Ph.D. project (2022-2025)

Magnetism of curved thin structures: geometrical and deformation effects

Ph.D. supervisors:	Mohamed Haboussi & Fatih Zighem
Contacts :	haboussi@univ-paris13.fr & zighem@univ-paris13.fr
	01.49.40.34.70 & 01.49.40.34.60
Laboratory:	CNRS - Laboratoire des Sciences des Procédés et des Matériaux
	Université Sorbonne Paris Nord, 93430 Villetaneuse, France

Since the discovery in 1847 by J. P. Joule of the macroscopic deformation of a magnetic material by a magnetic field (direct magnetostriction), magneto-mechanical effects have not ceased to be studied both for their fundamental aspects and for the industrial applications involving them. Magneto-mechanical effects are essentially those related to magnetostriction, resulting either in the deformation of a ferromagnetic body under the application of a magnetic field (direct effect) or in the induced magnetoelastic anisotropy when a stress is applied to this body (indirect effect). After having been the subject of numerous fundamental studies and having given rise to many applications over the last century (particularly in the 1960s and 1970s), these magneto-mechanical effects have been the subject of renewed interest in recent years, due to their involvement in new hot research topics in nanomagnetism, such as "straintronic-magnetism". In this domain, elastic (stationary) strains imposed on the system allow certain magnetic properties of the latter to be controlled. The influence of these magnetoelastic effects is also being studied in flexible magnetic devices that are very present in microelectronic applications.

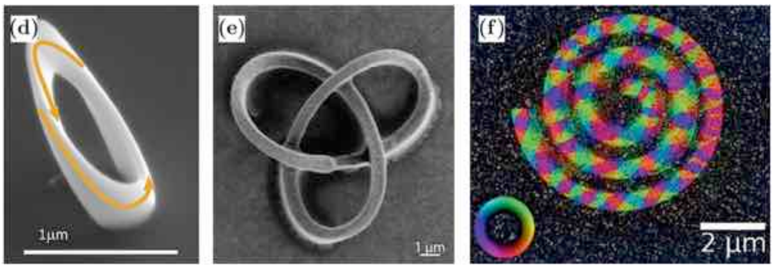

Figure 1: Different curved objects. Image (f) shows the complex magnetic induction pattern within a complex object obtained by magnetic holography, [1].

Furthermore, many recent theoretical and numerical studies have shown that strongly curved magnetic objects can give rise to complex magnetic textures. These effects are generating great enthusiasm in the magnetism community[1-2]. A central question in the resulting new research is how geometrical features such as curvature, thickness, or material features such as interface quality, or more generally the mechanical deformation and its heterogeneity impact or even control the changes of the magnetic properties of the studied systems as well as the new (magnetic) phenomena they generate (e.g. the stabilization of magnetic skyrmions without *a priori* the Dzyaloshinskii-Moriya type interaction but under the influence of the curvature of the magnetic object or other of its shape characteristics). At present, only geometrical effects are generally taken into account in the theoretical and numerical modelling of curved magnetic objects[1-2]. However, such systems are necessarily subjected to mechanical deformations in reality, resulting in additional magnetic (magneto-mechanical) effects in addition to the pure effects due to the initial geometry.

A major scientific challenge in the field of nanomagnetism is therefore to quantify and discriminate the evolutions of the magnetic properties due to the geometry of the object and/or its deformation thanks to a complete and relevant modelling, leading to a robust and efficient numerical simulation tool of these phenomena. However, such a tool accounting for both the effects of curvature and deformations, which may be large and heterogeneous, on the magnetic properties is not available and still to be developed. This is the main objective of this thesis project.

To achieve this task, we will build on a work already initiated at the LSPM, during the Ph.D. thesis of N. Challab (2021), which resulted in a first numerical simulation tool developed in COMSOL Multiphysics®. Based on the solution of the Landau-Lifshitz-Gilbert (LLG) equation, coupled with the magnetostatic and mechanical equations, this simulation tool was first validated on multiple applications involving objects, rather without curvature, before being used to analyze various experimental observations[3-5]. In the present thesis, this tool will be first used to highlight the effects of curvature alone on the magnetism of the studied objects, before considering their deformation. The latter will be assumed to be small, as for the rotation, before addressing the more complex case of large deformations and more generally of finite transformations. This will necessarily require a modification of the mathematical modelling on which the numerical simulation tool implemented in COMSOL Multiphysics® is based. Particular attention will be paid in this case to the treatment of finite rotations and the problem of objectivity of the constitutive equations and tensorial quantities involved.

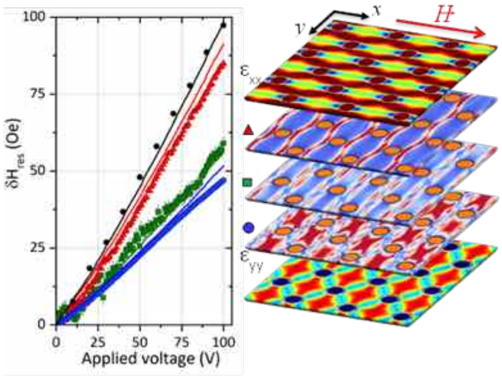

Figure 2: Magnonic crystal deposited on a ferroelectric substrate and subjected to elastic mechanical deformations. The maps show different localized magnetic modes as well as complex deformation fields, [6].

This work will be conducted within the groups of nanomechanics and nanomagnetism of LSPM under the supervision of M. Haboussi and F. Zighem, with close interactions with other members of the groups (Y. Roussigné and D. Faurie). The PhD student would also benefit from two international collaborations with, i) D. Makarov's group (Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany) for the theoretical and numerical aspects, ii) Adekunle Adeyeye's group (Durham University & National University of Singapore, UK & Singapore) for the magnonic crystal fabrication.

Candidate profile: Engineer (5 years of higher education) or Master's degree with solid scientific knowledge in theoretical and numerical mechanics and/or solid state physics, confirmed programming skills as well as very good writing and oral communication skills in English (or in French). Good knowledge of COMSOL Multiphysics® software will be highly appreciated.

Interested candidates are invited to send their application (CV + covering letter + academic transcripts + recommendations) to haboussi@univ-paris13.fr & zighem@univ-paris13.fr

Bibliographical references

[1] D. D. Sheka, *A perspective on curvilinear magnetism,* **Applied Physics Letters 118 (23), 230502 (2021)**

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