



HAL
open science

A JUSTIFICATION OF NONLINEAR TWO-DIMENSIONAL MODEL FOR FERROMAGNETIC PLATES WITH MAGNETOSTRICTION

Mouna Kassan, Gilles Carbou, Mustapha Jazar

► **To cite this version:**

Mouna Kassan, Gilles Carbou, Mustapha Jazar. A JUSTIFICATION OF NONLINEAR TWO-DIMENSIONAL MODEL FOR FERROMAGNETIC PLATES WITH MAGNETOSTRICTION. SIXTEENTH INTERNATIONAL CONFERENCE ZARAGOZA-PAU ON MATHEMATICS AND ITS APPLICATIONS, Sep 2022, Jaca,Huesca, Spain. hal-04037816

HAL Id: hal-04037816

<https://hal-univ-pau.archives-ouvertes.fr/hal-04037816>

Submitted on 20 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A JUSTIFICATION OF NONLINEAR TWO-DIMENSIONAL MODEL FOR FERROMAGNETIC PLATES WITH MAGNETOSTRICTION

Mouna Kassan, Gilles Carbou and Mustapha Jazar

Abstract. We consider a three-dimensional model of ferromagnetic material with magnetostriction, coupling the Landau-Lifschitz-Gilbert equation and the elasticity wave equation, with mixed boundary condition. We establish the existence of global in time weak solutions. By asymptotic method when the thickness of the sample tends to zero, we obtain and justify a new two-dimensional model for thin plates of ferromagnetic magnetostrictive material.

Keywords: Magnetostriction, weak solutions, thin plates..

AMS classification: 35K55, 35Q55, 35Q74.

§1. Introduction

Ferromagnetic materials have promising applications in several domains, in particular for data storage (see [15]). In such materials, the magnetization induces deformations because of magnetostrictive effects (see [12], [14], [16] and references therein). Let us recall the three-dimensional model for ferromagnetic material with magnetostriction. We denote by Ω the domain occupied by the ferromagnetic material, and by $m(t, x)$ the magnetic moment, satisfying the saturation constraint $|m(t, x)| = 1$ a.e. when the material is saturated. The variations of m are described by the Landau-Lifschitz-Gilbert equation (see [1], [5], [7] and [13]):

$$\begin{cases} \frac{\partial m}{\partial t} - m \times \frac{\partial m}{\partial t} = -m \times H_{eff} & \text{in } \mathbb{R}^+ \times \Omega, \\ \partial_n m = 0 & \text{in } \mathbb{R}^+ \times \partial\Omega, \end{cases} \quad (1)$$

where \times is the usual cross product in \mathbb{R}^3 and H_{eff} is the effective field given by:

$$H_{eff} = \Delta m + h_d(m) + (\lambda^m : \sigma)m.$$

The demagnetizing field $h_d(m)$ is calculated from m by solving the static Maxwell equations coupled with the law of Faraday:

$$\operatorname{div} (h_d(m) + \bar{m}) = 0 \quad \text{and} \quad \operatorname{curl} h_d(m) = 0, \quad (2)$$

where \bar{m} is the extension of m by zero outside Ω .

In the magnetostriction field $(\lambda^m : \sigma)m$, σ is the stress tensor and λ^m is a symmetric positive 4-tensor.

Remark 1. The usual notations and definitions of tensor calculus are detailed in [7], Section 1.2.1. Additionally, we say that a symmetric 4-tensor λ is positive, if there exists $\lambda^* > 0$ such that:

$$\forall \xi^{ij} \text{ symmetric, } \sum_{ijkl} \lambda_{ijkl} \xi^{ij} \xi^{kl} \geq \lambda^* \sum_{ij} (\xi^{ij})^2.$$

The Landau-Lifschitz equation (1) is coupled with the following elasticity wave equation:

$$\left\{ \begin{array}{ll} \frac{\partial^2 u}{\partial t^2} - \operatorname{div} \sigma = 0 & \text{in } \mathbb{R}^+ \times \Omega, \\ u = 0 & \text{on } \mathbb{R}^+ \times \Gamma_1, \\ \sigma \cdot n = f & \text{on } \mathbb{R}^+ \times \Gamma_2, \end{array} \right. \quad (3)$$

where the stress tensor σ is given by:

$$\sigma = \lambda^e : \varepsilon^e, \text{ with } \varepsilon(u) = \varepsilon^e + \varepsilon^m,$$

where:

- the deformation tensor $\varepsilon(u)$ is given by:

$$\varepsilon_{ij}(u) = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),$$

- the magnetic tensor ε^m satisfies :

$$\varepsilon^m = \lambda^m : m \otimes m.$$

We assume that we are in the isotropic case, so that the 4-tensor λ^e is given by:

$$\lambda_{ijkl}^e = \frac{E}{1+\nu} \left(\frac{1}{2} (\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk}) + \frac{\nu}{1-2\nu} \delta_{ij} \delta_{kl} \right) \text{ for } i, j, k, l \in \{1, 2, 3\},$$

where $E > 0$ and $0 < \nu < \frac{1}{2}$.

