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# Dynamics of solenoidal magnetic structures in soft magnetic thin-film elements

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**Abstract**

We report on the dynamics of magnetic domain structure conversions exhibited by soft magnetic thin-film elements of elementary geometrical shape (square, disc, triangle) when exposed to a strong external magnetic field. Starting from flux closure vortex patterns, the magnetic structures evolve towards an in-plane saturated state under the influence of an external field. This irreversible and nucleation-free magnetization process occurs on the time scale of picoseconds. The details of this conversion are investigated by means of a time-resolved micromagnetic finite element modeling. We find a sensitive dependence of the temporal evolution of the magnetic structure on the value of the damping parameter in Gilbert's equation of motion. In the case of high damping, domain wall motion dominates the process, while lower damping leads to the formation of a 360° wall which collapses by emitting magnetization waves. It is shown that the mobility of vortices is generally much lower than that of domain walls. The calculations indicate that at a low damping, a magnetic vortex can act almost as a source for concentric waves in ferromagnetic thin-film elements.


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*Keywords:* Magnetization dynamics; Thin-film elements; Saturation process; Vortex mobility; Mircromagnetic modelling

## 1. Introduction

The dynamics of magnetization processes and of magnetic structures has recently become one of the major topics in magnetism [1–3]. This is partly due to the technological requirements for fast-switching magneto-electronic devices. On the other hand, many fundamental properties of non-equilibrium magnetic structures on the picosecond time scale are yet to be explored. In contrast to the broad knowledge of static magnetic domain structures [4,5], the nature of inhomogeneous non-equilibrium magnetic structures occurring, e.g., during magnetization reversal processes is still largely unknown.

In this paper, we present the micromagnetic simulations of the domain structure dynamics of nucleation-free saturation processes in soft magnetic thin-film elements. Conceptionally following, the experimental studies of Acremann et al. [1], we examine the dynamics of a stable closed-flux vortex structure exposed instantaneously to an external field. With this procedure, details of the magnetization dynamics are explored, like

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different mobility of magnetic microstructures and the properties of magnetization waves. This approach is different from the frequently investigated and technologically important switching problem, where the question of the reversal of magnetization in a magnetic storage unit is addressed [2]. In magnetization reversal processes induced by a reversed field, magnetization waves frequently occur and persist after reversal as a technologically unfavorable 'ringing' [6,7]. An ultrafast magnetization reversal mechanism with efficient suppression of this ringing has been recently demonstrated by means of the so-called precessional switching [8], which is achieved by applying a specially shaped magnetic pulse, causing the magnetization to rotate coherently into the desired direction.

In an effort to understand fundamental features of magnetization dynamics, investigations on simple model systems are required. For this purpose, it is, e.g., more useful to study a homogeneous ferromagnetic specimen of elementary geometrical shape than a sample with a complicated grain structure. Similarly, the motion of a well-defined magnetic pattern is more advantageous to investigate than an instability point, like a magnetization reversal connected with a nucleation problem, which generally leads to strongly turbulent transient magnetization states. By starting from a flux-closure pattern and thus avoiding nucleation of reversal, a dynamic problem is simple enough to allow for the identification of general aspects of domain-structure dynamics.

