

Analytical modeling of the multi-physical magnetic-thermal coupling in the conceptual design phase of a mechatronic system

Yethreb Ben Messaoud

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Modélisation analytique du couplage multi-physique magnétique-thermique dans la phase de préconception d'un système mécatronique

Thèse de doctorat de l'Université Paris-Saclay préparée à CentraleSupélec

École doctorale n°573 interfaces : approches interdisciplinaires, fondements, applications et innovation (Interfaces) Spécialité de doctorat : Sciences et technologies industrielles

Thèse présentée et soutenue à Saint Ouen, le 17/12/2018, par

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ÉCOLE DOCTORALE INTERFACES Approches Interdisciplinaires : Fondements, Applications et Innovation

Titre : Modélisation analytique du couplage multi-physique magnétique-thermique dans la phase de préconception d'un système mécatronique

Mots clés : Phase de préconception, Contraintes multi-physiques, Sélection d'architecture, Ingénierie Systèmes, Couplage magnétique-thermique, Aimants en néodyme

Résumé : Durant la phase de conception, les différentes équipes d'ingénierie procèdent à de multiples simulations par éléments finis traitant les comportements physiques variés afin d'assurer la vérification et la validation.

Cependant, les résultats insatisfaisants engendrent des changements tardifs et par conséquent de longues itérations et des coûts croissants.

Pour répondre à cette problématique, il est essentiel de prendre en considération les contraintes géométriques et multi-physiques dès la phase de préconception.

En effet, un processus appelé SAMOS est développé visant à sélectionner l'architecture multi-physique 3D la plus adéquate tout en garantissant une collaboration efficace entre les équipes d'ingénieurs. D'ailleurs, il est basé sur deux extensions en SysML permettant l'enrichissement de l'architecture par des informations géométriques et multi-physiques.

D'autre part, cette thèse se focalise sur l'étude des contraintes magnétiques et du couplage magnétique-thermique.

Comme cette phase ne supporte pas les simulations par éléments finis, les modèles analytiques basés sur des géométries simplifiées sont suffisants pour fournir des résultats approximatifs satisfaisants.

Dans ce contexte, différents modèles analytiques sont étudiés et validés à travers des simulations par éléments finis et des mesures pour plusieurs cas tels que les aimants permanents en Néodyme. En fait, l'augmentation de température ne fait pas seulement diminuer la densité du flux magnétique rémanente mais il est capable de causer des pertes irréversibles. En effet, lorsqu'on revient à la température initiale, les caractéristiques de l'aimant sont modifiées. Les différents facteurs affectant le processus de démagnétisation sont examinés.

De plus, l'impact de la température sur les performances d'un moteur sans balais est étudié étant donné que ce dispositif représente un système mécatronique complexe.



ÉCOLE DOCTORALE INTERFACES Approches Interdisciplinaires : Fondements, Applications et Innovation

Title : Analytical modeling of the multi-physical magnetic-thermal coupling in the conceptual design phase of a mechatronic system

Keywords : Conceptual design phase, Multi-physical constraints, Architecture selection, Systems Engineering, Magnetic-thermal coupling, Neodymium magnets

Abstract : During the design phase, the different engineering teams make multiple FE simulations dealing with various physical behaviours in order to ensure both verification and validation.

However, the unsatisfactory results lead to late changes and hence to long iterations and increasing costs.

In order to tackle this problem, it is essential to take into account the geometrical and multiphysical constraints in the complex system architecture since the conceptual design phase. In fact, a process called SAMOS is developed aiming at selecting the most adequate 3D multiphysical architecture while ensuring an efficient collaboration between the engineering teams. Moreover, this framework is based on two SysML extensions which allow the enrichment of the architecture with geometrical and multiphysical data.

Furthermore, this thesis focuses on magnetic constraints and magnetic-thermal coupling.

Since this phase does not support long FE simulations, the analytical models based on simplified geometries are sufficient to provide satisfactory approximate results.

In this context, different analytical models are studied and validated through FE simulations and measures for several cases such as NdFeB permanent magnets. Indeed, the temperature rise does not only decrease the remanent flux density but is able also to cause irreversible losses. In fact, once we go back to the initial temperature, the characteristics of the magnet are modified. The different factors impacting the demagnetization process are discussed.