Concerning the boundary conditions in (3), we assume that the sample is clamped on $\Gamma_1 \subset \partial\Omega$, where the surface measure of Γ_1 is non vanishing. On the other part $\Gamma_2 = \partial\Omega \setminus \Gamma_1$, a surface force f is supposed to be applied.

We define the space $V(\Omega)$ by:

$$V(\Omega) = \{v \in H^1(\Omega; \mathbb{R}^3); v = 0 \text{ on } \Gamma_1\}.$$

By Korn inequality (see [10], Theorem 6.3-4 page 292), there exists $c(\Omega) > 0$, such that for all $v \in V(\Omega)$, we have

$$\int_{\Omega} \varepsilon(v) : \varepsilon(v) \geq c(\Omega) \int_{\Omega} |v|^2. \quad (4)$$

This gives that $\|\cdot\|_V = \left(\int_{\Omega} \varepsilon(\cdot) : \varepsilon(\cdot) \right)^{\frac{1}{2}}$ is a norm on $V(\Omega)$ equivalent to the norm $\|\cdot\|_{H^1(\Omega)}$.

§2. Weak solutions for the Landau-Lifschitz-Gilbert equation with magnetostriction

First, we establish the existence of global-in-time weak solutions for System (1)-(3).

Theorem 1. *Let $m_0 \in H^1(\Omega; S^2)$, $u_0 \in V(\Omega)$, $u_1 \in L^2(\Omega)$ and $f \in H^{\frac{1}{2}}(\Gamma_2)$. Then, there exist m and u with $m \in L^\infty(\mathbb{R}^+; H^1(\Omega; \mathbb{R}^3))$, $|m(t, x)| = 1$ a.e., $\frac{\partial m}{\partial t} \in L^2(\mathbb{R}^+; L^2(\Omega; \mathbb{R}^3))$, $u \in L^\infty(\mathbb{R}^+; V(\Omega))$ and $\frac{\partial u}{\partial t} \in L^\infty(\mathbb{R}^+; L^2(\Omega; \mathbb{R}^3))$, satisfying:*

1. $m(0, \cdot) = m_0$, $u(0, \cdot) = u_0$ and $\frac{\partial u}{\partial t}(0, \cdot) = u_1$ in the trace sense,
2. for all $\chi \in C_c^\infty(\mathbb{R}^+; H^1(\Omega; \mathbb{R}^3))$,

$$\begin{aligned} \int_{\mathbb{R}^+ \times \Omega} \left(\frac{\partial m}{\partial t} - m \times \frac{\partial m}{\partial t} \right) \cdot \chi(t, x) dt dx &= 2 \int_{\mathbb{R}^+ \times \Omega} \left[\sum_{i=1}^3 m \times \frac{\partial m}{\partial x_i} \cdot \frac{\partial \chi}{\partial x_i} - m \times h_d(m) \cdot \chi \right] \\ &- 2 \int_{\mathbb{R}^+ \times \Omega} m \times \left[(\lambda^e : \varepsilon(u))m - (\lambda^m : (\lambda^e : (\lambda^m : m \otimes m)))m \right] \cdot \chi, \end{aligned} \quad (5)$$

3. for all $\chi \in C_c^\infty(\mathbb{R}^+; V(\Omega))$,

$$\begin{aligned} \int_{\mathbb{R}^+ \times \Omega} \frac{\partial u}{\partial t} \cdot \frac{\partial \chi}{\partial t} - \int_{\mathbb{R}^+ \times \Omega} (\lambda^e : \varepsilon(u)) : \varepsilon(\chi) + \int_{\mathbb{R}^+ \times \Gamma_2} f \cdot \chi \\ - \int_{\Omega} u_1 \cdot \chi(0, x) = - \int_{\mathbb{R}^+ \times \Omega} (\lambda^e : (\lambda^m : m \otimes m)) : \varepsilon(\chi), \end{aligned} \quad (6)$$

4. we have the following energy inequality: for all $t \geq 0$,

$$\mathcal{E}(t) + \int_0^t \int_{\Omega} \left| \frac{\partial m}{\partial t} \right|^2 \leq \mathcal{E}(0), \quad (7)$$

where

$$\begin{aligned} \mathcal{E}(t) &= \int_{\Omega} |\nabla m|^2 + \int_{\mathbb{R}^3} |h_d(m)|^2 + \frac{1}{2} \int_{\Omega} \left[Q(m) - 2\varepsilon(u) : (\lambda^e : (\lambda^m : m \otimes m)) \right] \\ &+ \frac{1}{2} \int_{\Omega} \left[(\lambda^e : \varepsilon(u)) : \varepsilon(u) + \left| \frac{\partial u}{\partial t} \right|^2 \right] - \int_{\Gamma_2} f \cdot u d\Gamma, \end{aligned}$$

with $Q(m) = (\lambda^e : (\lambda^m : m \otimes m)) : (\lambda^m : m \otimes m)$

