

PhD thesis subject

Robust multiphysics topological optimization: application to electrical machines

October 2025 – september 2028

Keywords : Robust topology optimisation : machine learning; Multiphysics

Subject summary:

The electric machine design sector is experiencing significant growth due to energy transition efforts and the electrification of uses, particularly in the transportation sector, where electric and plug-in hybrid vehicle sales have surged. This growth presents challenges in designing innovative and efficient electric machines, especially given the difficulties in sourcing raw materials. The sector is moving towards avoiding rare earths and using recycled materials, which necessitates redefined specifications and the consideration of uncertainties in design and optimization processes. Parametric and topological optimization methods are becoming more prevalent, enabling technological breakthroughs, though they still face challenges in achieving robust optimal solutions within practical timeframes.

This thesis aims to advance methodologies in this context, focusing on three main axes: enhancing the consideration of multiphysical aspects in electric machine design, incorporating uncertainty into multiphysical optimization, and improving overall method performance through artificial intelligence and machine learning. Building on previous doctoral research at ENS Paris-Saclay, this work will integrate mechanical criteria into topological optimization, addressing the antagonistic nature of these phenomena and the numerical difficulties they introduce. The research will also explore robust optimization approaches, leveraging machine learning techniques like Bayesian Optimization to reduce computation times and achieve robust solutions.

The main objectives include developing a robust optimization methodology that minimizes prior bias, providing design assistance tools that establish performance indicators and validity ranges concerning variabilities. The thesis will involve incorporating uncertainties into topological optimization, implementing and analyzing the complete approach, integrating mechanical phenomena, and potentially using neural networks to enhance optimization methods.

Description :

The electric machine design sector is currently experiencing significant growth, partly due to efforts in energy transition and combating climate change, which rely in part on the massive electrification of uses [1]. In the transportation sector, the market for electric and plug-in hybrid vehicles is witnessing exponential growth (with 18% of sales in 2023 compared to 14% in 2022) [2]. In this context, the design of innovative and efficient electric machines is a major challenge for industry players [3]. Furthermore, the electric machine design sector is currently heavily impacted by difficulties in sourcing raw materials [4]. This leads, in practice, to (1) avoiding the use of rare earths and thus promoting the development of electric machines without permanent magnets and/or (2)

settling for recycled materials with lower magnetic, thermal, and/or mechanical properties [5] and significant variability. These developments contribute to the redefinition of specifications and highlight the necessity of considering uncertainties in design and optimization processes. Parametric and especially topological optimization methods [6] are increasingly present in design offices and allow for real technological breakthroughs. However, they still do not enable the pursuit of robust optimal solutions within timeframes compatible with design iterations in these offices (especially in 3D). This thesis topic is situated within this context and aims to make a significant methodological advancement. The research will focus on three major axes: (1) increasing the consideration of multiphysics aspects related to the design of electric machines by aligning more closely with real design specifications, (2) incorporating uncertainty within multiphysics optimization itself, and (3) improving the overall performance of the method through the use of artificial intelligence or machine learning.

Theme :

The issue addressed is a continuation of doctoral research conducted at the SATIE and LMPS laboratories of ENS Paris-Saclay [7], [8], [12] located in the very vibrant and dynamic scientific cluster of the Plateau de Saclay area, which proposed an initial approach to multiphysical topological optimization. This work primarily integrates considerations related to stationary electromagnetic phenomena. Elements concerning mechanical criteria have been included, revealing a strong antagonism to those of electromagnetism. Moreover, incorporating mechanics into topological optimization introduces additional numerical difficulties that require specific treatments, which have not been fully implemented.

The necessity of adding criteria related to the mechanical integrity of proposed solutions, as well as manufacturability constraints, is now essential to approach viable solutions. The same applies to the inclusion of thermal phenomena, which are critical for achieving innovative solutions that break away from existing ones. Finally, the methods currently deployed remain purely deterministic and do not easily allow for questioning the robustness of the obtained solution or accounting for parametric variability (materials, geometries, loads, etc.), which is often present during pre-design phases or due to technical choices that introduce uncertainty (additive manufacturing, recycled materials, etc.). Current work being conducted in collaboration between the SATIE laboratory and IFPEN for the development of a robust parametric optimization approach [9], [10] tailored to electric machines also provides a solid methodological foundation for moving towards a comprehensive multiphysical robust topological optimization approach.

Multiphysical optimization is now present in design processes. It often relies on loosely coupled or even decoupled solvers [11] to obtain optimal solutions based on multiple objective functions and constraints. The issue of incorporating multiphysical characteristics in the context of topological optimization applied to electric machines has been addressed several times [12], [13], [14], [15], yet several questions remain open, such as the simultaneous consideration of mechanical and thermal integrity.