Besides, the temperature impact on brushless motors' performances is studied since this device represents a complex mechatronic system.

أبو القاسم الشابي

"If to a goal I aspire, I pursue the object of desire and prudence obliviate Neither the rugged canyons will I shun Nor the gushing of the blazing fire He who does not like to climb mountains Will forever live among the hollows"

The Will To Live Abu Al-Qasim Al-Shabbi

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Dedications

I would like to dedicate this work firstly, to my beloved parents Leila and Salem who have, not only, raised in me the passion for knowledge and the ambition to achieve the highest mattresses but also surrounded me with their care and love. I wish I could thank them enough for the sacrifices they have always made to see me get to this day.

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List of Abbreviations

AC	Alternative Current
AMB	Active Magnetic Bearings
BLDC	Brush Less Direct Current motor
BPMM	Brush-less Permanent Magnet Motor
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DC	Direct Current
DCM	Direct Coupling Model
DFA	Design For Assembly
EMF	Electromotive Force
ES	Evolution Strategy
FBS	Functional Behaviour Structure
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
G	Geometer
GPS	Global Product Specifications
GUI	Graphical User Interface
HTML	HyperText Markup Language
ICM	Indirect Coupling Model
IEEE	Institute of Electrical and Electronics Engineers
IFAC	International Federation of Automation Control
INCOSE	International Council on Systems Engineering
IPMM	Interior Permanent Magnet Motor
ISO	International Organization for Standardization
M2M	Model to Model
MBSE	Model Based Systems Engineering
MHD	Magneto-Hydro-Dynamic
MRGE	Minimal Reference Geometric Element
OMG	Object Management Group
PM	Permanent Magnet
PMBM	Permanent Magnet Brush-less Motor
PMM	Permanent Magnet Motor
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RGE	Reduced Geometric Element
SA	System Architect
SAGE	Semi Ground Automatic Environment

SAMOS	Spatial Architecture based on Multi-physics and Organization of Systems
SA-CAD	System Architecting Computer Aided Design
SE	Systems Engineering
ST	Simulation Team
SysML	System Modelling Language
TRN	Thermal Resistance Network
TTRS	Technologically and Topologically Related Surfaces
UML	Unified Modelling Language
VRML	Virtual Reality Modelling Language

Introduction

1 General context

The world of industry has been revolutionized thanks to the development of mechatronic systems which are used in multiple fields (cars, aerospace, computers, etc). The competition known in the industry field has pushed companies to renovate their products and use efficiently technology in order to give to their clients the best products. In fact, such an evolution has resulted in higher costs and longer design time caused by finite element simulations of the physical behaviours and long iterations taking place in the design process.

In fact, a mechatronic system is the result of integrating and merging different engineering disciplines such as mechanics, electronics, control, magnetics, etc in one autonomous system. Contrarily to traditional systems that include only one field, this multi-disciplinarity generates numerous couplings between the multiple physical phenomena present in the mechatronic system. Indeed, new methodologies and design tools are required to be developed in order to take into account since the first phases of the system design all the impacts of the multidisciplinary aspect of mechatronic systems, improve their performance and reduce the time and thus the cost linked to the system design process.

Hence, companies aim at ensuring the collaboration between different engineering teams and the efficiency of the integration of multidisciplinarity since the first design phases without cost or time losses.

Moreover, the modelling of the multi-physical constraints and their resulting couplings has to be taken into account since the conceptual design phase throughout analytical equations since engineering teams require only generalized results to validate their work at this step.

Indeed, the project proposed in Quartz laboratory takes into account three physical phenomena such as temperature, magnetics and vibration studied separately in three different PhD works with basically the same conditions. In this PhD work, a special focus on the magnetic constraints and their coupling with the thermal ones is realized.