Sketch of the proof: the proof of Theorem 1 follows the method due to Alouges and Soyeur [2] and generalized in [8]. First, we prove the existence of solution for a penalized system, in which the saturation constraint is relaxed. Then, we take the limit when the penalization constant tends toward zero. In [7], global existence for (1)-(3) is obtained in the case of a clamped sample, that is with $u = 0$ on $\partial\Omega$. We use essentially the same method to address mixed boundary condition.

§3. Asymptotic model for plates

We consider a thin plate Ω_η of the form:

$$\Omega_\eta = \omega \times] - \eta, \eta [,$$

where ω is a smooth bounded domain of \mathbb{R}^2 . We assume that this plate is clamped on $\Gamma_1^\eta = C_1 \times] - \eta, \eta [,$ (where $C_1 \subset \partial\omega$ such that the one-dimensional measure of C_1 is non vanishing). We denote by $C_2 = \partial\omega \setminus C_1$, $\Gamma_2^\eta = C_2 \times] - \eta, \eta [,$ and $\Gamma_\pm^\eta = \bar{\omega} \times \{\pm\eta\}$.

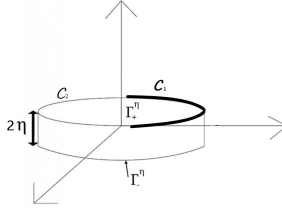


Figure 1: $\Omega_\eta = \omega \times] - \eta, \eta [,$

For given initial data (precised below), we consider the weak solution (m^η, u^η) given by Theorem 1 on the domain Ω_η . In order to work on a fixed domain, we perform the following rescaling: for $t \geq 0$ and $x = (x_1, x_2, x_3) \in \Omega_1 = \omega \times] - 1, 1 [,$ we define M^η, H^η and U^η by:

$$\begin{aligned} M^\eta(t, x_1, x_2, x_3) &= m^\eta(t, x_1, x_2, \eta x_3), \\ H^\eta(t, x_1, x_2, x_3) &= (h_d(m^\eta(t, \cdot)))(x_1, x_2, \eta x_3), \\ U_\alpha^\eta(t, x_1, x_2, x_3) &= u_\alpha^\eta(t, x_1, x_2, \eta x_3) \text{ for } \alpha = 1, 2, \\ U_3^\eta(t, x_1, x_2, x_3) &= \eta u_3^\eta(t, x_1, x_2, \eta x_3). \end{aligned} \quad (8)$$

We also assume that the boundary conditions are of the form:

$$\begin{aligned} g_\alpha^{\eta\pm}(x_1, x_2, \pm\eta) &= \eta g_\alpha^\pm(x_1, x_2) \quad \text{and} \quad g_3^{\eta\pm}(x_1, x_2, \pm\eta) = \eta^2 g_3^\pm(x_1, x_2) \quad \text{on } \Gamma_\pm^\eta, \\ h_\alpha^\eta(x_1, x_2, x_3) &= h_\alpha(x_1, x_2) \quad \text{and} \quad h_3^\eta(x_1, x_2, x_3) = \eta h_3(x_1, x_2) \quad \text{on } \Gamma_2^\eta, \end{aligned}$$

where $g^\pm \in H^{\frac{1}{2}}(\omega)$ and $h \in H^{\frac{1}{2}}(C_2)$. Then, the rescaled quantities satisfy:

- for all $\chi \in C_c^\infty(\mathbb{R}^+; H^1(\Omega_1; \mathbb{R}^3))$, we have

$$\begin{aligned} \int_{\mathbb{R}^+ \times \Omega_1} \left(\frac{\partial M^\eta}{\partial t} - M^\eta \times \frac{\partial M^\eta}{\partial t} \right) \cdot \chi &= 2 \int_{\mathbb{R}^+ \times \Omega_1} \sum_{\alpha=1}^2 M^\eta \times \partial_\alpha M^\eta \cdot \partial_\alpha \chi \\ + \frac{2}{\eta^2} \int_{\mathbb{R}^+ \times \Omega_1} M^\eta \times \partial_3 M^\eta \cdot \partial_3 \chi &- 2 \int_{\mathbb{R}^+ \times \Omega_1} M^\eta \times (H^\eta + (\lambda^m : (\lambda^e : \varepsilon(\eta, U^\eta)))M^\eta) \cdot \chi \\ + 2 \int_{\mathbb{R}^+ \times \Omega_1} M^\eta \times ((\lambda^m : (\lambda^e : (\lambda^m : M^\eta \otimes M^\eta)))M^\eta) \cdot \chi, \end{aligned} \quad (9)$$