Parametric optimization has seen significant advancements [16], [20] in deterministic and robust frameworks but requires substantial prior knowledge, particularly regarding the space of possible solutions and their parameterization. Conducting robust topological optimizations, although developed in a monophysical context [21], [22], [23],

remains underexplored in a multiphysical framework suitable for electric machines due to the complexity of the physical models involved, the antagonistic phenomena related to the involved physics, and the computational costs necessary to obtain optimal solutions [15]. Reducing computation times is primarily feasible through minimizing the number of solver calls, for example, by employing surrogate models [24], [25], [9]. However, these approaches are still based on a parametric approach to the problem and do not reduce the design prior. Recent approaches applied to monophysical problems [26] propose the use of isogeometry to reduce parametric dimensionality, thus making robust considerations viable in terms of performance.

Goals :

The main objectives of this thesis are part of a process aimed at developing an effective robust optimization methodology that minimizes prior bias. It will contribute to the advancement of design assistance tools by providing indicators capable of establishing not only the performance of the obtained solution(s) but also framing their validity range concerning the considered variabilities.

From an activity perspective, the thesis work will be structured around the following points:

- **Incorporating uncertainties** within the considered topological optimization approach. This can be achieved through (1) adapting the topological optimization approach to a stochastic framework by deploying a Robust Topological Optimization [21], [26] approach that will be tailored to the multiphysical context [27], or (2) developing a two-level hybrid optimization approach [28]. The first level would consist of deterministic topological optimization leading to an initial optimal solution. The second level would then involve robust parametric optimization, continuing the ongoing work [9], [10]. The proposed approach relies on methodologies derived from Machine Learning, based on Bayesian Optimization with iteratively enriched Gaussian Processes, allowing for significant reductions in computation times to achieve robust optimum.
- **Implementing the complete approach** and analyzing its performance regarding both the obtained solution and the numerical efficiency in obtaining it. This approach will be applied to electric machines with permanent magnets and synchronous reluctance. A significant inquiry will be conducted to develop a method that is usable in design offices and capable of providing designers with a framework for uncertainties and their impact on the identified optimal solution.
- **Complementary integration of mechanical physical phenomena** within the topological optimization approach, primarily in 2D. This could be done by adapting the SIMP method [29] currently used for other physics through ad hoc numerical methods if necessary. A significant effort will be required to reflect on the performance of the developed numerical method and the robustness of the optimal solutions obtained in relation to the uncertainty consideration adopted approach.
- **Additionally**, the use of learning models, such as neural networks, could be considered to assist topological and parametric optimization methods for performance gains [30], [31], [32].

Supervision :

The thesis will be supervised by **Pr. François Louf** from LMPS at ENS Paris-Saclay (<https://lmps.ens-paris-saclay.fr/en/presentation>), with co-supervision from **Pr. Luc Laurent** (LMSSC, Cnam, <https://www.lmssc.cnam.fr/en/>), **Pr. Sami Hlioui** (SATIE, Cergy-University, <https://satie.ens-paris-saclay.fr/en/>), and **Dr. Delphine Sinoquet** (IFPEN, <https://www.ifpenergiesnouvelles.com/>).

Applicant profile :

- **Equivalent to M2 Level:** Candidates should have a master's level education in applied mathematics or structural mechanics.
- **Strong Interest in Numerical Modeling:** A keen enthusiasm for numerical modeling and the underlying numerical methods is essential.
- **Background in Multiphysics, Statistics, or Optimization:** Experience in these areas would be a significant advantage.
- **Programming Skills:** Proficiency in programming languages such as Python and MATLAB is preferred.
- A strong interest in carrying out high-level scientific work in order to contribute to a very active and innovative research field in a very active and high-level research team.

This PhD topic is participating to the Université Paris-Saclay EU COFUND DeMythif.AI program: <https://www.dataia.eu/en/open-call-cofund-demythifai-call-application-2024>. It is especially advertised to international students who have spent less than 12 months in France in the last 3 years. The candidates will be evaluated by a jury who will select 20 PhD to start in fall 2025. The successful candidates will be fully funded for 3 years (monthly gross salary 2 430 €, mobility indemnities 3 000€ and financial support to the host laboratories 10 000 €), have access to specific scientific and non-scientific training, and be fully part of the Université Paris-Saclay AI community.

Collaborations :

Laboratoire de Mécanique Paris-Saclay (LMPS) (<https://lmps.ens-paris-saclay.fr/en/presentation>)

Laboratoire des Systèmes et Applications des Technologies de l'Information et de l'Energie (SATIE) (<https://satie.ens-paris-saclay.fr/en/>)

Laboratoire de Mécanique des Structures et des Systèmes Couplés (LMSSC) (<https://www.lmssc.cnam.fr/en/>)

IFP Energies nouvelles (IFPEN) (<https://www.ifpenergiesnouvelles.com/>)

Valuation :

The work from this thesis will be presented at both national and international conferences, as well as published in international journals. Additionally, the developments made during the research will lead to the creation of a software prototype based on existing frameworks.

