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A Multimaterial Topology Optimization considering the PM Nonlinearity

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Abstract

Density-based topology optimization methodologies in magnetostatics interpolate either the magnetic permeability μ or the magnetic reluctivity ν to define intermediate materials and compute the problem sensitivities. These choices may lack physical interpretation and are not suited to model realistic permanent magnets. This work proposes the interpolation of the vector magnetic polarization \mathbf{m} as a more general alternative, which can model any magnetic material. It is then applied to the multi-material topology optimization of the rotor of a permanent magnet synchronous machine. The case of an ideal permanent magnet with a constant magnetic polarization is compared to that of AlNiCo. The results show that considering the non-linearity of the permanent magnet can significantly impact the optimized geometry.

Keywords: Density Method – Multi-Material Topology Optimization – Magnetic Polarization – Nonlinear Magnetostatics – Permanent Magnet Synchronous Machine

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1. Introduction

Topology optimization (TO) is a fast-growing structural conception tool issued from mechanical engineering [1], which was introduced in the field of electromagnetic actuators with [2]. These methods aim to find Ω an admissible material distribution, which minimizes an objective function f :

$$\text{find } \Omega^* = \arg \min f(\Omega). \quad (1)$$

Some methodologies try to solve this problem directly using heuristic algorithms such as particle swarm optimization [3], or genetic algorithms [4]; see [5] for a comparison. While they can handle a wide variety of problems easily and may be able to find their global optimum, heuristic approaches suffer from the high computing time due to the numerous variables $N > 10^3$ involved in TO [6]. Other works prefer faster optimization algorithms based on first-order derivatives. Among a wide variety of different approaches, such as the level set method [7] or the phase-field method [8] (see [9], [10] for exhaustive overviews), density-based methodologies are the most popular. They aim to solve a discretized and relaxed version of (1):

$$\text{find } \boldsymbol{\rho}_{\text{opt}} = \arg \min_{\boldsymbol{\rho} \in [0,1]^N} f(\boldsymbol{\rho}), \quad (2)$$

where $\boldsymbol{\rho}$ is the vector containing N optimization variables, called "densities", representing the filling level of each mesh element, similar to how pixels represent a geometry. A density value of 0 represents air, and a value of 1 represents a solid element such as steel, as shown in Fig. 1. The properties of

materials, for example, Young modulus in mechanical engineering, or magnetic permeability in electrical engineering, can then be continuously interpolated with respect to the optimization variables ρ . So, first-order derivatives can be computed efficiently with the Adjoint Variable Method (AVM) [9] in order to then use fast optimization algorithms based on gradient descent. However, the relaxed optimization problem (2) introduces the possibility of "gray materials", associated with a density ρ between 0 and 1. They may be interpreted as a mixture between solid material and void, organized as micro-structures in homogenization methods such as [11].

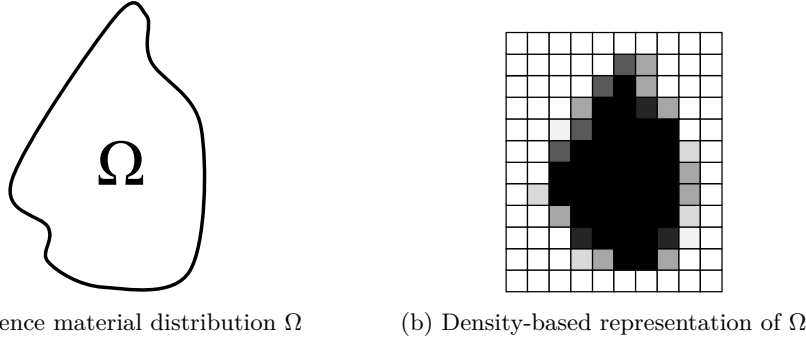


Figure 1: Density based geometry representation. Black elements ($\rho = 1$) represent solid material and white elements ($\rho = 0$) represent void.

There is some freedom in the material interpolation function. Concerning magnetic actuators, two trends exist in the literature. The magnetic permeability $\mu = |\mathbf{b}|/|\mathbf{h}|$ can be considered as the reference variable to interpolate, as in the seminal article [2]. A common interpolation, used in [12]–[15], which mimics the SIMP scheme in mechanical engineering [16], is the following:

$$\mu(\rho, |\mathbf{b}|) = \mu_0 + (\mu_{\text{steel}}(|\mathbf{b}|) - \mu_0)\rho^p. \quad (3)$$

The other possibility is to interpolate, in a similar manner, the magnetic reluctivity $\nu = 1/\mu$. It was introduced by [17] and is used in numerous papers such as [18]–[23].

As they do not have a proper physical interpretation in general, intermediate materials should be eliminated, with penalization schemes [24] or filtering [25]. To model linear hard-magnetic materials, an additional optimization variable to model the remanence should be considered as in [22]. However, this formalism seems inadequate to model non-linear Permanent Magnets (PM). To address this issue, this work proposes to interpolate the magnetic polarization \mathbf{m} , which is the common underlying magnetic property of both soft magnetic materials, such as steel, and hard magnetic materials, such as PM. In addition, this interpolation naturally models the non-linearity of PM, which is necessary to take into account the demagnetization of PM, previously only considered in analytical or parametric optimizations [26]–[28].

This new interpolation is first explained and compared to the other classical μ and ν interpolations. It is then applied, as an example, to the case of the Multi-Material Topology Optimization (MMTO) of a Permanent Magnet Synchronous Machine (PMSM) rotor. To do so, its numerical implementation is given with respect to the materials' behavior laws and the optimization framework is detailed. Next, the results are presented and analyzed for ideal and non-ideal magnets, highlighting the effect of the non-linearity. Finally, the conclusion draws some perspectives on this work.