- for all $\xi \in C_c^\infty(\mathbb{R}^+; V(\Omega_1))$, we have

$$\begin{aligned}
& \int_{\mathbb{R}^+ \times \Omega_1} \sum_{\alpha=1}^2 \frac{\partial U_\alpha^\eta}{\partial t} \frac{\partial \xi_\alpha}{\partial t} + \frac{1}{\eta^2} \int_{\mathbb{R}^+ \times \Omega_1} \frac{\partial U_3^\eta}{\partial t} \frac{\partial \xi_3}{\partial t} - \int_{\mathbb{R}^+ \times \Omega_1} (\lambda^e : \varepsilon(\eta, U^\eta)) : \varepsilon(\eta, \xi) \\
& + \int_{\mathbb{R}^+ \times \Gamma_-^1} g^+ \cdot \xi - \int_{\mathbb{R}^+ \times \Gamma_+^1} g^+ \cdot \xi + \int_{\mathbb{R}^+ \times \Gamma_2^1} h \cdot \xi - \int_{\Omega_1} u_1 \cdot \xi(0, x) \\
& = \int_{\mathbb{R}^+ \times \Omega_1} (\lambda^e : (\lambda^m : M^\eta \otimes M^\eta)) : \varepsilon(\eta, \xi),
\end{aligned} \tag{10}$$

- for all $t > 0$, we have

$$\mathcal{E}^\eta(t) + \int_0^t \int_{\Omega_1} \left| \frac{\partial M^\eta}{\partial t} \right|^2 \leq \mathcal{E}^\eta(0), \tag{11}$$

with

$$\begin{aligned}
\mathcal{E}^\eta(t) := & \frac{1}{\eta} \mathcal{E}(m^\eta, u^\eta) = \int_{\Omega_1} \sum_{\alpha=1}^2 \left[|\partial_\alpha M^\eta|^2 + \frac{1}{\eta^2} |\partial_3 M^\eta|^2 \right] + \int_{\mathbb{R}^3} |H^\eta|^2 + \frac{1}{2} \int_{\Omega_1} Q(M^\eta) \\
& - \int_{\Omega_1} \left[\varepsilon(\eta, U^\eta) : (\lambda^m : M^\eta \otimes M^\eta) + \frac{1}{2} (\lambda^e : \varepsilon(\eta, U^\eta)) : \varepsilon(\eta, U^\eta) \right] \\
& + \frac{1}{2} \int_{\Omega_1} \left[\sum_{\alpha=1}^2 \left| \frac{\partial U_\alpha^\eta}{\partial t} \right|^2 + \frac{1}{\eta^2} \left| \frac{\partial U_3^\eta}{\partial t} \right|^2 \right] - \int_{\Gamma_-^1} g^- \cdot U^\eta - \int_{\Gamma_+^1} g^+ \cdot U^\eta - \int_{\Gamma_2^1} h \cdot U^\eta,
\end{aligned}$$

where, for $\xi \in H(\Omega_1)$, the 2-tensor $\varepsilon(\eta, \xi)$ is given by

$$\begin{aligned}
\varepsilon_{\alpha\beta}(\eta, \xi) &= \varepsilon_{\alpha\beta}(\xi) \text{ for } \alpha, \beta \in \{1, 2\}, \\
\varepsilon_{\alpha 3}(\eta, \xi) &= \frac{1}{\eta} \varepsilon_{\alpha 3}(\xi) \text{ for } \alpha \in \{1, 2\}, \\
\varepsilon_{33}(\eta, \xi) &= \frac{1}{\eta^2} \varepsilon_{33}(\xi).
\end{aligned} \tag{12}$$

In order to ensure that the initial data are uniformly bounded, we assume that $\partial_3 m_0 = 0$, $\varepsilon_{i3}(u_0) = 0$ for $i \in \{1, 2, 3\}$ and $(u_1)_3 = 0$. Then, $\mathcal{E}^\eta(0)$ is independent of η and we can use inequality (11) to obtain that, for all $T > 0$ and η in a neighborhood of zero, there exists a constant C independent of η such that

- $\left\| \frac{\partial M^\eta}{\partial t} \right\|_{L^2(0, T; L^2(\Omega_1))} \leq C$,
- $\|\partial_1 M^\eta\|_{L^\infty(0, T; L^2(\Omega_1))} + \|\partial_2 M^\eta\|_{L^\infty(0, T; L^2(\Omega_1))} + \frac{1}{\eta} \|\partial_3 M^\eta\|_{L^\infty(0, T; L^2(\Omega_1))} \leq C$,
- $\left\| \frac{\partial U_1^\eta}{\partial t} \right\|_{L^\infty(0, T; L^2(\Omega_1))} + \left\| \frac{\partial U_2^\eta}{\partial t} \right\|_{L^\infty(0, T; L^2(\Omega_1))} + \frac{1}{\eta} \left\| \frac{\partial U_3^\eta}{\partial t} \right\|_{L^\infty(0, T; L^2(\Omega_1))} \leq C$,
- $\|\varepsilon(\eta, U^\eta)\|_{L^\infty(0, T; L^2(\Omega_1))} \leq C$,
- $\|H^\eta\|_{L^\infty(0, T; L^2(\mathbb{R}^3))} \leq C$.