Location : Laboratoire de Mécanique de Paris-Saclay, ENS Paris-Saclay (Gif-sur-Yvette, France)

Dates : october 2025 – september 2028

Contacts :

- francois.louf@ens-paris-saclay.fr
- luc.laurent@lecnam.net
- sami.hlioui@cyu.fr
- delphine.sinoquet@ifpen.fr

Application form:

https://adum.fr/as/ed/voirproposition.pl?site=PSaclay&matricule_prop=59488&langue=en

Instructions:

<https://www.dataia.eu/en/open-call-cofund-demythifai-call-application-2024>

References :

- [1] F. Knobloch *et al.*, « Net emission reductions from electric cars and heat pumps in 59 world regions over time », *Nature Sustainability*, vol. 3, n° 6, p. 437-447, juin 2020, doi: 10.1038/s41893-020-0488-7.
- [2] IEA, « Global EV outlook 2024 », International Energy Agency, Paris, 2024.
- [3] I. López, E. Ibarra, A. Matallana, J. Andreu, et I. Kortabarria, « Next generation electric drives for HEV/EV propulsion systems: Technology, trends and challenges », *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109336, 2019, doi: <https://doi.org/10.1016/j.rser.2019.109336>.
- [4] R. Gauß *et al.*, « Rare earth magnets and motors: a european call for action », Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, 2021.
- [5] T. Elwert *et al.*, « Current developments and challenges in the recycling of key components of (hybrid) electric vehicles », *Recycling*, vol. 1, n° 1, p. 25-60, 2016, doi: 10.3390/recycling1010025.
- [6] G. Lei, J. Zhu, Y. Guo, C. Liu, et B. Ma, « A Review of Design Optimization Methods for Electrical Machines », *Energies*, vol. 10, n° 12, Art. n° 12, déc. 2017, doi: 10.3390/en10121962.
- [7] T. Cherière *et al.*, « Multi-material topology optimization using Wachspress interpolations for designing a 3-phase electrical machine stator », *Structural and Multidisciplinary Optimization*, vol. 65, n° 12, p. 352, nov. 2022, doi: 10.1007/s00158-022-03460-1.
- [8] T. Cherière, S. Hlioui, F. Louf, et L. Laurent, « Multimaterial filtering applied to the topology optimization of a permanent magnet synchronous machine », *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 43, n° 4, p. 852-870, juill. 2024, doi: 10.1108/COMPEL-10-2023-0546.
- [9] A. Reyes, D. Sinoquet, A. Nasr, et S. Hlioui, « Robust design optimization taking into account manufacturing uncertainties of a permanent magnet assisted synchronous

reluctance motor », 29 novembre 2022, arXiv: arXiv:2211.16136. doi: 10.48550/arXiv.2211.16136.

[10] A. Reyes Reyes, A. Nasr, D. Sinoquet, et S. Hlioui, « Study on the impact of uncertain design parameters on the performances of a permanent magnet-assisted synchronous reluctance motor », *Science and Technology for Energy Transition*, vol. 79, p. 13, mars 2024, doi: 10.2516/stet/2024008.

[11] H. Engels, W. Becker, et A. Morris, « Implementation of a multi-level optimisation methodology within the e-design of a blended wing body* 1 », *Aerospace Science and technology*, vol. 8, n° 2, p. 145-153, 2004.

[12] T. Cherière, « Élaboration de méthodes et d'outils logiciels pour l'optimisation topologique magnéto-mécanique de machines électriques tournantes », Theses, Université Paris-Saclay, 2023. [En ligne]. Disponible sur: <https://theses.hal.science/tel-04636530>

[13] O. Sigmund, « Design of multiphysics actuators using topology optimization – Part I: One-material structures », *Computer Methods in Applied Mechanics and Engineering*, vol. 190, n° 49, p. 6577-6604, oct. 2001, doi: 10.1016/S0045-7825(01)00251-1.

[14] O. Sigmund, « Design of multiphysics actuators using topology optimization – Part II: Two-material structures », *Computer Methods in Applied Mechanics and Engineering*, vol. 190, n° 49, p. 6605-6627, oct. 2001, doi: 10.1016/S0045-7825(01)00252-3.

[15] F. Nishanth et B. Wang, « Topology Optimization of Electric Machines: A Review », in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, oct. 2022, p. 1-8. doi: 10.1109/ECCE50734.2022.9948073.

[16] X. Yi, A. Yoon, et K. S. Haran, « Multi-physics optimization for high-frequency air-core permanent-magnet motor of aircraft application », in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, mai 2017, p. 1-8. doi: 10.1109/IEMDC.2017.8002293.