2. Physical analysis of the interpolations

Macroscopic magnetostatics is entirely described by Maxwell's equations and material behavioral laws, which can be formulated following two different conventions [29]:

$$\text{Kennelly convention: } \mathbf{h} = \frac{1}{\mu_0}(\mathbf{b} - \mathbf{m}_b(\mathbf{b})), \quad (4a)$$

$$\text{Sommerfeld convention: } \mathbf{b} = \mu_0(\mathbf{h} + \mathbf{m}_h(\mathbf{h})), \quad (4b)$$

with \mathbf{b} the magnetic flux density, \mathbf{h} the magnetic field, $\mu_0 = 4\pi \times 10^{-7}\text{H/m}$ the void permeability, \mathbf{m}_h the magnetization, and $\mathbf{m}_b = \mu_0\mathbf{m}_h$ the magnetic polarization. We recall the expression of the magnetic permeability $\mu = |\mathbf{b}|/|\mathbf{h}|$ and reluctivity $\nu = |\mathbf{h}|/|\mathbf{b}|$ for isotropic materials. We denote the norm of the vector as $b = |\mathbf{b}|$, $h = |\mathbf{h}|$ and $m = |\mathbf{m}|$. The following linear interpolations are considered for M different materials:

$$\nu - \text{interpolation: } \tilde{\nu}(b) = \nu_0 + \sum_{i=1}^M \rho_i(\nu_i(b) - \nu_0), \quad (5a)$$

$$\mu - \text{interpolation: } \tilde{\mu}(b) = \mu_0 + \sum_{i=1}^M \rho_i(\mu_i(b) - \mu_0), \quad (5b)$$

$$\mathbf{m} - \text{interpolation: } \tilde{\mathbf{m}}(\mathbf{b}) = \sum_{i=1}^M \rho_i \mathbf{m}_i(\mathbf{b}), \quad (5c)$$

where ρ_i is the optimization variable associated with material i . We assume that $\{\rho_i\}_{1 \leq i \leq M}$ partitions the unit:

$$\sum_{i=1}^M \rho_i = 1. \quad (6)$$

At macroscopic scale, Ampere's theorem reads:

$$\oint_{\Gamma} \mathbf{h} \cdot d\mathbf{l} = I \quad (7)$$

where Γ is a closed path oriented along the flux line of a macroscopic solenoid represented in Fig. 2, which embraces a current I . Equation (7) helps to interpret the different interpolations at a smaller scale in a mesoscopic Representative Volume Element (RVE). In the numerical implementation detailed in section 3, the RVE is a mesh element.

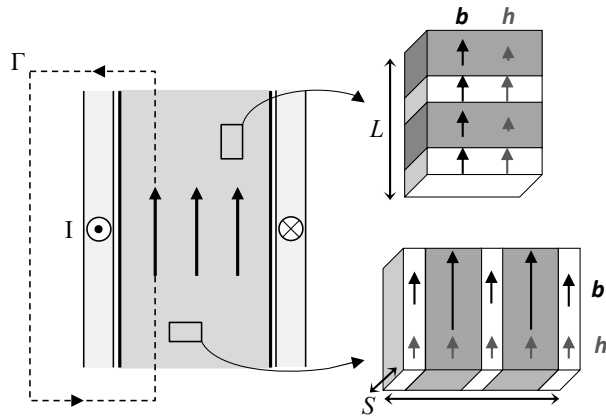


Figure 2: Illustration of the magnetic situation with a serial and a parallel RVE.

2.1. Serial assembly - ν -interpolation

Let us define the average magnetic field on the RVE by $\langle h \rangle = \frac{1}{L} \int_0^L \mathbf{h} \cdot d\mathbf{l}$, with L the length of the RVE. Then, using the classical behavior law $h = \nu b$, the partition of unity (6), the Ampère's theorem (7) and the non-divergence of the flux density which induces a constant b in an RVE containing a serial assembly of materials, we obtain:

$$\langle h \rangle = \sum_{i=1}^M \frac{l_i}{L} \nu_i(b) b = \underbrace{\left(\nu_0 + \sum_{i=1}^M \frac{l_i}{L} (\nu_i(b) - \nu_0) \right)}_{\tilde{\nu} \text{ from (5a)}} b, \quad (8)$$

with l_i the elementary length of material i . Equation (8) can be directly identified with (5a), the optimization variable ρ_i playing the role of lineic fraction l_i/L of material i . Therefore, linear ν -interpolation can be identified with a serial assembly of materials along the flux lines. This interpolation is suitable when b is the degree of freedom of the behavior law, *i.e.* when expressed in the Kennelly convention (see (4a)). This is the case of the majority of finite element implementations, which are based on the "primal" vector potential \mathbf{a} ; the associated magnetic behavior is shown in Fig. 3a. However, there is no indication that such an interpolation has a physical meaning when it is based on the magnetic field h as in Fig. 3b.

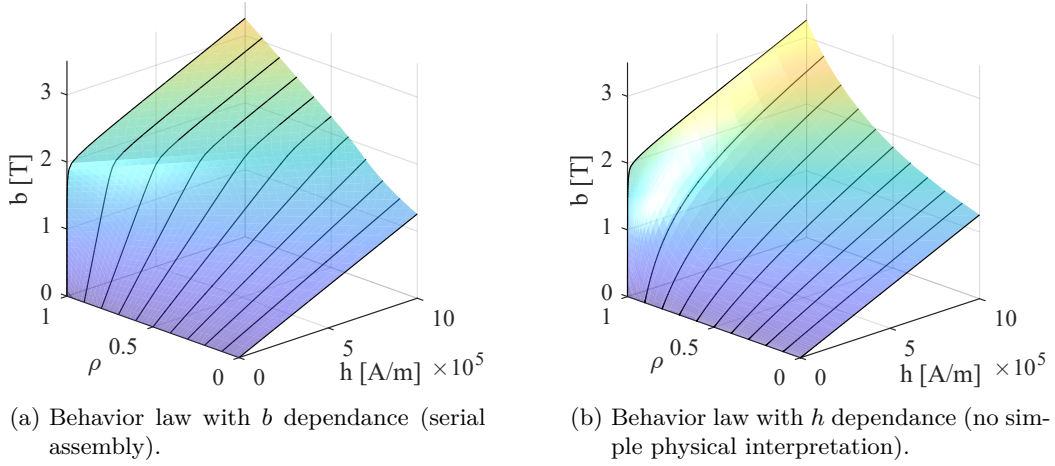


Figure 3: BH curves of intermediate materials for linear ν -interpolation.