So, we can extract subsequences, still denoted (M^η, U^η) and H^η , such that:

- $M^\eta \rightharpoonup M$ in $L^\infty(0, T; H^1(\Omega_1))$ weak-*,
- $\frac{\partial M^\eta}{\partial t} \rightharpoonup \frac{\partial M}{\partial t}$ in $L^2(0, T; L^2(\Omega_1))$ weak,
- $U^\eta \rightharpoonup U$ in $L^\infty(0, T; V(\Omega_1))$ weak-*,

- $\frac{\partial U^n}{\partial t} \rightharpoonup \frac{\partial U}{\partial t}$ in $L^\infty(0, T; L^2(\Omega_1))$ weak-*,
- $H^n \rightharpoonup H$ in $L^\infty(0, T; L^2(\mathbb{R}^3))$ weak-*

Furthermore, we have $\partial_3 M^n \rightarrow 0$ in $L^\infty(0, T; L^2(\Omega_1))$ strong, so M only depends on $(t, x_1, x_2) \in \mathbb{R}^+ \times \omega$. In addition, $\frac{\partial U_3^n}{\partial t} \rightarrow 0$ in $L^\infty(0, T; L^2(\Omega_1))$ strong, so U_3 does not depend on t .

Since $(\varepsilon(\eta, U^n))_\eta$ is bounded, we obtain that $\varepsilon_{i3}(U^n) \rightarrow 0$ strongly in $L^\infty(0, T; L^2(\Omega))$, for all $T > 0$, i.e. $\varepsilon_{i3}(U) = 0$ for $i \in \{1, 2, 3\}$. So, $U \in L^\infty(\mathbb{R}^+; V_{KL}(\Omega_1))$, where

$$V_{KL}(\Omega_1) = \left\{ \xi \in H^1(\Omega_1); \xi = 0 \text{ on } \Gamma_1^1 \text{ and } \varepsilon_{i3}(\xi) = 0 \text{ in } \Omega_1 \text{ for } i \in \{1, 2, 3\} \right\}.$$

Therefore, by Theorem 1.4.1 in [9], there exist $\tilde{u} \in L^\infty(\mathbb{R}^+; V(\omega))$ such that

$$\begin{aligned} U_\alpha(t, x_1, x_2, x_3) &= \tilde{u}_\alpha(t, x_1, x_2) - x_3 \partial_\alpha \tilde{u}_3 \text{ for } \alpha \in \{1, 2\}, \\ U_3(t, x_1, x_2, x_3) &= \tilde{u}_3(t, x_1, x_2), \end{aligned} \quad (13)$$

where

$$V(\omega) = \left\{ v = (v_i) \in H^1(\omega) \times H^1(\omega) \times H^2(\omega); v_i = 0 \text{ on } C_1 \text{ and } \partial_1 v_3 = \partial_2 v_3 = 0 \text{ on } C_1 \right\}.$$

Hereafter, we denote $\tilde{u}_T = (\tilde{u}_1, \tilde{u}_2)$. Since $U^n \rightharpoonup U$ in $V(\Omega_1)$ weak, we have

$$\varepsilon(\eta, U^n) \rightharpoonup A \quad \text{weakly in } L^2(\Omega_1), \quad (14)$$

where A is the 2-tensor defined by $A_{\alpha\beta} = \varepsilon_{\alpha\beta}(U)$ for $\alpha = 1, 2$.

Moreover, we can prove that $M^n \rightarrow M$ in $L^\infty(0, T; L^r(\Omega_1)) \cap C^0([0, T]; L^2(\Omega_1))$ strong for $r < 6$ by using the Aubin-Simon lemma in [3], Theorem II.5.16. Thus, we can extract a subsequence, still denoted by $(M^n)_\eta$, such that $M^n \rightarrow M$ a.e. in $[0, T] \times \Omega_1$. Hence M satisfies the saturation constraint $|M(t, x_1, x_2)| = 1$ a.e. in $\mathbb{R}^+ \times \omega$, and by continuity in time with values in $L^2(\Omega_1)$, $M(0, x) = m_0(x)$ in the trace sense.

