magnetism

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*Editorial*

# Mathematical Modelling and Physical Applications of Magnetic Systems

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## 1. Introduction

Recently, nanoscale magnetic materials have attracted widespread attention due to their intriguing properties in both theoretical and experimental contexts. During the last two decades, the underlying physics of the complex magnetization dynamics in magnetic systems, such as ferromagnetic and antiferromagnetic films and confined magnetic systems of different shapes, including nanopillars and waveguides, has been widely studied via the formulation of sophisticated mathematical models, both in terms of classical and quantum descriptions. On the other hand, during the same period, intense experimental activity has successfully confirmed the existence several phenomena predicted by the theoretical models and revealed their effects. Concrete applications, such as magnetic memory, logic devices, diodes, transistors, microwave oscillators, and spintronic devices, etc., have been observed. Two main physical phenomena—spin transfer torque (STT) and spin-Hall effects (SHE)—paved the way for the fabrication of spintronic devices. The main goal of this Special Issue of *Magnetism*, "Mathematical Modelling and Physical Applications of Magnetic Systems," was to encourage world-leading scientists to present their latest exciting theoretical and experimental results at the nanoscale dimension, discussing the fundamental physics of these systems. The collection of articles highlights theoretical, experimental, and technological applications in the field of low-dimensional magnetic systems; the contributions are summarized in the following sections.

## 2. The Present Special Issue

In the SI "Mathematical Modelling and Physical Applications of Magnetic Systems" 9 papers were selected for publication following a strict review process. The main findings of these articles are described and discussed below.

However, before delving into the realm of the published articles, it is important to address three main inquiries: (1) What are the main arguments discussed, and why are they so important for magnetic systems? (2) Are these systems 1D, 2D, or 3D or all of them? (3) If they are also 3D, what are the advantages of studying them compared to low-dimensional 1D and 2D magnetic systems?

**(1) What are the main arguments discussed and why are they so important for magnetic systems?**

In this Editorial, the main topics addressed are the mathematical modeling, deep phenomenological physics, and technological application of magnetic systems at different

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scales of dimensionality. Accurate descriptions of magnetization dynamics, spin–orbit coupling, nonlinear effects, and topological phenomena are gathered to tailor strong advanced theoretical approaches, such as the ones based on the extension of the Landau–Lifshitz–Gilbert (LLG) equation.

These arguments are crucial for

- A better understanding of magnetism at low dimensions, taking into account that theory and experiments need to be correlated.
- A deeper comprehension of physical phenomena, such as spin transport, spin torque effects (STT, SHE), and emergent electrodynamics, which are crucial for tailoring spintronic devices.
- Wider use of technological applications ranging from magnetic memory, logic devices, to neuromorphic computing with special regard to quantum technology based on 3D solitons like hopfions.

Topological spin-textures, magnetoelastic effects, and thermal–magnetic coupling are promising candidates for the development of next-generation technological applications correlated with magnetic materials.

**(2) Are the magnetic topological systems studied 1D, 2D, or 3D—or all of them?**

This collection investigates 1D, 2D, and 3D magnetic topological systems.

- 1D magnetic topological systems consist of domain walls and nanowires and were studied in the framework of spin transport and torque.
- 2D magnetic topological systems are mainly represented by magnetic skyrmions hosted in thin films, multilayers, and planar structures characterized by collective excitations such as spin waves.
- 3D magnetic topological magnetic systems are mainly represented by magnetic hopfions and torons and reveal a novel way to provide topologically protected knots in three dimensions.

One crucial consideration is the search for a novel approximation based on the inclusion of spin–orbit and topological torques in the LLG equation, which leads to a unified theory for 1D, 2D and 3D magnetic systems.

**(3) If they are also 3D magnetic systems, what are the advantages of studying them compared to the low-dimensional 1D and 2D magnetic systems?**

- Topological richness: 3D systems have a topologically complex spin-texture, such as a magnetic hopfion, characterized by the Hopf invariant, where magnetic field lines are linked. This phenomenon cannot exist in 1D and 2D.
- Enhanced stability: greater stability is one of the main factors that makes 3D systems more robust in relation to thermal fluctuations and defects, due to their volumetric topology.
- Improved information density: through the 3D profile, a high storage capacity can be achieved.
- New functionalities: 3D topological Hall transport and volumetric spin-wave modes propagation can be obtained through the coupling between magnetic, electric, and optical fields, paving the way for novel control mechanisms.

3D magnetism is harnessed for technological applications (spintronics, magnonics, neuromorphic architectures, and quantum devices), suppressing the limitation of a planar geometry.