2 Problematic

The design of multidisciplinary systems is a complex process because of the large number of components and the multi-physical constraints between them. Moreover, the lack of collaboration between the different engineering teams working on various disciplines and the use of non-interoperable simulation tools result in long iterations during the embodiment and detailed design phases. Furthermore, if the geometrical and the multi-physical constraints are not taken into consideration in the physical architecture since the conceptual design, late changes would take place in the embodiment and detailed design phases leading to an increase of time and costs. Thus, the various possible 3D architectures should integrate geometrical and physical information.

Therefore, a MBSE approach, not only, ensuring the consistency of the modelling data, the traceability process and the effective collaboration between all the teams, but also, taking into account geometrical and multi-physical constraints is required. This would facilitate the selection of the convenient physical architecture by the System Architects. In fact, this approach has to meet these requirements in relation with the conceptual design phase: simulations are based on simple components' geometry using analytical multi-physical equations, in order to provide approximate results with simplified geometry allowing the comparison and the validation of the possible 3D architectures in the conceptual design phase with no big precision since all this work is realized in this specific phase which does not support long and costly finite element simulations.

Our main issues in this PhD work are:

- On the one hand, how to select the most convenient physical architecture that includes geometrical and multi-physical constraints of such complex systems during the conceptual design phase, in order to reduce the risks of late changes that result in big losses of time and costs.
- On the other hand, to study the magnetic constraints for different systems and their coupling with thermal constraints.

3 Outline of the dissertation

The thesis manuscript is composed of three chapters.

Firstly, the chapter 1 entitled State of the art describes firstly the mechatronic system design throughout a general overview of traditional design methodologies and the issues faced by the companies. Moreover, the section 1.2 defines some important notions related to mechatronic systems and describes the different steps of their design life cycle. Besides, it provides a description of Model Based Systems Engineering (MBSE) approach which represents a very adequate process to design complex systems.

Then, multiple manners of studying multi-physical constraints and their resulting couplings are cited with a focus on magnetic-thermal coupling. The second part (section 1.3) describes generally the Multi-physical coupling affecting different types of systems then focuses on the magnetic constraints coupled with the thermal ones for the case of permanent magnet materials. Finally, a general description of permanent magnets (PMs) is given while underlining the importance of magnetic-thermal coupling for this application case.

Secondly, the chapter 2 entitled Selection of multi-physical architecture generation approach begins with a description of the conceptual design phase and all the existing solutions realized to reduce time and costs during it. Then, it describes the whole process of selecting an approach for architecture assessment under geometrical and multi-physical constraints. In fact, three different approaches based on the system geometrical and multi-physical (thermal, magnetic, electric, etc) requirements and the collaboration between the various engineering teams (system architects, geometers and simulation teams) are described and their ability to fulfil the mission of generating the most adequate spatial architecture are compared. Thanks to this comparison, only one approach is selected and the whole description of this platform is provided.

Thirdly, the chapter 3 entitled Study of magnetic and thermal constraints makes a study of magnetic constraints for some systems such as permanent magnets throughout a comparison between analytical, experimental and finite element methods for different application cases such as coils and permanent magnets. Furthermore, the coupling between magnetic and thermal constraints is studied for permanent magnets and permanent magnet synchronous motors. Finally, the validation of these analytical models ensures their integration in the proposed platform in order to enable the different engineering teams to efficiently select the 3D multiphysical architecture since the conceptual design phase.

Finally, this report ends with Conclusions and perspectives that summarize the whole PhD work.

Chapter 1

State of the art

1.1 Introduction

The chapter 1 is composed of two sections.

Firstly, the section 1.2 includes the definition of "mechatronics", its history and its multi-disciplinarity. Then, a description of traditional design approaches is provided while highlighting their shortages. Moreover, the mechatronic design process is detailed and "System engineering (SE) approach" which is one of the most efficient methodologies is fully described.

Secondly, the section 1.3 is devoted to multi-physical couplings having as main focus the study of thermal-magnetic coupling. Indeed, it starts with a general description where some important notions are defined such as *"multi-physics"* and *"coupling"*. A state of the art of some of the fields and methods used to deal with the multi-physical couplings is provided especially the magnetic-thermal coupling. Secondly, a theoretical background of permanent magnet materials (PM) is provided including all the specific terms linked to this field that would be used all along this work. Finally, the different models that describe the coupling between the magnetic and the thermal properties for permanent magnets which would be used in the next chapters are given.