Let $\tilde{\chi} \in C_c^\infty(\mathbb{R}^+; \mathcal{D}(\bar{\omega}))$, and define χ in $\mathbb{R}^+ \times \Omega_1$ by $\chi(t, x_1, x_2, x_3) = \tilde{\chi}(t, x_1, x_2)$. Then, $\chi \in C_c^\infty(\mathbb{R}^+; H^1(\Omega))$ and $\partial_3 \chi = 0$, so we can put χ as a test function in (9). Taking the limit as η tends to zero in (9), by using weak and strong convergences for M^n and U^n respectively, and by using (14) (see [7] for more details), we obtain that for all $\tilde{\chi} \in C_c^\infty(\mathbb{R}^+; H^1(\omega))$,

$$\begin{aligned} & \int_{\mathbb{R}^+ \times \omega} \left(\frac{\partial M}{\partial t} - M \times \frac{\partial M}{\partial t} \right) \cdot \tilde{\chi} = -2 \int_{\mathbb{R}^+ \times \omega} M \times \nabla M \cdot \nabla \tilde{\chi} - 2 \int_{\mathbb{R}^+ \times \omega} M \times H \cdot \tilde{\chi} \\ & -2 \int_{\mathbb{R}^+ \times \omega} M \times (\lambda^m : (\lambda^e : \bar{A})) M \cdot \tilde{\chi} + 2 \int_{\mathbb{R}^+ \times \omega} M \times ((\lambda^m : (\lambda^e : (\lambda^m : M \otimes M))) M) \cdot \tilde{\chi}, \end{aligned} \quad (15)$$

where \bar{A} is given by $\bar{A} = \frac{1}{2} \int_{-1}^1 A \, dx_3$. Since $\int_{-1}^1 x_3 \, dx_3 = 0$, using (13), \bar{A} satisfies:

$$\bar{A}_{\alpha\beta} = \varepsilon_{\alpha\beta}(\tilde{u}) \text{ for } \alpha, \beta \in \{1, 2\}. \quad (16)$$

We recall that λ^e is given by: for all symmetric 2-tensors S ,

$$(\lambda^e : S) = \frac{E}{1 + \nu} \left(S + \frac{\nu}{1 - 2\nu} \text{tr}(S) I_3 \right), \quad (17)$$

where

$$\text{tr}(S) = S_{11} + S_{22} + S_{33}.$$

Now, we take the limit as η tends to zero in (10). For this, we take a test function ξ in this equation of the form

$$\xi(t, x_1, x_2, x_3) = \begin{pmatrix} v_1(t, x_1, x_2) \\ v_2(t, x_1, x_2) \\ 0 \end{pmatrix},$$

where $v_\alpha \in H^1(\omega)$, such that $v_\alpha = 0$ on C_1 . Then, $\varepsilon_{i3}(\xi) = 0$ for $i \in \{1, 2, 3\}$ and we obtain

$$\begin{aligned} \int_{\mathbb{R}^+ \times \Omega_1} \sum_{\alpha=1}^2 \frac{\partial U_\alpha^\eta}{\partial t} \cdot \frac{\partial \xi_\alpha}{\partial t} - \int_{\mathbb{R}^+ \times \Omega_1} (\lambda^e : \varepsilon(\eta, U^\eta)) : \varepsilon(\xi) + \int_{\mathbb{R}^+ \times \Gamma_-^1} g^+ \cdot \xi - \int_{\mathbb{R}^+ \times \Gamma_+^1} g^+ \cdot \xi \\ + \int_{\mathbb{R}^+ \times \Gamma_2^1} h \cdot \xi - \int_{\Omega_1} u_1 \cdot \xi(0, x) = \int_{\mathbb{R}^+ \times \Omega_1} (\lambda^e : (\lambda^m : M^\eta \otimes M^\eta)) : \varepsilon(\xi), \end{aligned} \quad (18)$$

By the weak convergence of $\frac{\partial U^\eta}{\partial t}$ and $\varepsilon(\eta, U^\eta)$ and by the strong limit of M^η , the limit of (18) as $\eta \rightarrow 0$ gives that for all $v_T \in H^1(\omega)$, with $v_T = 0$ on C_1 , we have

$$\begin{aligned} \int_{\mathbb{R}^+ \times \omega} \frac{\partial \tilde{u}_T}{\partial t} \cdot \frac{\partial v_T}{\partial t} - \int_{\mathbb{R}^+ \times \omega} \sum_{\alpha\beta=1}^2 (\lambda^e : \bar{A})_{\alpha\beta} \varepsilon_{\alpha\beta}(v_T) + \frac{1}{2} \int_{\mathbb{R}^+ \times \omega} (g_T^+ + g_T^-) \cdot v_T + \int_{\mathbb{R}^+ \times C_2} h_T \cdot v_T \\ - \int_{\mathbb{R}^+ \times \omega} u_{1,T} \cdot v_T(0, x) = - \int_{\mathbb{R}^+ \times \omega} \sum_{\alpha\beta=1}^2 (\lambda^e : (\lambda^m : M \otimes M))_{\alpha\beta} \varepsilon_{\alpha\beta}(v). \end{aligned} \quad (19)$$