**The topics can be subdivided into three main subjects:**

**1. Advanced Magnetic Phenomena and Theoretical Insights**

**Included Articles**

- Magnetic Hopfions: A Review (Guslienko, 2024).
- A Study on the Effect of Plastic Strain on Magnetic Phenomenology and Microstructure (Hasičić et al., 2025).
- Can We Still Find an Ideal Memristor? (Wang, 2024).

**2. Magnetic Materials, Devices, and Applications**

**Included Articles**

- Loss Mitigation in Self-Biased Microstrip Circulators (Kong et al., 2023).
- Practical Study of Mixed-Core High Frequency Power Transformer (Paul, 2022).
- Magneto Elasticity Modeling for Stress Sensors (Diguet et al., 2022).

**3. Magnetic Modelling and Computational Methods**

**Included Articles**

- Vector-Based Magnetic Circuit Modelling of Induction Motors (Kidd, 2022).
- Numerically Stable and Computationally Efficient Expression for the Magnetic Field of a Current Loop (Ortner et al., 2022).
- The Role of Blood Perfusion in the Thermal Interaction Between Magnetic Nanoparticles and Cancerous Tumors (Maniotis et al., 2025).

The review article by K. Guslienko, ***Magnetic Hopfions: A Review***, deals with magnetic hopfions, which are the 3D topological counterpart of well-known 2D topological spin textures, such as magnetic skyrmions. Magnetic hopfions can be classified as field magnetic solitons because they exhibit stable and localized spin configurations that maintain their structure under continuous magnetic field deformation. Their creation can be numerically reproduced by means of micromagnetic simulations using software such as Mumax3 [1] or OOMMF [2]. On the other hand, their theoretical description is based on the LLG equation, which governs the magnetization motion. The 3D topological charge, also known as the Hopf index, can be extracted through the lens of emergent magnetic vector potential and magnetic field. Magnetic hopfions are physically explained using classical field theory and with toroidal coordinates which become crucial for properly describing them. Their stability and dynamics, especially in ferromagnetic films and dots, are discussed.

In M. Hasičić et al.'s article, "***A Study on the Effect of Plastic Strain on Magnetic Phenomenology and Microstructure***", it is revealed that magnetic properties are affected by plastic strain, correlating macroscopic behavior with microscopic mechanisms. The effect of the strain on the magnetization depends on the anisotropy profile. Based on micromagnetic simulations of hysteresis loops for different magnetic anisotropies, the different equilibrium configurations are discussed as a function of anisotropy, demagnetizing, and energy exchange contributions. The magnetization can change in two ways: it can flip suddenly (switching) or turn gradually to follow the magnetic field (rotation). A hard layer around soft grains is created by compressive stress. Future research should focus on investigating the secondary peak in permeability and how the angle alters between hard and soft areas.

The article "***Can We Still Find an Ideal Memristor***?" by F. Z. Wang sheds light on the role of a memristor. An ideal memristor was invented by Chua in 1971 [3]. It correlates the magnetic flux $\Phi$ and the electric charge $q$ with the two physical quantities nonlinearly correlated. The direct interaction between $\Phi$ and $q$ behaves like a memristor. It is shown that the "ideal/real/perfect" memristor requires magnetism, but the structure still faces two major limitations: (1) an inductive effect, and (2) bistability along with dynamic sweeping across a continuous resistance range. Several innovations based on an "open" structure, nanoscale dimensions, magnetic materials with cubic anisotropy and sequential switching

of magnetic domains are proposed. This discovery paves the way for next-generation ideal memristors, even though they can still be considered a purely a mathematical concept.

L. Kong et al. focus on "***Loss Mitigation in Self-Biased Microstrip Circulators***". The use of ferrite devices in radio frequency (RF) systems and antennas is quite challenging because they need external magnets. Hexaferrite-based devices can work without magnets at high frequencies, but the loss of energy is recorded at lower frequencies used in wireless communication. This paper examines La-Co (lanthanum-cobalt)-substituted hexaferrite materials for low-GHz circulators.

A. K. Paul deals with the "***Practical Study of Mixed-Core High Frequency Power Transformer***". In the core of power electronics, the use of medium to high frequency aims to remove heat in order to facilitate optimal use of both the core and copper. The thermal conduction of a transformer device is complicated by the presence of loss centers. By taking the core made by a soft magnetic material, a mixed-core profile to achieve superior temperature profile and better long-term performance is employed. The new cores replace the original ones under the windings. In addition, they share more of the heat dissipation load. The magnetic and thermal behavior of the transformer is assessed through the lens of two high-power applications. In the first case, the core operates at its rated flux, while in the second case, the windings operate at their rated currents.