## 2. Micromagnetic simulation

Based on these ideas, we have chosen the following configuration for our dynamic micromagnetic modelling. Consider a ferromagnetic thin-film element of quadratic shape at zero external field. The platelet has an aspect ratio (edge length over thickness) of 100, and the thickness is one exchange length $l_{\rm ex} = \sqrt{A/K_{\rm d}}$, where $K_{\rm d} = \mu_0 M_{\rm s}^2/2$ is the stray field constant, $A$ is the exchange constant, and $M_{\rm s} = |\boldsymbol{M}|$ is the saturation magnetization. The exchange length describes the order of magnitude of the typical extension of micromagnetic structures like magnetic vortices and domain walls. A soft magnetic material is assumed, with an out-of-plane anisotropy corresponding to a quality factor of $Q = 0.1$. The quality factor $Q = K_{\rm u}/K_{\rm d}$ is a measure of the magnetic hardness of the material. Let the platelet be in a symmetric demagnetized state with four domains of equal size. The magnetization lies in the film plane, except for the vortex core region at the junction of the four domains, where the magnetization is normal to the plane. At the time $t_0$, an external magnetic field $H_{\rm ext}$ is applied. The field is of sufficient strength to saturate the sample, $H_{\rm ext} = 0.05 \cdot M_{\rm s}$. The field is oriented in-plane, parallel to an edge of the platelet. In this scenario, initial and final state are clear. The structure evolves from the demagnetized state to a mostly homogeneous state with the magnetization directed along the external field. The question of interest is the domain structure *dynamics* of this process. The instantaneous application of the external field is obviously an idealized model. In a real system, the field would increase with a certain finite rise time. Generally, the extent to which the response of the system to the field is rather driven by dynamic effects than by quasi-static sequences of equilibrium states, depends on the rise time of the field. As an example for this, the decisive influence of the rise time on the switching field of a spherical particle has been demonstrated most clearly by Leineweber et al. [9]. In the present case, we have chosen the limiting case of a purely dynamic response. A very similar process based on quasi-static considerations has been discussed previously [10].

Computational micromagnetism gives the possibility to solve the equation of motion of the magnetization vector field [Eq. (1)] for nano-sized ferromagnetic particles. It represents a powerful tool to gain insight into processes of non-equilibrium magnetic microstructures. The task of dynamic micromagnetism consists in calculating the directional field $\boldsymbol{M}(\boldsymbol{r}, t)$, which evolves according to Gilbert's equation [11]

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

where $\alpha$ is a damping parameter and $\gamma$ is the gyromagnetic ratio. The effective field $\boldsymbol{H}_{\text{eff}}$ is the negative variational derivative of the micromagnetic energy density $e$ with respect to the magnetization [12]

$$\boldsymbol{H}_{\text{eff}} = -\frac{1}{M_s}\frac{\partial e}{\partial \boldsymbol{M}}. \tag{2}$$

The stray field $\boldsymbol{H}_{\text{s}}$ is calculated by introducing a magnetic scalar potential $U$ and solving Poisson's equation

$$\Delta U = 4\pi \boldsymbol{\nabla} \cdot \boldsymbol{M}. \tag{3}$$

The stray field is derived from the scalar potential according to $\boldsymbol{H}_{\text{s}} = -\boldsymbol{\nabla} U$. In our numerical implementation, we obtain fast and precise solutions for the stray field using a hybrid method which combines the finite element method and the boundary element method, by means of which Eq. (3) is solved numerically with exact consideration of Neumann and Dirichlet boundary conditions [13].

The essential feature of dynamic magnetization processes is the magnetization precession. It distinguishes a dynamic micromagnetic calculation from a quasi-static one. In simulations, the influence of the precession on the magnetization process can be varied by the damping parameter $\alpha$. Obviously, to investigate dynamic effects, the damping should be low enough to ensure that precessional effects play a significant role, so that the evolution in time differs sufficiently from the quasi-static approach.

## 3. Results and discussion

### 3.1. Vortex motion

First, we consider a case of high damping, $\alpha = 0.5$. The demagnetized starting configuration is calculated by minimizing the total energy. Snapshots of the dynamic domain structure conversion are shown in Fig. 1.