By (16) and (17), we have:

$$(\lambda^e : \bar{A})_{\alpha\beta} = \frac{E}{1 + \nu} \left(\varepsilon_{\alpha\beta}(\tilde{u}_T) + \frac{\nu}{1 - 2\nu} \text{tr}(\bar{A}) \delta_{\alpha\beta} \right),$$

where

$$\text{tr}(\bar{A}) = \varepsilon_{11}(\tilde{u}_T) + \varepsilon_{22}(\tilde{u}_T) + \bar{A}_{33}.$$

To determine \bar{A}_{33} , we multiply (10) by η^2 , and we take the test function ξ such that $\xi_\alpha = 0$ for $\alpha = 1, 2$ and $\xi_3 = x_3 \varphi$, where $\varphi \in \mathcal{D}(\mathbb{R}^+ \times \omega)$. Taking the limit when $\eta \rightarrow 0$, we obtain:

$$2 \int_{\mathbb{R}^+ \times \omega} (\lambda^e : \bar{A})_{33} \varphi = \int_{\mathbb{R}^+ \times \omega \times]-1, 1[} (\lambda^e : (\lambda^m : M \otimes M))_{33} \varphi,$$

since M and φ are independent of x_3 . Then

$$(\lambda^e : \bar{A})_{33} = (\lambda^e : (\lambda^m : M \otimes M))_{33} \text{ in } L^2(\mathbb{R}^+ \times \omega). \quad (20)$$

Replacing λ^e by its value in (20), we obtain

$$\bar{A}_{33} = \left[\frac{1 - 2\nu}{1 - \nu} (\lambda^m : M \otimes M)_{33} + \frac{\nu}{1 - \nu} \text{tr}(\lambda^m : M \otimes M) - \frac{\nu}{1 - \nu} \sum_{\alpha=1}^2 \varepsilon_{\alpha\alpha}(\tilde{u}_T) \right], \quad (21)$$

and we deduce that

$$\frac{1}{2}(\lambda^e : \bar{A})_{\alpha\beta} - (\lambda^e : (\lambda^m : M \otimes M))_{\alpha\beta} = (\lambda^{et} : \varepsilon(\tilde{u}_T))_{\alpha\beta} - (\lambda^{et} : (\lambda^m : M \otimes M))_{\alpha\beta}, \quad (22)$$

where λ^{et} is a 4-tensor given by: for a symmetric 2-tensor S ,

$$\begin{aligned} (\lambda^{et} : S)_{\alpha\beta} &= \frac{E}{1+\nu} \left[S_{\alpha\beta} + \frac{\nu}{1-\nu} \tilde{\text{tr}}(S) \delta_{\alpha\beta} \right] \quad \text{for } \alpha, \beta \in \{1, 2\}, \\ (\lambda^{et} : S)_{i3} &= 0 \quad \text{for } i \in \{1, 2, 3\}, \end{aligned} \quad (23)$$

with

$$\tilde{\text{tr}}(S) = S_{11} + S_{22}.$$

This 4-tensor is also obtained in [11].

To describe H , the limit for the demagnetizing field H^η , we use Lemma 2.1 in [6], to obtain that

$$H(t, x_1, x_2, x_3) = \begin{cases} 0 & \text{for } x \notin \mathbb{R}^3 \setminus \Omega_1, \\ -(M(t, x_1, x_2) \cdot \vec{e}_3) \vec{e}_3 & \text{for } x \in \Omega_1. \end{cases} \quad (24)$$

Since (M, \bar{A}) is a solution for (15) and (19), and by using (22) and (24), (M, \tilde{u}_T) is a weak solution for

$$\begin{cases} \frac{\partial M}{\partial t} - M \times \frac{\partial M}{\partial t} = -2M \times H_{eff}(M) & \text{in } \mathbb{R}^+ \times \omega \\ H_{eff}(M) = \Delta M - (M, \vec{e}_3) \vec{e}_3 + (\lambda^m : \tilde{\sigma}) M, \end{cases} \quad (25)$$

coupled with

$$\begin{cases} \frac{\partial^2 \tilde{u}_T}{\partial t^2} - \tilde{\text{div}} \tilde{\sigma} = \frac{1}{2}(g_T^+ + g_T^-) & \text{in } \omega \\ \tilde{u}_T = u_{0T} & \text{on } \omega, \\ \frac{\partial \tilde{u}_T}{\partial t}(t=0) = u_{1T} & \text{on } \omega, \\ \tilde{u}_T = 0 & \text{on } \mathbb{R}^+ \times C_1, \\ \tilde{\sigma} n = h_T & \text{on } \mathbb{R}^+ \times C_2, \end{cases} \quad (26)$$

where

$$\tilde{\sigma} = ((\lambda^{et} : \varepsilon(\tilde{u})) - (\lambda^{et} : (\lambda^m : M \otimes M))) \quad \text{and} \quad (\tilde{\text{div}}(\tilde{\sigma}))_\alpha = \sum_{\beta=1}^2 \partial_\beta \tilde{\sigma}_{\alpha\beta}.$$