1.2 Mechatronic system design

1.2.1 General description

The integration of mechanics and electronics in one autonomous system results in a system merging both disciplines called *mechatronic system* coming from the concatenation of MECHAnics and elecTRONICS. In fact, since the nineteenth century until the 1980s, the pure mechanical systems had known a big development (see Figure 1.1) taking into account electrical drives, automatic control until the integration of different disciplines and the use of synergy by the engineering teams during the design process [1].



FIGURE 1.1: Historical development of purely mechanical systems to mechatronic systems [1]

The word Mechatronics was the first time created in 1969 by the Japanese engineer Tetsuro MORI from Yaskawa Electric Corporation [2]. Since then, many definitions were given to the word "mechatronics" such as

the both published in the editorials of the journals "International Mechatronics" in 1991 [3] and "International IEEE Transactions on Mechatronics" in 1996 [2, 4]. In 2000, the IFAC Technical Committee on Mechatronic Systems provided this definition: "Many technical processes and products in the area of aerospace, mechanical and electrical engineering show an increasing integration of mechanics with electronics and information processing. This integration is between the components (hardware) and the information-driven functions (software), resulting in integrated systems called mechatronic systems. Their development involves finding an optimal balance between the basic mechanical structure, sensor and actuator implementation, automatic digital information processing and overall control, and this synergy results in innovative solutions." [5].

Moreover, mechatronic systems have known several developments thanks to the integration of digital information processing such by using sophisticated control functions. Thus, they have evolved and become *"intelligent mechatronic systems"* [6].

All these developments and the fundamental aspects of mechatronics can be found in the literature such as the books of Kitaura [7], Bradley [8], McConaill et al. [9], Heimann et al. [10], Bishop et al. [11] and the journal articles by Hiller [12] and Lückel [13].

In general, mechatronics is an interdisciplinary field (see Figure 1.2) where mechanics, electronics and information technology are integrated with a multi-physical aspect in which magnetics, vibrations, temperature, etc. act together.



FIGURE 1.2: Interdisciplinarity of mechatronics [14]

The application of information systems to physical systems results in a mechatronic system. The physical system is composed of mechanical, electrical and computer systems with sensors, actuators and real-time interfaces too.

Despite the frequent use of the representation in Figure 1.2 in the literature, the representation shown in Figure 1.3 is clearer but more complex.



FIGURE 1.3: Mechatronic systems components [14]

1.2.2 Traditional design methodologies

Since mechatronic systems are complex and interdisciplinary, the traditional design process also called *sequential engineering approach* consisting in performing the design steps sequentially is no more convenient and needs to be improved.

Indeed, this methodology has many drawbacks. In spite of the optimality of the design steps, the optimality of the final product is not ensured because of the absence of interaction. It has very high costs and consumes a lot of time spent on long iterations as the whole design process has to be repeated if the final product does not satisfy all the specifications as it is shown in Figure 1.4.



FIGURE 1.4: Traditional design process

In their book entitled "*Mechatronics system design*", Shetty et al. [14] mentioned that according to a Standish Group survey of software dependent projects, there is:

- 31.1% of software development projects were cancelled,
- 222% time overrun for completed projects,
- 200% maintenance costs excess compared to initial development costs for delivered software,
- Only 16.2% of the software projects were achieved within budget and on time.

These rates are the result of the shortages of this traditional method. The interdisciplinary aspect of mechatronic systems with all the physics and their couplings present in the system are not dealt with. Added to this, there is no collaboration between the engineering teams. Thus, it does not constitute a convenient design methodology for mechtronic systems.

The system life-cycle is composed of these steps: requirements analysis,

architectural definition, detailed design, verification and validation. It is a graphical representation that summarizes the main activities and results that have to be performed during the product development. Indeed, there are many types of cycles representing the most important design steps that can be mentioned like *"waterfall life-cycle model"* (Figure 1.5), *"V life-cycle model"* (Figure 1.6) and *"spiral life-cycle model"* (Figure 1.7).