It can be recognized clearly that the vortex has a lower mobility than the domain walls. After $t = 180$ ps, a considerable part of the sample is already magnetized in the field direction, see the white region in Fig. 1(b), upper row. However, the vortex is still close to its original position in the center of the sample. With increasing time, the vortex is apparently dragged towards the boundary by the walls, which move much faster. The fast motion of the four 90° walls quickly leads to a 360° domain wall structure, as can be recognized in Fig. 1(c), upper row. Technical saturation is reached after the vortex touches the sample's edge and annihilates [Fig. 1d)]. This unexpected motion of the vortex compared with the domain walls is a genuinely dynamic feature. Energy considerations cannot help to explain the formation of the 360° wall. In the quasi-static case, if an external field is slowly incremented, the vortex moves towards the boundary while the 90° domain walls are pinned at the corners [10,14], in contrast to the present case. Evidently, transient magnetic structures of a fast saturation process are very different from those of a quasi-static one, even in the high-damping case. It is noteworthy that the resonant motion of a magnetic vortex in a high-frequency (HF) field has been the subject of an older study by Argyle et al. [15]. These authors found that under certain conditions, the vortex moves in a circular orbit, however, using the assumption that the surrounding 90° domain walls are not bowing during the process. Considering the disparate mobility of walls and vortices, a detailed micromagnetic study of the dynamics of a vortex structure in a square

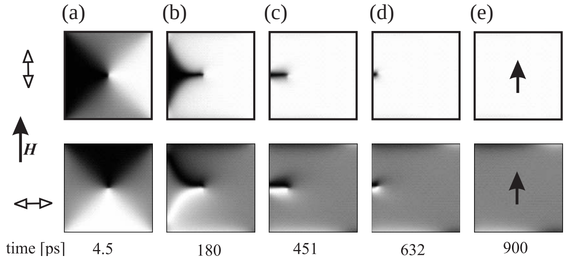


Fig. 1. Domain structure dynamics in the high-damping case, $\alpha = 0.5$. The grey scaling represent the projection of the local in-plane magnetization component in the direction of the external field, and perpendicular to the field in the upper and lower row, respectively. The numbers are picoseconds elapsed after application of the field. The initial structure (a) transforms into a saturated state (e). Note the fanning of the magnetization at the corners of the sample ('Flower state').

particle exposed to a HF field is desirable in order to verify the correctness of this assumption.

For the simulation, the sample is discretized into 20,886 tetrahedral finite elements. A linear interpolation scheme is used within each element. The size of the elements is somewhat larger than the exchange length, by a factor of about 1.6. Generally, caution is required if a discretization size larger than the exchange length is used, since a too coarse mesh can lead to discretization errors. The only place where the mesh size is possibly of decisive importance in this case is the region near the vortex core. There, the magnetization points perpendicular to the plane, and a high discretization density is required to resolve the structure of the magnetization in and around such a singular point. It has been shown [16,17] that the resolution of the vortex core in a thin-film element does not have a visible effect on the in-plane structure, and its influence on the total energy is usually negligible. However, Donahue and McMichael have demonstrated [18] that the motion of domain walls and vortices can be hampered by too coarse a mesh, due to artificial grid pinning effects. In the present case, the mesh is not fine enough to fully resolve the structure of the magnetization in the vortex core, though it can be recognized as bright spots in the middle of Fig. 2(a) and in the initial configurations in Fig. 4. We obtain a resolution of about 30% of the fully perpendicular magnetization in the middle of the vortex core. Whether the low mobility of the vortex is induced by this possibly too coarse discretization scheme is an important question. To check this, we scaled down the problem to half its original size, i.e. $50 \times 50 \times 0.5$ units of an exchange length. Using the same mesh as before, the vortex core was then fully resolved. We obtained a maximum of about 90% perpendicular magnetization in the vortex core. Under the same conditions as before, we simulated the saturation process of the element (not shown). The results clearly demonstrate that the low mobility of the vortex is not due to grid effects. As a consequence of this low vortex mobility, we again observe the formation of the 360° wall. There is a complicated, small-amplitude oscillatory motion of the vortex core superimposed to its slow propagation perpendicular to the field. This additional effect results from the precession of the vortex core magnetization and becomes visible in this small element using a fine discretization mesh.