§4. Conclusion

We have obtained an equivalent 2d-model for thin ferromagnetic plates with magnetostriction. This model will be easier to study, to discretize and to solve numerically than the 3d-model. As observed in [6], the 2d demagnetizing field is local while it is not the case in 3d.

The obtained model does not take into account the third component of the deformation, since in the studied regime, the magnetization does not influence the normal deformations.

We remark also that the forces applied on the two faces of the plate appear as a source term in the 2d-model whereas they are modeled by boundary conditions in the 3d-model.

Acknowledgements

This work is supported by the ANR project MOSICOF, ANR-21-CE40-0004.

References

- [1] AHARONI, A. *Introduction of the Theory of Ferromagnetism*, vol. 109 of *International Series of Monograph on Physics*. Oxford University Press, 2000.
- [2] ALOUGES, F., AND SOYEUR, A. On global weak solutions for landau-lifshitz equations: Existence and nonuniqueness. *Nonlinear Analysis: Theory, Methods & Applications* 18, 11 (1992), 1071–1084.
- [3] BOYER, F., AND FABRIE, P. *Elements of analysis for the study of some models of incompressible viscous fluid flow*. Mathematics & Applications. Springer, Berlin Heidelberg New York, 2006.
- [4] BREZIS, H. *Functional Analysis, Sobolev Spaces and Partial Differential Equations*. Universitext. Springer New York, NY, 2010.
- [5] BROWN, W. F. *Micromagnetics*, vol. 40. Classics in Applied Mathematics, Wiley, Philadelphia, 1963.
- [6] CARBOU, G. Thin layers in micromagnetism. *Mathematical Models and Methods in Applied Sciences* 11, 09 (2001), 1529–1546.
- [7] CARBOU, G., EFENDIEV, M., AND FABRIE, P. Global weak Solutions for the Landau-Lifschitz equation with magnetostriction. *Mathematical Methods in the Applied Sciences* 34, 10 (2011), 1274–1288.
- [8] CARBOU, G., AND FABRIE, P. Time average in micromagnetism. *Journal of Differential Equations* 147, 2 (1998), 383–409.
- [9] CIARLET, P. G. *Plates and junctions in elastic multi-structures : an asymptotic analysis*. Recherches en mathématiques appliquées. Masson Springer-Verlag, Paris Milan Barcelone Mexico Berlin Heidelberg New-York, 1990.
- [10] CIARLET, P. G. *Three-dimensional elasticity*, vol. 1 of *Studies in mathematics and its applications*. Elsevier, Amsterdam San Diego (Calif.) Kidlington (UK) London, 1993.

- [11] CIARLET, P. G., AND DESTUYNDER, P. A justification of a nonlinear model in plate theory. *Computer methods in applied mechanics and engineering* 17 (1979), 227–258.
- [12] FLUGGE, S., AND WIJN, H. *Ferromagnetism*, vol. XVIII / 2 of *Encyclopedia of Physics*. Springer Verlag, Berlin, 1966.
- [13] LABBÉ, S., AND HALPERN, L. Modélisation et simulation du comportement des matériaux ferromagnétiques. *Matapli* 66 (2001).
- [14] LANDAU, L., AND LIFSCHITZ, E. *Electrodynamique des milieux continus*, vol. VIII of *cours de physique théorique*. (ed. Mir) Moscou, 1969.
- [15] PALERMO, X. *Proximity and flux pinning effects in superconductor-ferromagnet hybrids*. Theses, Université Paris Saclay (COMUE), 2019.
- [16] REKIK, M., HUBERT, O., DANIEL, L., WAECKERLE, T., AND TUNIZINI, M. Comportement magneto-mécanique dissipatif des matériaux ferromagnétiques sous chargement mécanique multiaxial. *Mecat2012* (2012).

Mouna Kassan and Gilles Carbou

Universite de Pau et des Pays de l'Adour, E2S UPPA, CNRS, LMAP, Pau, France
mouna.kassan@univ-pau.fr and gilles.carbou@univ-pau.fr

Mouna Kassan and Mustapha Jazar

LaMA, Laboratoire de Mathématiques Applications,
Lebanese University,
Tripoli, Lebanon.
mouna.kassan@univ-pau.fr and mjazar@laser-lb.org