The oldest one is the waterfall life-cycle that was formally developed in 1970 in an article by Royce et al. [15] without mentioning the term *waterfall* [16]. However, the use of similar phases was mentioned at the first time by Benington [17] at Symposium on advanced programming methods for digital computers on 29 June 1956. This model was developed for SAGE (Semi Ground Automatic Environment). This cycle consists in executing the different stages shown in Figure 1.5 successively with the possibility of making returns to the previous step or to the design phase. According to Petersen et al. [18], there is an agreement in the literature on problems related to the use of waterfall model. Indeed, changes are difficult to implement, iterations are lengthy and costly and problems are often left to last phases. Hence, this methodology is connected to high costs and efforts [19, 20].



FIGURE 1.5: Waterfall life-cycle model [21]

The V life-cyclel (Validation & Verification model) was firstly used "Das V-Modell" as the official project management methodology of the German government [22]. It is a modified version of the waterfall model. The parallel relationship between the development of the process and the verification at every stage is one of its important characteristics. In spite of the possibility of making requirement changes in any phase, the V model remains rigid and the least flexible [23].



FIGURE 1.6: V life-cycle model [6]

The spiral model was described at the first time by Boehm in two articles published in 1986 and 1988 [24, 21]. For this model, an appropriate process for a certain project is based on the project's risks [25]. Hence, it is really recommended for medium to high-risk projects where costs and risk evaluation are important.

The advantages of the spiral model are [26] :

• The high amount of risk analysis which ensures the avoidance of risks during the project,

- Better for large projects
- Additional functionalities may be added later on...

Its limits are [26] :

- The possibility to be a costly model,
- The highly dependence of the project on the risk analysis stage
- The difficulty to be used in small projects...



FIGURE 1.7: Spiral life-cycle model [21]

The selection of a certain model depends on the nature of the project and its size since the detail levels are different. To conclude, even though these three different life-cycles modes have approximately the same phases, they have this limitation: How to ensure the integration between various disciplines, physics and levels in the system?

1.2.3 Mechatronic design process

Due to the important number of its components, its multiphysical aspect and the generated couplings, mechatronic systems are highly complex.

Therefore, the design methodology has to take into consideration multiple requirements simultaneously such as different physical constraints (magnetics, electrostatics, vibrations, temperature, mechanics...). Hence, this approach implies the importance of the design of the mechatronic system as a unit gathering the different aspects.

In general, the design of mechatronic systems does not only require a systematic development but also modern software design tools with a good collaboration between engineering services.

Consequently, there is a need of a concurrent (instead of sequential) approach for the design of mechatronic systems that ensures the synergy in the integration of the different disciplines such as mechanics, electrics and computer systems. In fact, this synergy which is the result of the right combination of all the parameters is necessary to achieve some of the performance characteristics of the final machatronic product.

Moreover, it is an important tool that has to take into consideration a simultaneous type of engineering based on collaboration aiming to design an integrated system.

Hence, the concurrent engineering comes from the idea that expert engineering teams are able to deliver a final mechatronic product on time and without additional costs if they cooperate to achieve this common goal during all the design steps [14]. The characteristics of this type of engineering are:

- Better definition of the product's specifications in order to avoid late changes,
- Good estimation of costs

- Economize time spent on long iterations,
- Decrease the barriers between design and manufacturing,
- Take into consideration all the steps (manufacturing, assembly...) in the early design stage.

However, there is a lack of common software tools and interface language that can facilitate the information exchange between the engineering teams.

Once the concurrent engineering is used, it is very probable that the final product meets these basic requirements:

- Robustness,
- Good quality,
- Adequate cost
- Time to market
- Customer satisfaction

Essentially, the concurrent engineering in an improved approach that revolutionizes the long and expensive design processes. In fact, engineers coming from all disciplines work simultaneously and cooperatively on one project. Moreover, all the engineering disciplines are merged and are independent from making various physical prototypes. Thus, this ensures a reduction in the design time lost in returns and iterations and an elimination of problems caused by design incompatibilities.

