [15]. This fact makes it difficult to numerically estimate the power loss in these regions. Therefore, here we restrict ourselves to the case of deterministic behavior of \mathbf{m} .

The results of numerical determination of $E(h)$ in the case of linearly polarized field are presented in Fig. 2. All curves are obtained for the deterministic motion of \mathbf{m} whose period is equal to the half of the external field period. The breaks of the curves at $\omega = 0.6$ and $\omega = 0.7$ designate the appearance of the chaotic mode. The jump of $E(h)$ for $\omega = 0.8$, which occurs at $h \approx 0.13$, indicates that, like in the previous case, the magnetic moment has performed the mode transition.

It should be noted that at small frequencies the power loss in the case of linearly polarized magnetic field is less (at the same other conditions) than in the case of circularly polarized one [8]. Therefore, the authors of this paper made the conclusion that the magnetic fields with circular polarization are more preferable. However, as Fig. (3) shows, this conclusion is not general. Instead, even in the regions where the chaotic mode does not appear, the opposite dependence of the power loss on the field polarization can exist.

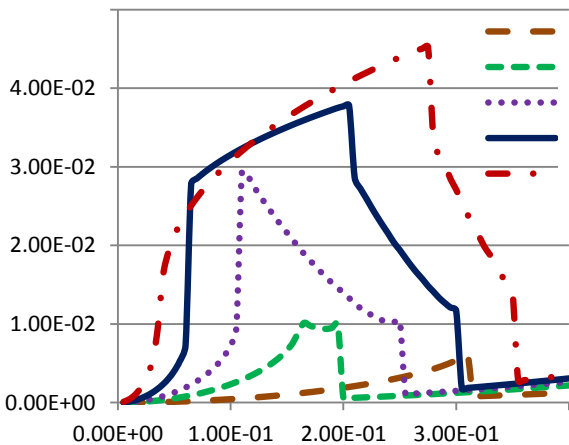


Fig. 1 – The reduced power loss as a function of h in the case of circularly polarized magnetic field with $\rho = 1$ and $\lambda = 0.1$

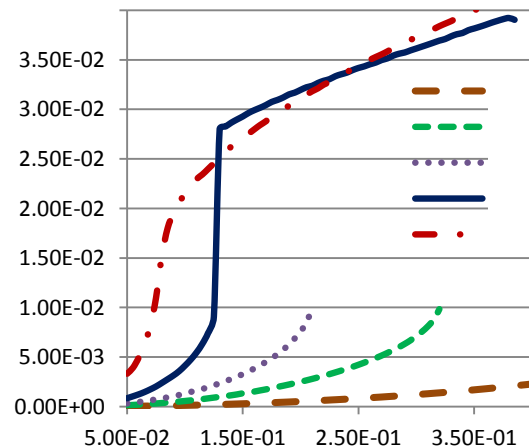


Fig. 2 – The reduced power loss as a function of h in the case of linearly polarized magnetic field ($\lambda = 0.1$)

