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# Resonant modes of vortex structures in soft-magnetic nanodiscs

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## Abstract

We present micromagnetic finite-element simulations on the dynamic response of a soft-magnetic disc exposed to an oscillatory field applied in the disc plane. The disc is magnetized in a vortex state. At lower frequencies (about 200 MHz in our example) we find a motion of the vortex core on an elliptical orbit as a resonant mode. At higher frequencies, the out-of-plane component of the magnetization becomes resonant by the excitation of standing magnetostatic waves.

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It is well known that the switching fields, switching times and magnetization patterns of magnetic nanostructures are, generally, completely different from those of extended films or bulk material. These size-dependent properties have been the subject of numerous investigations in the last years [1]. However, probably because of their less evident technological relevance, questions concerning the dynamic response of nanostructures exposed to weak oscillatory fields have hardly been pursued. The understanding of the high-frequency response of magnetic nanostructures is of fundamental interest. The absorption of oscillatory fields by magnetic nanoparticles may also have a medical importance for novel smart methods to fight cancer by means of local hyperthermia [2].

We consider a permalloy-like disc of 3 nm thickness and 300 nm diameter. The material parameters are: saturation polarization $J_s = 1.00\,\mathrm{T}$, exchange constant $A = 13\,\mathrm{pJ/m}$. Magnetocrystalline anisotropy is neglected.

Resonant modes of nanodiscs in vortex states have been reported recently [3]. A spiralling motion of the vortex around the center of the disc was found [4], similar to the one described by Argyle et al. [5] in an earlier paper. A remarkable study on this issue has been published very recently [6]. In a joint experimental, numerical and analytical work, these authors have shown that the magnetization state of nanodiscs has an influence on the resonant modes. In all the numerical studies on this issue that we are aware of, the spectra have been obtained by shifting the magnetization away from the equilibrium configuration by means of a small external field which is then switched off, so that the structure oscillates and relaxes back to the equilibrium state. The Fourier transform of the oscillations of the average magnetization components gives the resonance frequencies. With this method, one obtains practically the whole spectrum at once, but only those modes which lead to a non-zero variation of the average magnetization can be detected [6]. In the present study, we examine the effect of an oscillating field. This allows us to directly observe the response of the magnetization, and the method is free from any restriction concerning observable modes. The problem is that we have to choose one frequency of the applied field, so that an overview of the complete spectrum is difficult to obtain. The micromagnetic simulations are performed using the finite-element method. The temporal evolution of the

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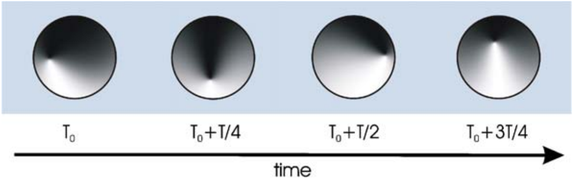

Fig. 1. Snapshots of the evolution of the magnetic structure in a 200 MHz field. The vortex core rotates around the center of the sample.

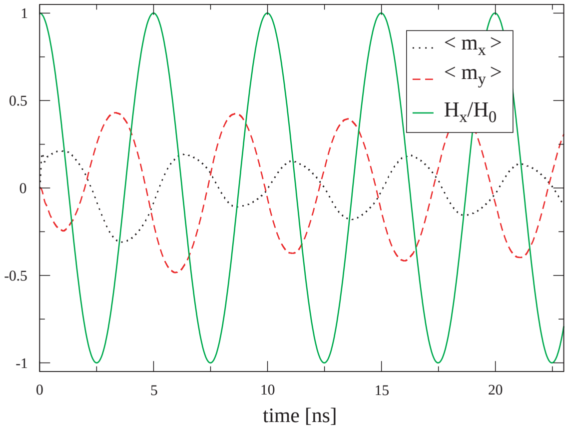

Fig. 2. Average in-plane magnetization components and reduced applied field as a function of time ($f = 200$ MHz).

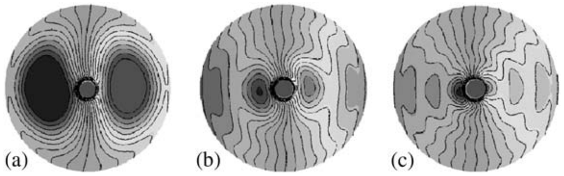

Fig. 3. Contour lines of the out-of-plane component in three cases of standing waves: (a) 7.2 GHz, (b) 14.4 GHz and (c) 21.6 GHz.

magnetic moments is given by Gilbert's equation

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma(\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}) + \frac{\alpha}{M_{\mathrm{s}}}\left(\boldsymbol{M} \times \frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}\right), \tag{1}$$

where the effective field $\boldsymbol{H}_{\mathrm{eff}}$ is the negative variational derivative of the energy density $e$ with respect to the magnetization $\boldsymbol{H}_{\mathrm{eff}} = -\partial e/\partial \boldsymbol{M}_{\mathrm{s}}$, $\alpha$ is the Gilbert damping constant and $\gamma$ is the gyromagnetic ratio. The total energy density contains contributions from the Zeeman, exchange and stray field term. The sample is discretized in 16 879 tetrahedral finite elements. The demagnetizing energy is calculated with a combined finite element–boundary element method [7]. The vortex state is obtained by means of energy minimization. It is used as the starting configuration for the dynamic calculation. The magnitude of the oscillating field is 10 mT. The Gilbert damping costant is set to $\alpha = 0.1$.

At a frequency of about 200 MHz the spiralling mode of the vortex core [3] is observed nicely (Fig. 1). Its motion on an almost circular orbit reflects in the changes of the average magnetization of the disc as a function of time, cf. Fig. 2. However, this does not appear to be a clearly defined resonance. The orbit corresponds rather to an ellipse, with the size of the semi-axes depending on the frequency of the applied field. If the frequency and field strength is reduced, this mode converts into a quasi-static field-driven displacement of the vortex core.

We observe a different type of resonance at higher frequencies, in our case at 7.2 GHz. This frequency is too high for the vortex core to follow the field. While the in-plane structure remains unchanged, the out-of-plane component shows the occurrence of standing waves (Fig. 3). The oscillations have different sign on opposite sides of the vortex core, so that the average $m_z$ component is not changed. This mode can therefore not be found by analyzing Fourier transforms of the excitation spectrum. The excitations of the out-of-plane component occur mainly in regions where the in-plane magnetization has a considerable component perpendicular to the applied field. This is where the external field exerts a periodic torque on the magnetic moments, thus giving rise to standing waves. At integer multiples of the ground frequency, we find higher order excitations of this mode.

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