Unlike the conventional design of life cycle approach, the mechatronic design approach includes all life cycle factors during the product design stages, which results in final products well designed from conception to retirement. Several life cycle factors are cited here:

- Delivery: cost, time..
- Reliability: failure rate, materials...
- Maintainability: modular design
- Serviceability: prognostics, diagnostics...
- Upgradeability: futue compatibility with actual designs
- Disposability: recycling

1.2.4 System engineering approach

"Systems engineering" is a concurrent engineering approach where mechatronic systems are created as integrated products and collaboration between different teams dealing with various disciplines and physics is ensured. It is indeed an efficient method that helps to organize the life-cycle product especially when the projects dealt with are complex such as spacecraft design or robotics.

According to INCOSE (the International Council on Systems Engineering), "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. It considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" [27].



FIGURE 1.8: Systems engineering design cycle [28]

The life-cycle model under systems engineering is shown in Figure 1.8. The process starts with the definition of the customer requirements which constitutes the first phase called "Requirement analysis". The second phase called "Functional Analysis/Allocation" ensures the transformation of requirements such as performance and interfaces into well defined functions. Besides, functions are decomposed to lower-level ones and performance and other limiting requirements are allocated to functional levels. Hence, this step gives an initial architecture and minimizes functional interfaces thanks to the convenient management of different detail levels (functions are gathered with adequate components). Finally, the last phase Synthesis results in a physical architecture that can respond to the different requirements under the performance parameters. It allows the selection of the preferred physical architecture among various satisfactory ones.

In this context, in 2007, INCOSE began the popularization of a systems engineering methodology called *Model-based systems engineering (MBSE)* among industries [29]. It can be defined as "a formalized application of modelling to support system requirements, design, analysis, verification and validation, beginning in the conceptual design phase and continuing throughout

development and later life cycle phases". MBSE ensures a very consistent management of the information associated with the complete specification of a system. Indeed, it improves communication and collaboration among different teams. By viewing the system model from various perspectives and analysing the consequences, it manages system complexity effectively. Thanks to numerical and more standardized ways, it enhances the reuse of the information, which results in a reduction of cycle time and lower costs in case the design is modified [30]. In the INCOSE 2007 Symposium, Friedenthal et al. presented a roadmap of MBSE shown in Figure 1.9. They expect that MBSE would ensure distributed and secure model repositories crossing multiple domains in the 2020s.



FIGURE 1.9: MBSE roadmap [30]

In order to carry out the MBSE approach, there is a need of adequate languages and tools allowing the specification of requirements and system architecture independently of the discipline. SysML (*"Systems Modelling Language"*) [31] is one of the most known languages in the systems engineering field. Indeed, it is defined by Friedenthal et al. [32] as a general-purpose graphical model supporting the analysis, specification, design, verification and validation of complex systems. It ensures the design of multi-domain complex systems since it facilitates collaboration of different engineering teams, better understanding of models and traceability of the design procedure. To conclude, the intended results of SysML are:

• Reuse of the system specifications and design models,

- Improved communication among different teams,
- Better design quality,
- Enhanced specifications.

SysML uses seven of UML (Unified Modelling Language) diagrams and adds the requirement and parametric diagrams as it is shown in Figure 1.10.

UML was the first time developed by OMG (Object Management Group) in 1997 with the objective of standardizing the way of visualization of the system design. Since 2005, it is an approved standard by ISO (the International Organization for Standardization) with periodic revisions [33].



FIGURE 1.10: SysML diagrams [34]

The work of Mhenni et al. [35] shown in Figure 1.11 is a proposition of an MBSE design methodology based on SysML since this one does not provide specific procedures. This approach begins with a first step called *"Black box"* that, starting from the customer's requirements, defines the global mission, the system lifecycle, its context, its external interfaces, its operating modes, its provided services in order to obtain all the requirements that ensure the traceability and the definition of the physical architecture in the next step called *"White box"* taking into consideration functional and logical allocation. Hence, the Black box analysis aims at
clarifying the task (functional scenarios) while the White box analysis describes the system's structure.



FIGURE 1.11: MBSE apprroach [35]

Finally, MBSE processes are very convenient for complex mechatronic systems since they support the collaboration between different teams, the consistency of the models on one hand and ensure the traceability and the reuse of the models on the other hand.