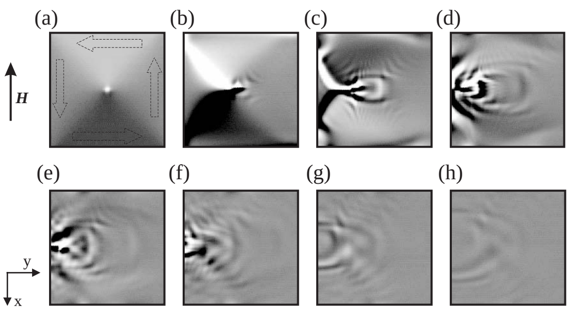


Fig. 2. Gray scale representation of the out-of-plane component of the magnetization during the saturation process for moderate damping, $\alpha = 0.1$. The series shows snaphots taken at various steps in time after application of the external field. ((a) 13.5 ps, (b) 85.8 ps, (c) 158.1 ps, (d) 230.4 ps, (e) 302.7 ps, (f) 375.0 ps, (g) 447.4 ps, (h) 519.7 ps).

The domain structure dynamics of Figs. 1(a)–(e) can be understood on two different length scales. On one hand, the vortex may be regarded as an isolated magnetic microstructure. On a larger length scale, the influence of the external field on the magnetic domain structure can be discussed. In both cases, it is necessary to consider the *torque* acting on the magnetic moments to understand the magnetization dynamics. Torque is the driving force for immediate changes of the magnetization.

Since the initial configuration is a minimum energy arrangement, the torque $\boldsymbol{M} \times \boldsymbol{H}_{\text{eff}}$ is zero throughout the sample. Just after switching on the field, the torque acting on the magnetic moments is entirely due to the external field, so that $\boldsymbol{H}_{\text{eff}}$ can be replaced with $\boldsymbol{H}_{\text{ext}}$. The torque has the highest value in the domains oriented perpendicular to the field, i.e., the grey regions in Fig. 1(a), upper row. These domains are the first regions to change their magnetization direction towards the external field. Though the domain with magnetization antiparallel to the external field, i.e., the black region in Fig. 1(a) (upper row) has the energetically most inconvenient alignment of the magnetization, it rotates only slowly towards the field, since the torque acting on magnetic moments in this region is small. This is in striking contrast to the quasi-static case, where domains are modified with an external field such as to minimize the total energy.

Microscopically, the reason for the low vortex mobility compared with the domain walls is its rotational in-plane symmetry. As a consequence of it, the net torque on the in-plane magnetization of the vortex is zero. Presuming that the structure of the vortex essentially remains unchanged, only the core of the vortex can give a contribution to the total torque on the structure. Compared with $90^\circ$ walls which connect large regions of maximum torque with regions of nearly zero torque, the torque exerted on the vortex core is negligible.

### 3.2. Magnetization waves

Reducing the damping parameter to a moderate value, $\alpha = 0.1$, yields more surprising effects. While the general features — low vortex mobility, high domain wall velocity — remain the same, the slower intrinsic energy dissipation has dramatic consequences. This can be seen readily in the out-of-plane component of the magnetization of the platelet during the process, shown in Fig. 2. The in-plane structure of the magnetization is not shown here. It is very similar to the high-damping case shown in Fig. 1, though the speed of the process is not exactly the same. The effect of the torque exerted by the external field is visible in Fig. 2(a). The domains perpendicular to the field show a bright/dark contrast indicating a small out-of-plane component of the magnetization. Precession around the external field causes this out-of-plane magnetization, which generates a stray field perpendicular to the plane, thus facilitating a precessional alignment towards the external field [19].