G. Diguet et al. delve into the realm of "***Magneto Elasticity Modeling for Stress Sensors***". In this article, the phenomena of stress/stress sensing hosted in the thin films is discussed and demonstrated. Different main pillars such as the application of stress (compressive and tensile) and the application of a DC electromagnetic field are the bases of the sensing phenomena. Physical phenomena—magnetic susceptibility and magnetic permeability—are examined by applying a strong exciting AC electromagnetic field aligned along the same direction of the applied stress. The magnetic susceptibility of the material changes with the applied stress and reaches a maximum value when the stress is close to a critical level. For the DC electromagnetic field applied along the direction of the exciting AC electromagnetic field and along the same direction as the applied stress, the critical stress is shifted toward negative values, and for the DC electromagnetic field applied perpendicularly, the critical stress is shifted towards larger positive values. Specifically, when the DC electromagnetic field is in the same direction as the AC one, the critical stress becomes smaller, while the critical stress becomes larger when the two fields are perpendicular. In summary, in this investigation experimental endeavors were conducted to obtain a clear overview on magnetoelastic properties for stress sensors.

B. Kidd proposes "***Vector-Based Magnetic Circuit Modelling of Induction Motors***". An electro-mechanical system is used together with applied and rotating magnetic fields. Efficiency and accuracy are the two main factors needed to create a robust device. The developed vector-based magnetic circuit equations give more accurate results to describe the operational characteristics of induction motors if compared to regular flux models. The exact equations are extracted through the shape and design of the device and the results are reliable with a short calculation time.

M. Ortner et al. propose "***Numerically Stable and Computationally Efficient Expression for the Magnetic Field of a Current Loop***". In this work, the authors show that direct implementations of standard textbook formulas for the off-axis magnetic field of a current loop become numerically unstable over a wide region. Near the axis of symmetry and at large distances from the loop, accuracy deteriorates rapidly. The instability comes from numerical cancellation, which cannot be fixed algebraically. All exact expressions reported in the literature suffer from similar issues. The authors explore unconventional computing compared to conventional methods. Different approaches such as dipole, Taylor, and

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binomial approaches are compared with classical ones. The novel method is based on an analytic expression using Bulirsch's complete elliptic integral.

N. Maniotis et al. propose "***The Role of Blood Perfusion in the Thermal Interaction Between Magnetic Nanoparticles and Cancerous Tumors: A Computational Study***". The model studies how blood flow affects tumor heating during treatment with magnetic nanoparticles. Blood flow removes heat from the tumor, so the temperature increase is reduced. The heat produced by 15 nm magnetite nanoparticles is calculated from micromagnetic simulations. In the numerical simulations are use a magnetic field of about 20 mT and a frequency of 100 kHz. The energy loss of nanoparticles is used to model the tumor and healthy tissue. Normal and cancer tissues are distinguished based on experimental differences in how blood flow changes with temperature. 2D bioheat model is used with nanoparticles evenly spread in the tumor. The results show that tumors retain more heat than healthy tissue because their blood flow increases less under heating, which helps therapy. The tumor reaches a temperature ranging between 41 °C and 45 °C, while the other nearby tissues are unaffected. As a main result, tumor heating treatments are presented and improved through nanoparticles and blood flow.

## 3. Future Directions

In our opinion, there are numerous promising avenues for future technology based on magnetism. First, in the framework of advanced magnetic phenomena and theoretical insights, magnetic hopfions, which are 3D topological spin-textures, are highly promising, with potential applications in the field of spintronics, memory data storage, and neuromorphic computing. Research focused on magnetic materials, devices, and applications presents future smart materials and potential sensing applications that are built on magnetoelasticity modeling. However, not all of these smart materials and sensing applications rely exclusively on magnetoelastic effects. Some are based on other magnetic phenomena and mechanisms beyond magnetoelasticity. Another main endeavor is based on magnetic modeling and computational methods, mainly related to the efficiency and accuracy of electromechanical systems, and focuses on linking analytical and numerical approaches for real-time applications. The analysis is not limited to electromechanical systems but it can also be applied to other magnetic and multi-physics systems. We pose two open questions which arise as a continuation of the topics discussed in this Special Issue: What about quantum computing linked to magnetism? And what about the synergy between theory and experiment? At the moment, there are no final answers to these questions.

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