1.3 Multi-physical coupling

1.3.1 General description

As it was mentioned in section 1.2, mechatronic systems function under geometrical, spatial and multi-physical constraints. Indeed, *multi-physics* is a computational discipline that treats systems involving multiple simultaneous physical phenomena. This term has been used very often since 2000 by researchers. According to Michopoulos et al. [36], it has been used in different contexts.

- Multi-field context: denotes the simultaneous excitation and response of the system by multiple physical fields,
- Multi-domain context: denotes the interaction among continuous representations of systems with different properties through shared boundaries,

- Multi-scale context: denotes the consistent bridging of various behavioural models of the system as it is required from different scopes of use in the system life-cycle,
- and the combination of the previous possibilities which reflects the coexistence of all of them as it is defined in the Figure 1.12.



FIGURE 1.12: Multi-physics space [36]

These multi-physical constraints such as electro-magnetics, temperature, vibrations, etc. act together in the same system and have several interactions called *couplings* which can evolve state variables independently ("weak coupling") or simultaneously ("strong coupling"). The coupling can be strong in both directions or weak in one direction and strong in the other; we speak then about ("two-way coupling") or ("one-way *coupling*") [37]. From one hand, the resolution of the equations in the weak coupling is executed successively. From the other hand, the resolution of the strong coupling requires an important number of long and costly iterations for a three-dimensional problem. For e.g., Sadek et al. [38] investigated multi-physical interactions within capacitive shunt RF MEMS switches by considering field model which studies electrostatic, а coupled electromagnetic, thermal and structural aspects varying with residual stress, geometry and operational current frequency. In this analysis, there are three different multi-physics interactions (see Figure 1.13) :

- The first interaction is a two-way electromagnetic thermal coupling,
- The second interaction is a one-way thermal-structural coupling
- The third interaction is a two-way structural-electrostatic coupling.



FIGURE 1.13: Flow chart for coupled field analysis procedure for RF MEMS switch [38]

1.3.2 Different types of multi-physical coupling

The multi-physical coupling includes different domains such as mechanics, vibrations or material science.

- Journeaux [39] studied the magneto-thermo-mechanical coupling by considering the numerical computation of vibrations within the end windings of large turbo-generators,
- Fasquelle [40] studied the coupled electromagnetic, acoustic and thermal-flow modelling of an induction motor of railway traction where she compared different modelling approaches like FEM (2D and 3D), semi-analytical and analytical. Besides, she made a diagram showing the composition of the multi-physical model of her system. She classifies the coupling problems faced in her study according to geometry, physic, method and time spent on resolution,

- Taher [41] analysed the impact of thermal effects on the mechanical behaviour of the material by providing all the mathematical modelling of the thermo-elastic and the thermo-elasto-plastic couplings. Moreover, he underlined the impact of various factors on the numerical results such as geometry, flux density, material properties and change in Young modulus.
- KADID et al. [42] studied the magneto-hydrodynamic and thermal coupling in a linear induction MHD pump by formulating mathematically electromagnetic, thermal and hydrodynamic (Navier Stokes equations) models. Finite element and volume finite methods were used for these weak couplings (see Figure 1.14).



FIGURE 1.14: Diagram of couplings [42]

In this paragraph, we detail the coupling taking into consideration the thermal-magnetic interaction.

The fields including thermal-magnetic coupling are multiple and some of them are cited subsequently.

The induction heating is one of the most relevant applications known for the magneto-thermal phenomenon. Indeed, there are many researchers interested by this thematic. In 1991, Feliachi et al. [43] developed a new FE formulation called DCM (Direct Coupling Model) to represent the real coupling between both physics and applied it to a 2D study case in order to determine the electric power densities and temperatures. The obtained results are more accurate than the ones given by ICM (Indirect Coupling Model) procedure. An other FE method was used by Dughiero et al. [44] allowing the resolution of coupled non-linear electromagnetic and thermal problems separately in induction heating applications. The validation of this procedure was ensured by its application on two typical industrial problems:

- Induction through heating of cylindrical billets before hot working,
- Longitudinal flux heating of non-magnetic slab.