After 86 ps, the four $90^\circ$ domain walls have merged to a $360^\circ$ domain wall, while the vortex has not changed its position visibly, similar to the high-damping case, cf. Fig. 1(b)–(d). The strong contrast in Fig. 2(b) shows that the $360^\circ$ wall contains considerable out-of-plane magnetization. More details of this transient wall type are shown in Fig. 5. The beginning of an instability can be seen in the centre of Fig. 2(b): at the rightmost end of the $360^\circ$ domain wall, i.e., where the vortex is located, magnetization waves are generated. The propagation of these waves is displayed in the subsequent Figs. 2(c)–(h). The wavefronts are reflected at the particle's edge, in accordance with previous reports [1]. The effect of the boundary is more clearly visible in an animated illustration [20]. While the two wave fronts which are reflected on the left hand side in Fig. 2(c) are due to the motion of two $90^\circ$ walls quickly propagating towards the edge after reversal of the corresponding domain, the almost circular wavefronts emitted from the center have a different origin. Sudden formation of a $360^\circ$ domain wall due to dynamic effects means the generation of a small region of high energy density. Obviously, the system has a tendency to reduce its total energy and to even out strong energy gradients within the sample. If the intrinsic damping given by $\alpha$ is low, energy density is dissipated by the emission of magnetization waves. The waves generated by the fast saturation process interfere with each other after reflection at the boundary. Even after the sample is nominally saturated, a slow evanescence of the waves continues for a long time, as Figs. 2(e)–(h) indicate.

We have simulated the same process also with a lower damping parameter, $\alpha = 0.05$. Low intrinsic energy dissipation generally results in the generation of numerous, complicated magnetization waves, leading to hardly comprehensible magnetization patterns.

However, the basic processes remain the same, so that this low damping case does not give a significant new insight. Examples on low-damping processes are shown in Fig. 4. The temporal evolution of the magnetization direction at two points in different domains in the square platelet is shown in Fig. 3. As a guide for the eye, the diagram is subdivided in the previously mentioned three regimes: domain wall motion (I), wave generation (II), and evanescence of waves (III). Fast domain wall motion (I) locally results in a quick alignment of the magnetization towards the field, (Section I in Fig. 3(a)), followed by the generation of waves, see Section II of Fig. 3b.

Aligning the external field exactly parallel to the specimen's edge might appear to be an artificial situation, which is unproducible in a real experiment. To account for this, and to analyze the dependence of the domain structure dynamics on the particle's shape, we have studied the behavior of discs and triangular thin-film elements. Except for lower values for the Gilbert damping, all the conditions of the calculation like material, field strength, thickness and aspect ratio are the same as in the previous case. The dynamics of the saturation process, which can be recognized in the perpendicular component of the magnetization, is shown in Fig. 4. In the initial stages, the process is the same in all cases of low damping: A 360° wall is formed (Fig. 5) and almost circular magnetization waves are emitted from the vortex. Projections of the magnetization components on a cutline through the 360° wall are shown in Fig. 5. In the vicinity of the wall, the magnetization is strongly inhomogeneous, and all components perform dramatic variations. The wall is neither of Bloch-type nor of Néel-type. This is a new non-equilibrium micromagnetic structure.

In the low-damping cases, the magnetization waves persist for a long time, leading to strong fluctuations in the perpendicular component which decay very slowly.

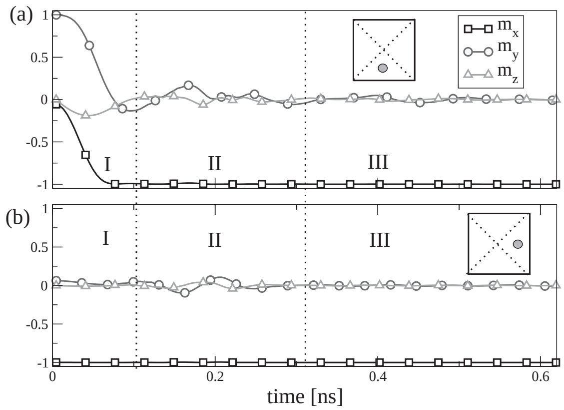


Fig. 3. Components of $\boldsymbol{M}$ vs. time at two selected points after switching on the external field. The point (a) is located in a domain originally perpendicular to the field, the magnetization in point (b) is already aligned along the field.