2.2. Parallel assembly - μ -interpolation

Let us define the average flux density $\langle b \rangle = \frac{1}{S} \iint_S \mathbf{b} \cdot d\mathbf{s}$, with S the section of the RVE. Equation (7) gives the exact and constant magnetic field $h = I/L$ within all the parallel assembly RVE. Then, the average $\langle b \rangle$ can be computed by using (6) and the traditional material behavior law $b = \mu h$ to obtain:

$$\langle b \rangle = \sum_{i=1}^M \frac{s_i}{S} \mu_i(h) h = \underbrace{\left(\mu_0 + \sum_{i=1}^M \frac{s_i}{S} (\mu_i(h) - \mu_0) \right)}_{\tilde{\mu}(h)} h, \quad (9)$$

with s_i the elementary section of material i . Note that (9) cannot be directly identified with (5b), as $\tilde{\mu}(h)$ depends on h and not on b . Therefore, (9) makes sense as a parallel assembly along the flux lines only in the Sommerfeld convention (4b), where the optimization variable ρ_i plays the role of surface fraction s_i/S of material i . While the Sommerfeld convention is typically used in physics, it is

rarely used in numerical implementation, where it is known as the dual formulation [30]: this magnetic behavior is plotted in Fig. 4b. Consequently, there is no simple physical interpretation of Equation (5b) which depends on b , or even no physical interpretation at all. Indeed, Fig. 4a shows that intermediate materials may have a differential permeability $\frac{\partial b}{\partial h}$ lower than μ_0 , which seems impossible.

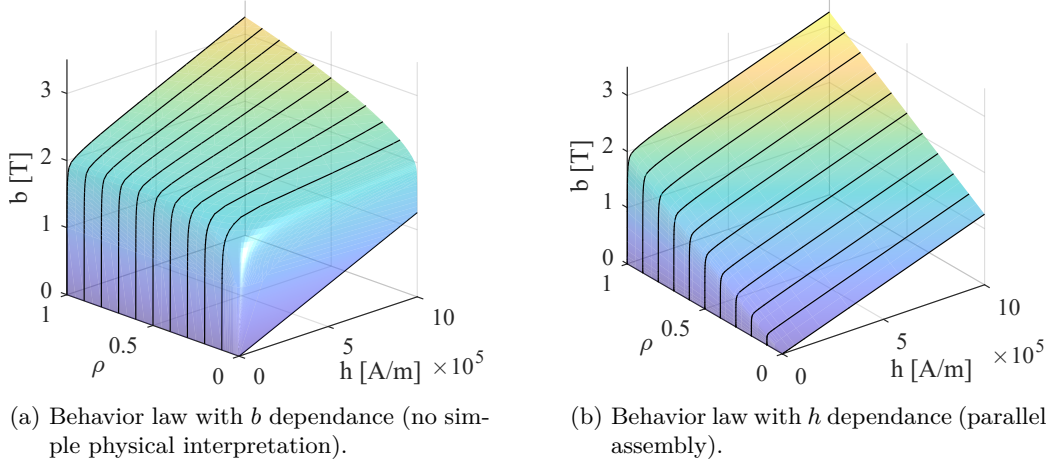


Figure 4: BH curves of intermediate materials for linear μ -interpolation.

2.3. m -interpolation

In fact, both Equations (8) and (9) can be rewritten to be identified with the unique physical quantity m – formulated either in Sommerfeld or in Kennelly convention:

- In a serial assembly, we obtain with (4a) and (7):

$$\langle h \rangle = \frac{1}{\mu_0} \left(b - \underbrace{\sum_{i=1}^M \frac{l_i}{L} m_{b_i}(b)}_{\text{Eq. (5c) - Kennelly}} \right). \quad (10)$$

- In a parallel assembly, we obtain with (4b) and (7):

$$\langle b \rangle = \mu_0 \left(h + \underbrace{\sum_{i=1}^M \frac{s_i}{S} m_{h_i}(h)}_{\text{Eq. (5c) - Sommerfeld}} \right). \quad (11)$$

Note that m_b and m_h represent the same physical quantity with a μ_0 factor. Therefore m -interpolation is suited in both convention and the associated numerical formulations, as shown in Fig. 5.

2.4. Discussion

As shown in the previous sections, \mathbf{m} seems to be the natural material property for interpolating magnetostatics topology optimization problems.

However, this interpolation is vectorial by nature – as in Equations (4a) and (4b) – so its numerical implementation detailed in Section 3 is more tedious than μ or ν interpolations. In addition, equivalent interpolations can be achieved with ν following the Kennelly convention (classical finite element formulation) or μ following the Sommerfeld convention (dual formulation) when dealing with soft magnetic materials only, as shown in Sec. 2.

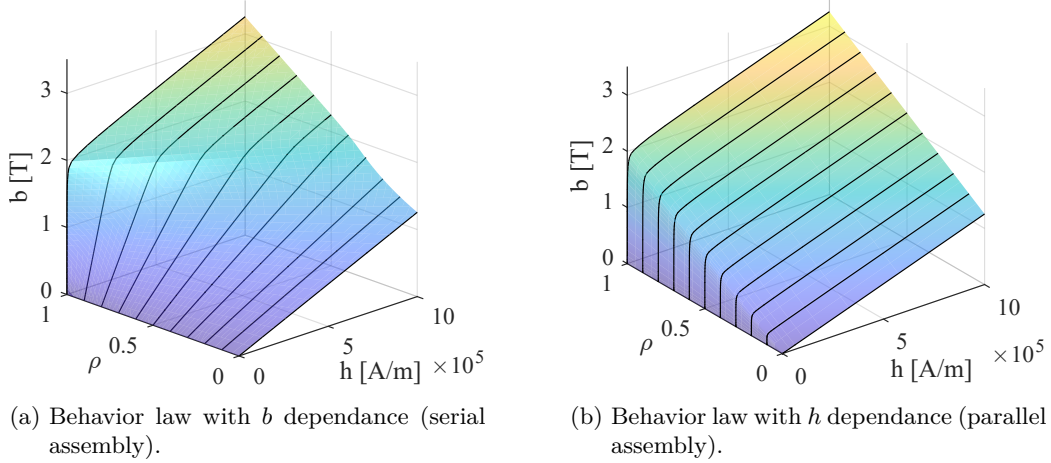


Figure 5: BH curves of intermediate materials for linear m -interpolation.