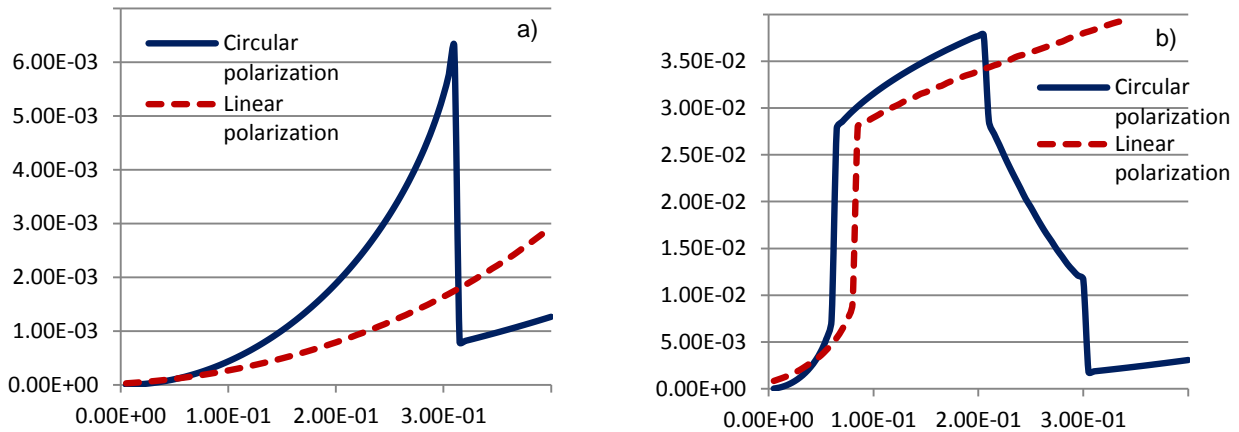


Fig. 3 – Plots of $E h$ for circularly and linearly polarized magnetic fields at a) $\omega = 0.4$ and b) $\omega = 0.8$

4. CONCLUSIONS

The power loss of the nanoparticle magnetic moment in the circularly and linearly polarized magnetic fields has been studied. Based on the numerical solution of the deterministic Landau-Lifshitz equation, we have investigated in detail the main features of the power loss for different precessional modes of the magnetic moment. It is shown that the power loss changes abruptly when the transitions between these modes occur. The comparison analysis of the power loss for circularly and linearly polarized magnetic fields has been con-

ducted. The preference of either polarization with respect to the power loss optimization is discussed.

ACKNOWLEDGEMENTS

T.V.L. and A.Yu.P. acknowledge the support of the Cabinet of Ministers of Ukraine, The Program of Studying and Training for Students, PhD Students and Professor's Staff Abroad (order dated April 13, 2011 No 411) and the support of the Ministry of Education, Science, Youth, and Sport of Ukraine (Project No 0112U001383).

REFERENCES

1. V.B. Bregar, *IEEE Trans. Magn.* **40**, 1679 (2004).
2. C. Thirion, W. Wernsdorfer, D. Maily, *Nat. Mater.* **2**, 524 (2003).
3. A. Jordan, R. Scholz, P. Wust, H. Fäahling, R. Felix, *J. Magn. Magn. Mater.* **201**, 413 (1999).
4. R.E. Rosensweig, *J. Magn. Magn. Mat.* **252**, 370 (2002).
5. J.-P. Fortin, F. Gazeau, C. Wilhelm, *Eur. Biophys. J.* **37**, 223 (2008).
6. X. Zhang, S. Chen, H.-M. Wang, S.-L. Hsieh, C.-H. Wu, H.-H. Chou, S. Hsieh, *Biomed. Eng.: App. Bas. C* **22**, 393 (2010).
7. P. Cantillon-Murphy, L.L. Wald, M. Zahn, E. Adalsteinsson, *Concepts Magn. Reson. A* **36**(1), 36 (2010).
8. P.F. de Châtel, I. Händori, J. Hakl, S. Mészáros, K. Vad, *J. Phys.: Condens. Matter* **21**, 124202 (2009).
9. I. Nándori, J. Rácz, [arXiv:1206.1544v1](https://arxiv.org/abs/1206.1544v1) (2012).
10. E.M. Lifshitz, L.P. Pitaevskii, *Statistical Physics, Part 2* (Pergamon Press, Oxford, 1980).
11. T.V. Lyutyy, A.Yu. Polyakov, A.V. Rot-Serov, C. Binns, *J. Phys.: Condens. Matter* **21**, 396002 (2009).
12. S.I. Denisov, T.V. Lyutyy, C. Binns, and P. Hänggi, *J. Magn. Magn. Mater.* **322**, 1360 (2010).
13. G. Bertotti, C. Serpico, I.D. Mayergoyz, *Phys. Rev. Lett.* **86**, 724 (2001).
14. S.I. Denisov, T.V. Lyutyy, P. Hänggi, and K.N. Trohidou, *Phys. Rev. B* **74**, 104406 (2006).
15. M. d'Aquino, C. Serpico, G. Bertotti, I.D. Mayergoyz, R. Bonin, *IEEE Trans. Magn.* **45**, 3950 (2009).