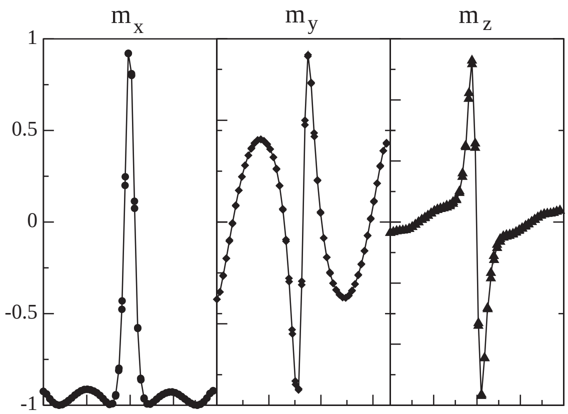


Fig. 5. Magnetization components on a cutline perpendicular to the 360° wall formed in the triangle of Fig. 4 after 90 ps (dotted line). The abscissa represent the position on the cutline. The field is applied along $-x$, so the $m_x$ component shows a twofold change of sign along the cutline. Note the change in the perpendicular component $m_z$, and of the $m_y$ component of almost 180°.

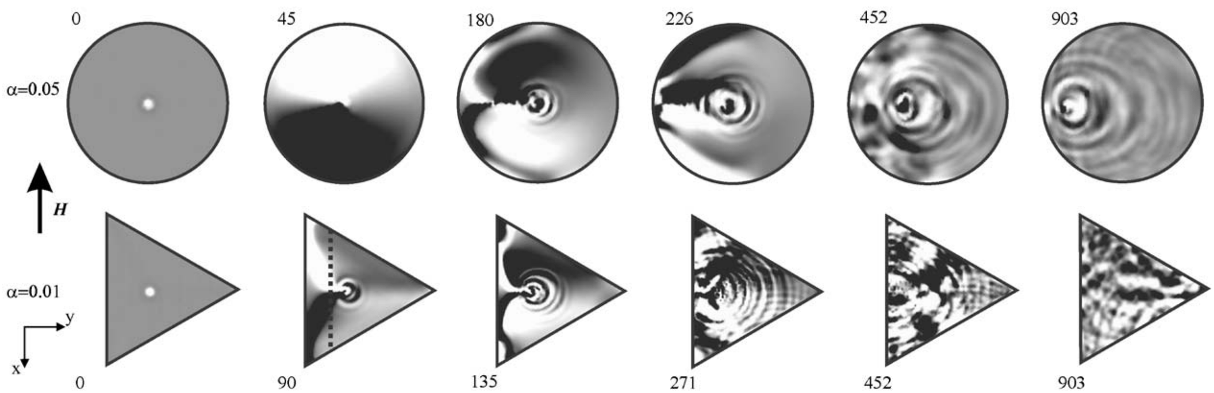


Fig. 4. Grey scale plot of the out-of-plane component of the magnetization during the saturation of a thin disc and of a thin-film element of triangular shape. Low damping leads to interference patterns of reflected waves. Eventually, multiple reflection yields a noisy structure of the perpendicular component. The numbers indicate picoseconds elapsed after applying the field.

## 4. Conclusion

In conclusion, the following findings of domain structure dynamics can be summarized: (a) In a fast magnetization process, the evolution of the magnetic structure is determined by the torque exerted on the magnetic moments, and not by the path of fastest energy minimization. (b) In a thin-film element, a vortex shows low mobility when exposed to an external field. It moves perpendicular to the applied field. Its low mobility is a consequence of the above point, since the net torque on such structures is small. (c) As a result of the low vortex mobility, compared with fast-moving domain walls, strongly frustrated magnetic structures (360° domain walls) can develop temporarily. The unstable 360° wall has a different structure than the usual domain wall types known from static micromagnetism. (d) At low damping, residual energy is dissipated by emitting magnetization waves. Interference patterns of the waves occur due to multiple reflection from the particle's boundary. (e) These processes are largely independent on the particle's shape. They are found in square, circular and triangular elements.

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