In fact, the practical usefulness of vectorial m -interpolation becomes apparent when dealing with a mixture of hard magnetic materials and non-linear soft magnetic materials. The usual material laws

- $\mathbf{h} = \nu \mathbf{b}$ for soft materials, where $\nu = \frac{h}{b}$, and
- $\mathbf{h} = \nu_0(\mathbf{b} - \mathbf{m}_b)$ for hard materials, where $\nu = \frac{\Delta h}{\Delta b}$,

are simplifications of (4a) that are valid under the assumptions $\mathbf{m}_b = 0$ when $\mathbf{b} = 0$ for soft materials, and \mathbf{m}_b is a constant for hard materials. Such conditions are in contradiction of each other, which makes the interpretation of intermediate materials obtained by ν -interpolation difficult to interpret. Indeed, the interpretation of the coefficient ν itself differs for hard and soft materials. Similarly, a non-linear permanent magnet behaves like a mixture of ideal soft and ideal hard materials, and its behavior is well-described through its magnetic polarization model.

Therefore, the m -interpolation handles general magnetic behaviors similar to gradient-free topology optimization, where an independent black-box magnetic solver is often used without the need of intermediate materials. In contrast, in density-based topology optimization, the user must consistently define the material models of the real and intermediate materials.

3. Numerical implementation

3.1. Magnetic materials behavior

The anhysteretic magnetic polarization of anhysteretic soft magnetic materials such as FeSi can be fully determined by its scalar BH curve, such as in Fig. 6a. Assuming its reciprocal function $h(b)$ is known, \mathbf{m} reads:

$$\mathbf{m}_{FeSi}(\mathbf{b}) = m_{FeSi}(b) \cdot \mathbf{u}_b, \quad (12)$$

where $m_{FeSi}(b) = b - \mu_0 h(b)$ is deduced from (4a) and the BH curve, $\mathbf{u}_b = \frac{\mathbf{b}}{b}$ a unitary vector oriented along the induction. Concerning ideal hard magnetic materials, \mathbf{m} is a constant. However, the magnetic polarization of realistic hard materials depends on the norm of b and its direction. It requires a vector hysteresis model such as [31], [32]. In addition, irreversibility and hysteresis models may be considered but increase the computation time significantly, which is a severe issue for topology optimization.

Therefore, the irreversibility of magnetic materials is not taken into account in this work, and the following simplified magnetic model of PM is considered to save computing time :

$$\mathbf{m}_{pm}(\mathbf{b}) = m_{pm}(\mathbf{b} \cdot \mathbf{u}_{pm}) \cdot \mathbf{u}_{pm}, \quad (13)$$

where \mathbf{m}_{pm} is the magnetic polarization of PM, \mathbf{u}_{pm} is the unitary vector indicating its fixed direction, and $m_{pm}(b) = b - \mu_0 h(b)$ is its norm. This model requires the magnet's $h(b)$ behavior along its d-axis, such as in Fig. 6b. More elaborated models are possible such as vectorized Jiles-Atherton [33].

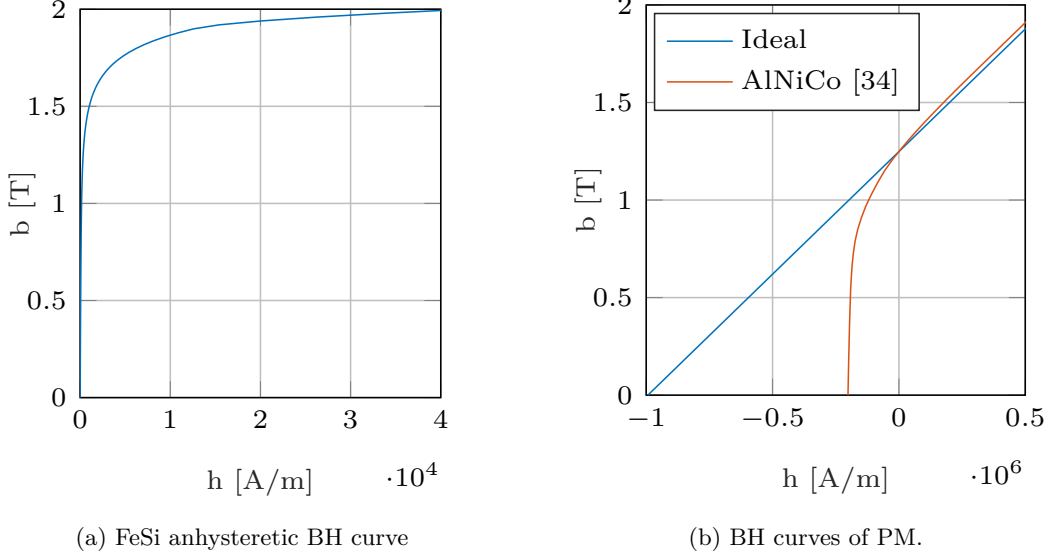


Figure 6: BH curves of soft and hard magnetic materials.

3.2. 2D magnetostatics with \mathbf{m} -formulation

Using the general behavior law in the Kennelly convention (4a), Maxwell's equations give the following magnetostatics equation:

$$\nabla \times (\nabla \times \mathbf{a}) = \mu_0 \mathbf{j} + \nabla \times \mathbf{m}(\mathbf{b}), \quad (14)$$

where \mathbf{a} is the magnetic vector potential verifying $\nabla \times \mathbf{a} = \mathbf{b}$, and \mathbf{j} is the current density. Magnetic polarization is not limited to a permanent magnet but to all magnetic materials, including soft magnetic materials, and is zero in non-magnetic materials. In 2D problems where $\mathbf{a} = [0 \ 0 \ a_z]$, $\mathbf{j} = [0 \ 0 \ j_z]$ and $\mathbf{m} = [m_x \ m_y \ 0]$, (14) becomes:

$$-\nabla \cdot (\nabla a_z) = \mu_0 j_z + \nabla \cdot (m_y(\mathbf{b}) - m_x(\mathbf{b})). \quad (15)$$

This equation can be discretized with the finite element method to obtain the non-linear system (16). After discretization, the finite element system can be assembled and reads:

$$\mathbf{K}\mathbf{a} = \mathbf{s}(\mathbf{a}, \boldsymbol{\rho}), \quad (16)$$

which is solved with a Newton-Raphson scheme.

The associated solver was implemented in Matlab and validated with GetDp [35]. More details are given in appendixes A and B.

4. Optimization formalism

This article considers the Multi-Material Topology Optimization (MMTO) of a Permanent Magnet Synchronous Machine (PMSM) rotor. Three different materials are considered:

- Anhyseretic steel (standard FeSi);
- PM with a fixed orientation of 15° for the sake of simplicity, which may restrict the possible solutions - note that it is possible to include the magnetization direction in the optimization problem [11], [22]. However, the PM can be non-linear;
- Air.