[17] L. Chen, X. Chen, J. Wang, et P. Lazari, « A computationally efficient multi-physics optimization technique for permanent magnet machines in electric vehicle traction applications », in *2015 IEEE International Electric Machines & Drives Conference (IEMDC)*, mai 2015, p. 1644-1650. doi: 10.1109/IEMDC.2015.7409284.

[18] T. Song, H. Liu, Q. Zhang, et Z. Zhang, « Multi-physics and multi-objective optimisation design of interior permanent magnet synchronous motor for electric vehicles », *IET Electric Power Applications*, vol. 14, n° 11, p. 2243-2254, 2020, doi: 10.1049/iet-epa.2020.0136.

[19] N. Rivière, M. Stokmaier, et J. Goss, « An Innovative Multi-Objective optimization Approach for the Multiphysics Design of Electrical Machines », in *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, juin 2020, p. 691-696. doi: 10.1109/ITEC48692.2020.9161650.

[20] W. Li, L. Gao, et M. Xiao, « Multidisciplinary robust design optimization under parameter and model uncertainties », *Engineering Optimization*, vol. 52, n° 3, p. 426-445, mars 2020, doi: 10.1080/0305215X.2019.1590564.

[21] P. D. Dunning et H. A. Kim, « Robust topology optimization: Minimization of expected and variance of compliance », *AIAA Journal*, vol. 51, n° 11, p. 2656-2664, 2013, doi: 10.2514/1.J052183.

[22] K. Gao, D. M. Do, S. Chu, G. Wu, H. A. Kim, et C. A. Featherston, « Robust topology optimization of structures under uncertain propagation of imprecise stochastic-based

- uncertain field », *Thin-Walled Structures*, vol. 175, p. 109238, 2022, doi: <https://doi.org/10.1016/j.tws.2022.109238>.
- [23] Y. Zheng *et al.*, « Robust topology optimization for multi-material structures considering material uncertainties », *Thin-Walled Structures*, vol. 201, p. 111990, 2024, doi: <https://doi.org/10.1016/j.tws.2024.111990>.
- [24] N. V. Queipo, R. T. Haftka, W. Shyy, T. Goel, R. Vaidyanathan, et P. Kevin Tucker, « Surrogate-based analysis and optimization », *Progress in Aerospace Sciences*, vol. 41, n° 1, p. 1-28, janv. 2005, doi: [10.1016/j.paerosci.2005.02.001](https://doi.org/10.1016/j.paerosci.2005.02.001).
- [25] Z.-H. Han et K.-S. Zhang, « Surrogate-Based Optimization », in *Real-World Applications of Genetic Algorithms*, IntechOpen, 2012. doi: [10.5772/36125](https://doi.org/10.5772/36125).
- [26] T. Komann, M. Wiesheu, S. Ulbrich, et S. Schöps, « Robust Design Optimization of Electric Machines with Isogeometric Analysis », *Mathematics*, vol. 12, n° 9, Art. n° 9, janv. 2024, doi: [10.3390/math12091299](https://doi.org/10.3390/math12091299).
- [27] C. Chu, « Multiscale and multiphysics robust design of a complex microstructure with uncertainties, and driven by target performances », phdthesis, Université de Lyon, 2022. Consulté le: 21 octobre 2024. [En ligne]. Disponible sur: <https://theses.hal.science/tel-03709305>
- [28] A. Credo, G. Fabri, M. Villani, et M. Popescu, « Adopting the Topology Optimization in the Design of High-Speed Synchronous Reluctance Motors for Electric Vehicles », *IEEE Transactions on Industry Applications*, vol. 56, n° 5, p. 5429-5438, sept. 2020, doi: [10.1109/TIA.2020.3007366](https://doi.org/10.1109/TIA.2020.3007366).
- [29] M. P. Bendsøe, *Optimization of structural topology, shape, and material*. Springer, 1995.
- [30] M. Goerigk et J. Kurtz, « Data-driven robust optimization using deep neural networks », *Computers & Operations Research*, vol. 151, p. 106087, mars 2023, doi: [10.1016/j.cor.2022.106087](https://doi.org/10.1016/j.cor.2022.106087).
- [31] V. Keshavarzadeh, R. M. Kirby, et A. Narayan, « Robust topology optimization with low rank approximation using artificial neural networks », *Comput Mech*, vol. 68, n° 6, p. 1297-1323, déc. 2021, doi: [10.1007/s00466-021-02069-3](https://doi.org/10.1007/s00466-021-02069-3).
- [32] G. B. Gavis et W. Sun, « Topology optimization with graph neural network enabled regularized thresholding », *Extreme Mechanics Letters*, vol. 71, p. 102215, 2024, doi: <https://doi.org/10.1016/j.eml.2024.102215>.