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GYROSCOPIC DYNAMIC OF VORTICES ON SPHERICAL CAPS

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Magnetic vortex can form a ground state in submicrone sized magnetic particle. By exciting gyroscopic dynamics of vortex one can efficiently control the vortex polarity switching process with a variety of applications in high density magnetic storage devises, ultrahigh speed magnetic random access memory etc. We study the gyrotropic properties of the vortex dynamics on the spherical caps. The vortex gyrofrequency for the spherical caps is shown to be lower than one for a disk. The analytical results were confirmed with micromagnetic simulations.

Artificial nanomagnetic systems (magnetic nanoparticles and their superstructures) have acquired a significant place in physics as well as in technology. Planar nanomagnets were well studied during last two decades [1, 2]. The influence of a curvature on magnetic properties of nanoparticles has been studied both experimentally and theoretically for several geometries. Vortex is one of the simplest in-surface topological structures on a spherical surface. Vortices in flat magnets are characterized by the following conserved quantities, which can be associated with a bit of information: the *polarity*, the sense of the vortex core magnetization direction (up or down) and the *chirality* or handedness, the sense of magnetization rotation (clockwise or counterclockwise) [3, 4]. The mutual connection between the vortex polarity and gyroscopical properties of the vortex dynamics provides an efficient way to tune the vortex polarity by exciting gyroscopical dynamics. In this work we study the influence of the curvature of the particle surface on the gyroscopic vortex dynamics.

Let us consider magnetically soft hemispherical nanoparticle, a so-called magnetic caps. We suppose that the particle is in the vortex ground state, which can be realized using the sample of few tens of nanometers. In equilibrium the vortex is located at the top of the caps. Under the action of a DC magnetic field the vortex starts to move. When the vortex shift is small enough (in harmonic approximation) one can assume the rigid vortex motion without change its shape, hence the magnetization $m(\vec{r},t) = m\left(\vec{r} - \vec{X}(t)\right)$ with $\vec{X}(t)$ being the vortex centre coordinate. The gyroscopic dynamics of a vortex as a particle can be described by the Thiele equation, $\vec{F}_g + \vec{F}_e = 0$ [5]. Here $\vec{F}_g = \frac{d\vec{X}}{dt} \times \vec{G}$ describes the gyroscopic force with a gyrovector $\vec{G}$ and $\vec{F}_e = -\frac{\partial E}{\partial \vec{X}}$ is an external force, which acts on the vortex under the influence of energy $E\left(\vec{X}\right)$. In the harmonic approximation $E = k X^2/2$ the force balanee results in gyroscopic vortex motion with the frequency $\Omega = k/|\vec{G}|$. Let us now consider the vortex gyromotion on a spherical caps. Similar to the vortex gyromotion in a disk it is expected that the main contribution to the effective force $\vec{F}_e$ is due to increase of the energy of the volume magnetostatic charges. Using the image-vortex ansatz [6] one can calculate the gyrofrequency in the form

$$\Omega_{caps} = C_{caps}\Omega_0\varepsilon, \quad C_{caps} \approx 0.1233,$$

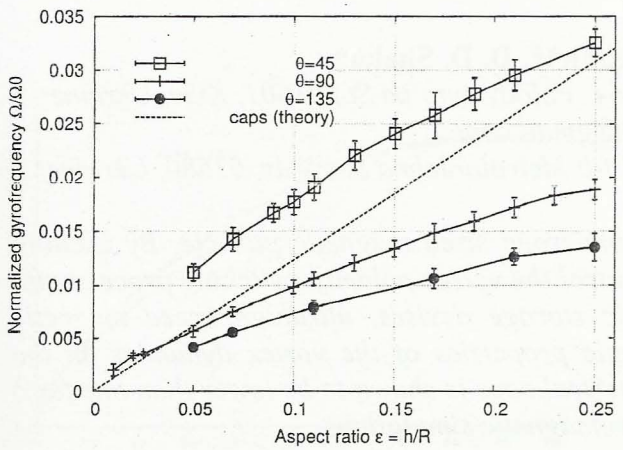

Fig1. Gyrofrequency vs nanoparticle aspect ratio for different cutoff angles.

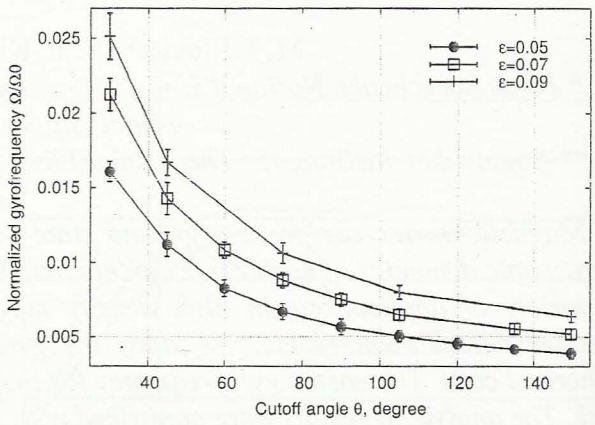

Fig2. Gyrofrequency vs cutoff angle for different aspect ratios.

where $\varepsilon = h/R$ is an aspect ratio (R is a sample radius, h is its thickness), and $\Omega_0 = 4\pi\gamma M_s$ (for Permalloy $\Omega_0 = 30.3\text{GHz}$). It is worth to compare this frequency with corresponding gyrofrequency of a disk-shaped particle, $\Omega_{disk} = C_{disk}\Omega_0\varepsilon$, $C_{disk} \approx 0.1765$.

In order to verify analytical predictions we performed micromagnetic simulations of Landau-Lifshitz-Gilbert equations using MAGPAR simulator [7] with Permalloy parameters: exchange constant $A = 1.05 \cdot 10^{-11}\, J/m$, saturation magnetization $M_S = 796\, kA/m$, and damping constant $\alpha = 0.01$. The mesh size varies from the 2nm near the vortex centre to 15nm on a periphery. Numerically we simulated 3D magnetization dynamics of the vortex on a spherical caps with different aspect ratios and different cutoff angles. Initially using the relaxation procedure, magnetization was relaxed to the vortex state. Then under the action of the field pulse the vortex was shifted from the centre. After that the vortex starts to move along the spiral trajectory moving toward the origin. Using the Fourier analysis of the magnetization oscillations we calculated the vortex gyroscopic frequencies in a wide range of aspect ratios $\varepsilon = 0.05 \div 0.25$ ($R = 100 \div 150\,\text{nm}$ and $h = 5 \div 25\,\text{nm}$), see Fig. 1 and the angle of cutoff of a spherical layer $\theta = 30^\circ \div 150^\circ$, see Fig. 2.

In conclusions, the gyroscopical vortex dynamics on spherical caps was studied theoretically. Our analytical results are in a good agreement with simulations data.

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