4.1. Multi-material interpolation

To use a density-based method, it is necessary to define an interpolation between the magnetic polarization of the different materials. To do so, two optimization variables contained in a square $\rho_1, \rho_2 \in [-1, 1]^2$ are used per mesh element. A material is attributed to each vertex of this square, so the interpolated $\tilde{\mathbf{m}}$ reads:

$$\tilde{\mathbf{m}}(\rho_1, \rho_2, \mathbf{b}) = \omega_{pm}(\rho_1, \rho_2)\mathbf{m}_{pm}(\mathbf{b}) + \omega_{FeSi}(\rho_1, \rho_2)\mathbf{m}_{FeSi}(\mathbf{b}), \quad (17)$$

with \mathbf{m}_{pm} the polarization of the permanent magnet, \mathbf{m}_{FeSi} the polarization of the steel, ω_{pm} and ω_{FeSi} the weight functions, associated to permanent magnet and steel, respectively. The weight functions, also used in [36], [37], are plotted in Fig. 7, and read:

$$\omega_{pm}(\rho_1, \rho_2) = \frac{1}{4}(\rho_1 + 1)(1 - \rho_2), \quad (18a)$$

$$\omega_{FeSi}(\rho_1, \rho_2) = \frac{1}{4}(1 - \rho_1)(\rho_2 + 1). \quad (18b)$$

Note that, \mathbf{m} -interpolation (17) can handle any magnetic material without additional variables, as long as a vector model is available for $\mathbf{m}(\mathbf{b})$. This is not the case with μ - or ν - interpolations that require the addition of the PM remanence, for example, which is already included within the magnetic polarization model.

Since the optimized designs do not contain intermediate materials, there is no need to introduce an exponent p as in Eq. (3). This is similar to ν -interpolation optimizations which are self-penalized [17], [21], and corresponds to the same serial-assembly interpretation as \mathbf{m} -interpolation in vector-potential magnetostatics formulation (see Sec. 2).

4.2. Objective function

The aim of this optimization is to maximize the average torque. From Maxwell's stress tensor Σ , the torque \mathbf{t} of a rotating machine can be written as a line integral within the airgap [38]:

$$\mathbf{t} = L \oint_{\gamma} \mathbf{r} \times \Sigma \mathbf{n} \, d\gamma, \quad (19)$$

where L is the axial length of the machine, \mathbf{r} the position vector, \mathbf{n} the outer normal vector from the path γ . Σ can be reduced to its magnetic component, which reads:

$$\Sigma_{ij} = \frac{1}{\mu_0} \left(b_i b_j - \frac{|\mathbf{b}|^2}{2} \delta_{ij} \right), \quad (20)$$

where δ_{ij} is the Kronecker delta. Equation (19) can be rewritten as a surface integral within the airgap's surface S_e , so the following expression is used:

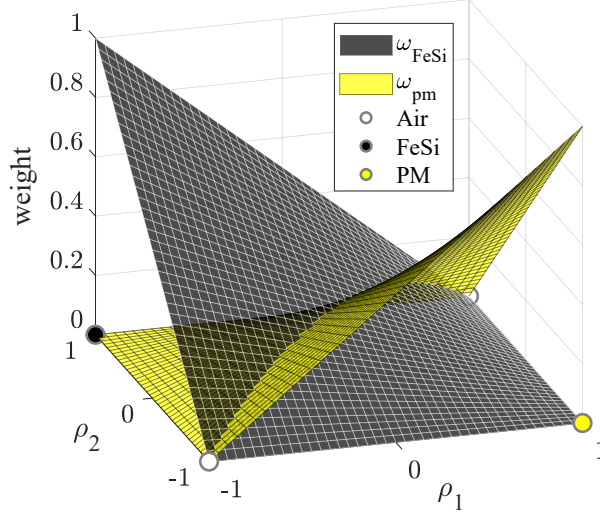


Figure 7: Weight functions ω_{FeSi} and ω_{pm} with material placement.

$$\mathbf{t} = \frac{2\pi L}{S_e} \iint_{S_e} \mathbf{r} \times \Sigma \mathbf{r} \, ds. \quad (21)$$

Only the z component of \mathbf{t} is interesting in 2D. This expression depends explicitly on the magnetic flux density \mathbf{b} , but not on the design variables $\boldsymbol{\rho}$. The design variables and the physical state (also called the *direct state*) are linked implicitly by the non-linear physical system (16). Therefore, the Adjoint Variable Method (AVM) [9] is necessary to compute the problem sensitivities.

4.3. Optimization problem

A volume constraint is set to avoid the rotor being filled entirely with the permanent magnet. The maximal volume of the permanent magnet is arbitrarily set to 10% of the total rotor volume. The optimization problem can now be formulated under the standard form:

$$\begin{aligned} \text{find} \quad & \boldsymbol{\rho}_{opt} = \arg \max \langle \mathbf{t}, \mathbf{e}_z \rangle, \\ \text{subject to} \quad & \iint_{\mathcal{R}} \omega_{pm} ds / \iint_{\mathcal{R}} 1 ds \leq 10\%, \end{aligned} \quad (22)$$

where \mathcal{R} is the optimization zone, *i.e.*, the rotor of the machine. The Method of Moving Asymptote [39] (MMA) is used to perform the optimization. The algorithm stops after 500 iterations. The optimization flowchart is given in Fig. 8. The average computing times per iteration were about 8.4s for the FEM, 1.0s for the AVM and 0.1s for MMA.

5. Numerical examples

The MMTO problem given in Equation (22) is applied to the rotor optimization of a single PMSM pole. The mesh generated by GMSH [40] contains 5890 nodes and 11331 first-order triangles, with 3441 located in the rotor leading to a total of 6882 design variables. A sliding band technique [41] emulates the rotation without remeshing. The torque is averaged on 60 angular positions. The stator is fixed, and the current feedings of the three phases read:

$$\begin{cases} J_{A+}(\theta_e) = J \cos(\theta_e + \phi) \\ J_{C-}(\theta_e) = J \cos(\theta_e - \frac{\pi}{3} + \phi) \\ J_{B+}(\theta_e) = J \cos(\theta_e - \frac{2\pi}{3} + \phi), \end{cases} \quad (23)$$

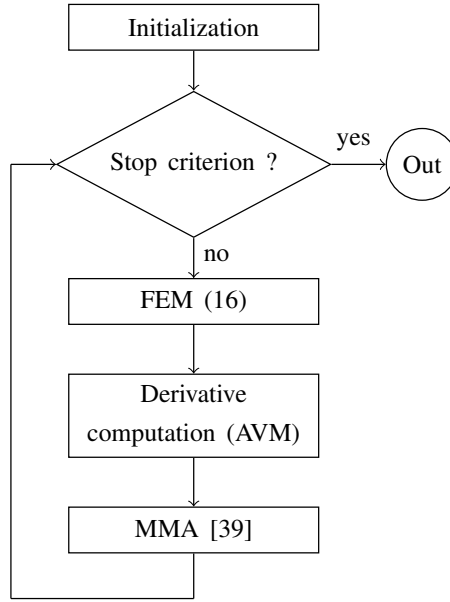


Figure 8: Flowchart of the optimization algorithm.

where J is the current density amplitude set to 10 A/mm^2 , θ_e the electric angle, and ϕ the load angle, which is an electrical rotation between the initial position of the rotor and the flux created by the stator. As only one orientation of permanent magnet is available in this optimization, $\phi = 240^\circ$ is chosen to place it in the center of the rotor pole. The optimization is performed with two different types of PM:

- Ideal permanent magnet with a constant magnetic polarization,
- AlNiCo magnet.

Their remanent flux densities are set to 1.25 T, representing the nominal remanence of AlNiCo magnets. Only their coercive fields are different; see Fig. 6b for their BH curves. The initial situation for both optimizations is homogeneous to demonstrate the ability of the methodology to find performing designs without any initial information and is given in Fig. 9. To avoid starting on the FeSi - PM diagonal representing a magnetic polarization saddle line, all the optimization variables are initialized to 0.1 and not in the center of the domain. A simple spatial mean-filter procedure [42] is applied to limit the geometry artifacts. The radius of the filter decreases from 3 mm to 0 mm every 50 iterations to obtain sharp interfaces in the final design. Other filtering schemes or post-processing [25] may be used to remove the remaining geometric artifacts.

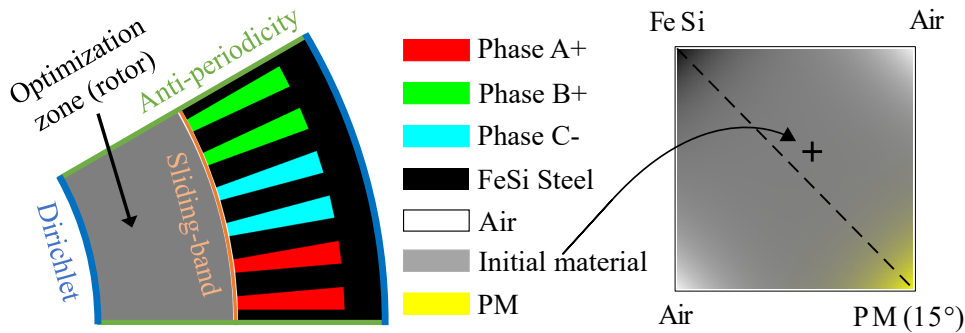


Figure 9: Initial situation corresponding to 6 pole pairs, and intermediate materials' colorscale.

5.1. Ideal permanent magnet

First, the optimization uses an ideal permanent magnet with a constant magnetic polarization as a candidate material. The final result is shown in Fig. 10. A Surface Permanent Magnet Synchronous Machine (SPMSM) rotor is obtained, in agreement with the results found in [43]. The optimization evolution and result are shown in Fig. 10. The final torque is 2836 Nm/m, and the PM volume constraint is respected.

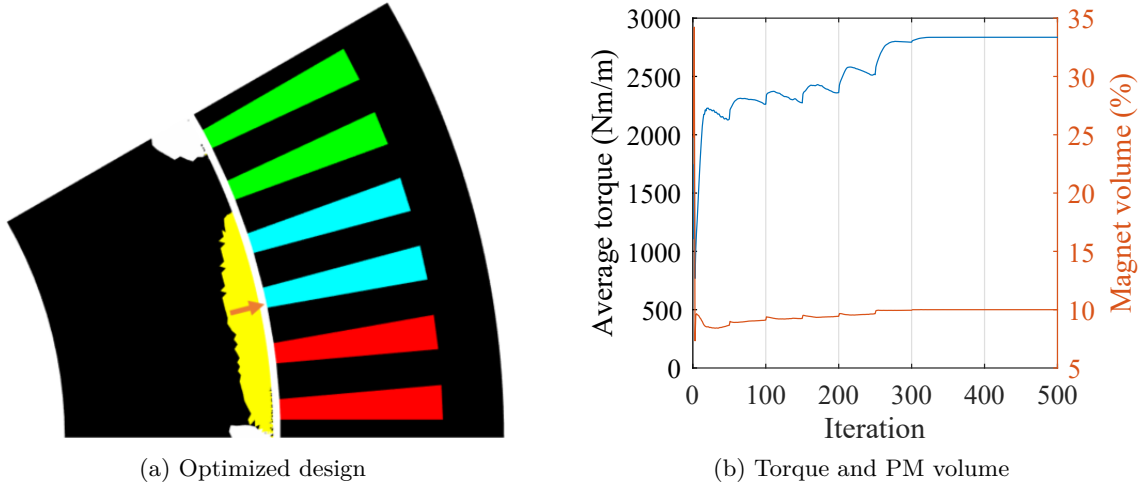


Figure 10: Results of the optimization with an ideal PM.

We note that the optimized permanent magnet area is thin. Therefore, there is a risk of demagnetization in a practical situation. Indeed, the high demagnetizing field within the PM shown in Fig. 11a locally reduces the flux density shown in Fig. 11b, and may cause demagnetization in practical situations.

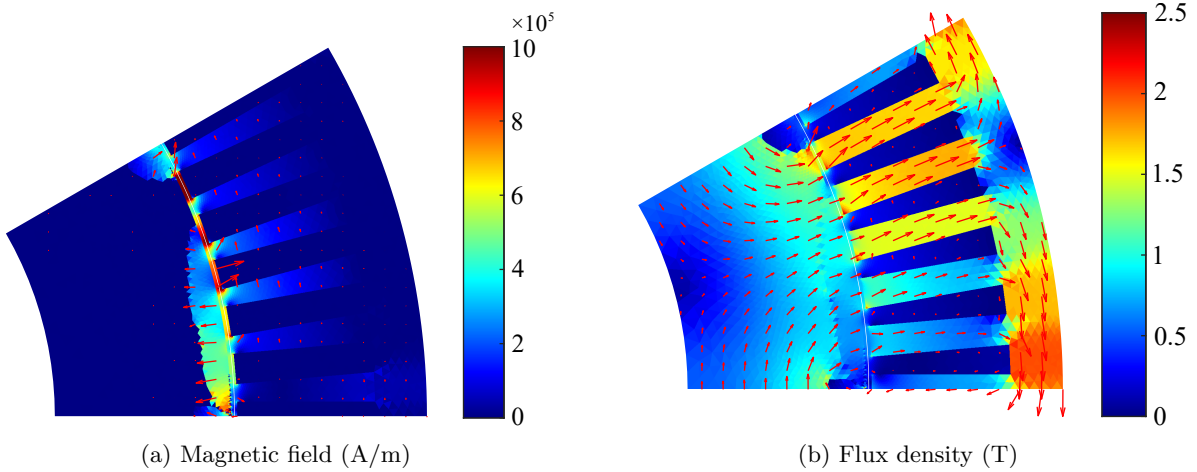


Figure 11: Magnetic field and flux density of the optimized design with an ideal PM.

This result highlights the importance of considering the non-linearity of the magnetic behavior during optimization, especially when using semi-hard magnetic materials such as AlNiCo.

5.2. Non-linear permanent magnet

The demagnetization can be partially taken into account in the optimization by considering the upper BH curve of an AlNiCo. This material was chosen due to its relatively low coercivity compared to other PM types. Only the non-linearity of the BH curve is considered and the recoil lines follow the hysteresis curve, which is not the case in real demagnetization, see [44]. However, this simplified model is enough to change significantly the obtained design shown in Fig. 12a from the ideal PM case. The torque plotted in Fig. 12b is degraded by 19 % and reaches 2293 Nm/m, while the PM volume constraint is still respected.

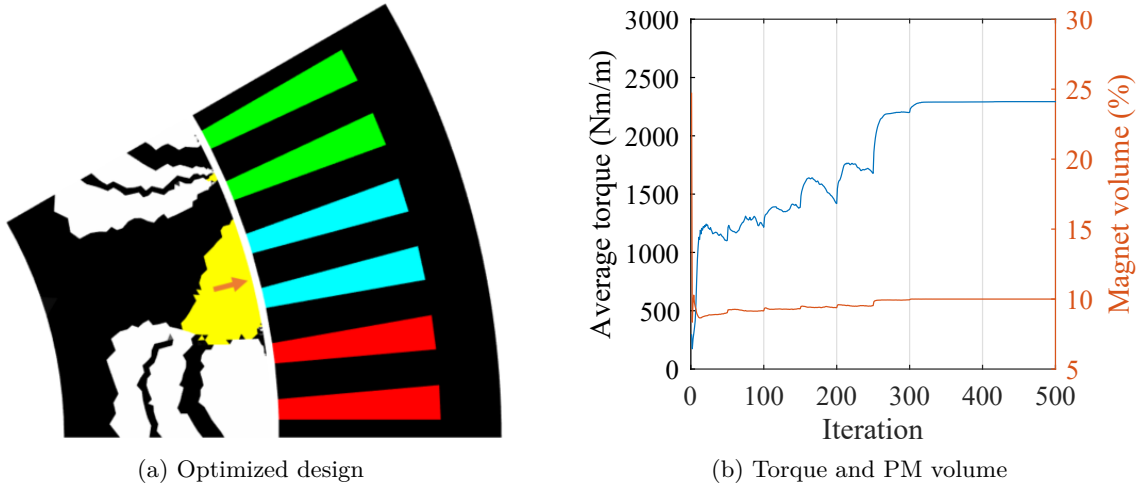


Figure 12: Results of the optimization with an AlNiCo PM.

Note that the position of the PM has changed to avoid the high demagnetizing field located at the bottom of Fig. 11a and its width has increased in the zone where the demagnetizing field is important. The demagnetizing field is now very limited in the PM and is more located in the air, as shown in Fig. 13a and Fig. 13b.

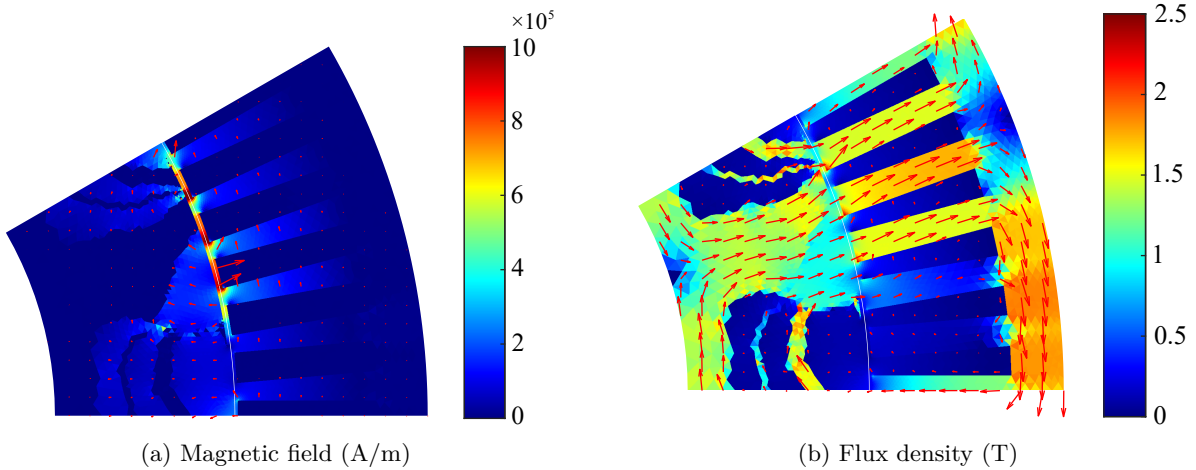


Figure 13: Magnetic field and flux density with AlNiCo PM.

The non-linear behavior of the PM seems to induce more artifacts, such as small isolated structures in the optimized design, shown in Fig. 12a. Additional filtering or regularization schemes may be necessary for a more general case.

5.3. Discussion

The instant torques are plotted in Fig. 14 and compared to a reference BMW i3 reference design adapted from [45] with ideal PM, the same rotor diameter and current feedings. Additional information such as the ripple $r = \frac{\max(T) - \min(T)}{\langle T \rangle}$ and the PM volume are given in Table 1.

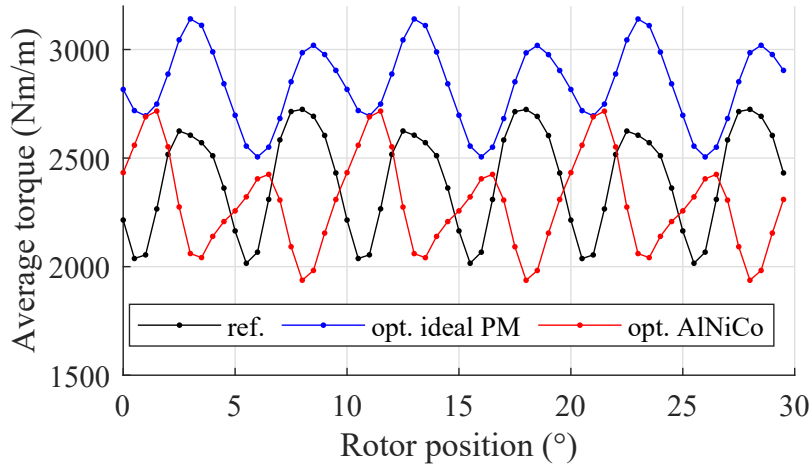


Figure 14: Instant torques associated with the designs obtained with ideal PM and AlNiCo compared to the reference.

Table 1: Performance of the designs.

	Ref. design (ideal PM)	Optim. design ideal PM	Optim. design AlNiCo
Avg. torque	2404 Nm/m	2836 Nm/m	2293 Nm/m
Ripple	29%	22%	34%
PM volume	20%	10%	10%

The optimized design with the ideal PM has a higher average torque than the reference one with a lower PM volume, which validates the topology optimization methodology. However, the higher torque may be explained by the lack of mechanical constraint, leading to magnetic short circuits. Note that the decrease of torque ripple was not expected in the optimized design with ideal PM. The torque ripple could be reduced even more by adding it explicitly as an objective function [20].

Moreover, it was recently shown in [46], [47] that the electric angle ϕ should be controlled during the optimization in the presence of PM to obtain better performance. Here, ϕ is fixed to compare the two final structures, which otherwise would reach different optimal ϕ .

6. Conclusion

This article presents the magnetic polarization interpolation applied to the MMTO of a PMSM rotor. In its physical interpretation and applications, the m -interpolation is more general than μ - or ν -interpolations. Indeed, it allows the consideration the non-linearity of the PM within the optimization process. Numerical examples show that the optimized design could be significantly modified by considering the non-linearity of the PM behavior, even with a simplified model.

This methodology can be extended to address dynamic demagnetization with more realistic vector hysteresis models such as [33]. Potential applications include innovative electrical actuators such as memory machines [48], which are beyond the current state of the art in topology optimization. Other perspectives include additional physics, such as thermals to obtain a realistic PM demagnetization model, or mechanics to ensure the rotor's strength.

A. Variational formulations

The finite element discretization (16) uses the weak form of Eq. (15) on the computational domain \mathcal{D} composed by the rotor, the stator, and the airgap. The weak form of its residual reads:

$$\forall(a, a^*) \in H_0^1(\mathcal{D}) \times H_0^1(\mathcal{D}), \quad r(a, a^*) = \int_{\mathcal{D}} \nabla a^* \cdot \nabla a - \int_{\mathcal{D}} a^* \mu_0 j_z + \int_{\mathcal{D}} \nabla a^* \cdot R_{-\pi/2} \mathbf{m}(\mathbf{b}), \quad (24)$$

with $R_{-\pi/2} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$ a rotation operator. Eq. (24) can be discretized with the FEM to obtain (16). To solve it, the Newton method comes from the first-order expansion of the residual:

$$r(a + \delta a, a^*) \simeq r(a, a^*) + \mathbf{d}_a r(\delta a, a^*) = 0, \quad (25)$$

where

$$\mathbf{d}_a r(\delta a, a^*) = \int_{\mathcal{D}} \nabla a^* \cdot \nabla \delta a + \int_{\mathcal{D}} \nabla a^* \cdot R_{-\pi/2} \mathbf{d}_{\mathbf{b}} \mathbf{m} \mathbf{d}_a \delta \mathbf{b}, \quad (26)$$

and $\delta a = a_{k+1} - a_k$. Since $\delta \mathbf{b} = R_{-\pi/2} \nabla \delta a$, we should assemble and solve iteratively until convergence:

$$\begin{aligned} \int_{\mathcal{D}} \nabla a^* \cdot (I_d + R_{-\pi/2} \mathbf{d}_{\mathbf{b}} \mathbf{m}(\mathbf{b}_k) R_{-\pi/2}) \nabla a_{k+1} \\ = \int_{\mathcal{D}} \nabla a^* \cdot (I_d + R_{-\pi/2} \mathbf{d}_{\mathbf{b}} \mathbf{m}(\mathbf{b}_k) R_{-\pi/2}) \nabla a_k - r(a_k, a^*), \end{aligned} \quad (27)$$

I_d being the identity matrix.

B. Derivation of the magnetic polarization

The term $\mathbf{d}_{\mathbf{b}} \mathbf{m}(\mathbf{b})$ is symmetric and can be explicitly calculated:

- for soft magnetic material, Eq.(12) gives:

$$\mathbf{d}_{\mathbf{b}} \mathbf{m}_{FeSi} = \frac{m'_{FeSi}(|\mathbf{b}|)}{|\mathbf{b}|^2} \cdot \mathbf{b} \otimes \mathbf{b} + \frac{m_{FeSi}(|\mathbf{b}|)}{|\mathbf{b}|^3} \cdot \begin{bmatrix} b_y^2 & -b_x b_y \\ -b_x b_y & b_x^2 \end{bmatrix} \quad (28)$$

- for hard magnetic material, Eq.(13) gives:

$$\mathbf{d}_{\mathbf{b}} \mathbf{m}_{pm} = m'_{pm}(\mathbf{b} \cdot \mathbf{u}_{pm}) \cdot \mathbf{u}_{pm} \otimes \mathbf{u}_{pm} \quad (29)$$

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