The research works used various coupling processes and different algorithms to analyse the coupling between magnetic and thermal phenomena in induction heating separately or simultaneously taking into account the physical characteristics of the heated object which evolve during the heating process (see Figure 3.3). In fact, Bastos et al. [45] established a weak coupled model between electrical and thermal phenomena taking into account the transient states.



FIGURE 1.15: Induction heating magnetic-thermal coupling process [46]

In summary, the published works dealing with the magnetic-thermal coupling are multiple and have different application fields. Indeed, every paper has its methodology and concept in evaluating the coupling; it may be strong or weak depending on the studied system. The mathematical models include two parts : the electromagnetic model represented by Maxwell equations and the thermal model represented by conduction, convection and radiation equations. Besides, the majority of the papers used an iterative process to evaluate the coupling (see Figure 1.16) and verified it using FEM. Some of the study cases are cited here : induction heating machines [47, 45], superconductors [48], cable terminations [49], magneto-hydro-dynamic (MHD) pump [42], microwave heating of temperature-dependent dielectric media [50], railgun (moving conductors) [51], high frequency transformer [52, 53], ferromagnetic materials and permanent magnet machines.



FIGURE 1.16: An example of iteration flow chart [51]

1.3.3 Permanent magnet materials

a. General presentation

One of the major fields including thermal-magnetic coupling is the permanent magnet materials. Indeed, the history of magnetic materials is detailed in the book of Cullity et al. [54] entitled "Introduction to magnetic materials". In fact, he told that it began 2500 years ago when magnetite (Fe_3O_4) was discovered. It was the first magnetic material known to man for its power to attract iron. However, the prime true study was published in 1600 in the book entitled "On the magnet" written by Gilbert [55]. The research on magnetic materials did not really begin until the invention of the electromagnet in 1825 and the discovery made by Oersted [56] in 1820 stating that an electric current produces a magnetic field.

As it is known, there are various types of magnetic materials. Nevertheless, our study focuses only on permanent magnet materials. In fact, permanent magnets (PM) has the ability to produce a magnetic field in an air-gap with no excitation winding and no dissipation of electric power [57]. They have become lately very important in our daily life as their contributions and application fields are multiple and various like computers, motors, microwave ovens, etc. Besides, like other ferromagnetic materials, PM is characterised by its hysteresis loop (called also a B-H curve). Figure 1.17 illustrating two hysteresis loops of a hard and soft ferromagnetic materials highlights the difference between both kinds. Indeed, a PM which is known for its wide hysteresis loop is a *hard magnetic material* and hence has high coercivity H_c and high remanence B_r . The hysteresis Loop is a plot of the value of the magnetic field (H) that is applied against the resultant flux density (B) achieved of the material as it is successively magnetized to saturation, demagnetized, magnetized in the opposite direction and finally remagnetized. This plot becomes a closed loop with continued recycles fully describing the characteristics of a certain magnetic material thanks to its size and shape.



FIGURE 1.17: Example figures of a hard magnetic material, to the left, and a soft magnetic material, to the right [58]

The key to evaluate PMs is the portion of its hysteresis loop located in the upper left-hand quadrant, called *the demagnetization curve* shown in Figure 1.18. The whole analysis of this diagram is detailed in the book *"Permanent magnet motor technology"* of Gieras et al. [57].



FIGURE 1.18: Demagnetization curve, recoil loop, energy of a PM, and recoil magnetic permeability [57]

The general relationship between the magnetic flux density B, intrinsic magnetization B_i (the result of the presence of ferromagnetic material) and

magnetic field intensity H is expressed as [59, 60]:

$$B = \mu_0 H + B_i = \mu_0 (H + M) = \mu_0 (1 + \chi) = \mu_0 \mu_r H$$
(1.1)

where:

- The magnetic permeability of free space $\mu_0 = 4\pi 10^{-7} H.m^{-1}$,
- The relative magnetic permeability of ferromagnetic materials $\mu_r = 1 + \chi \gg 1$,
- The magnetization vector \vec{M} is proportional to the magnetic susceptibility χ of the material,
- The flux density μ₀H would be present if the ferromagnetic core was not in place,
- The flux density *B_i* is the contribution of the ferromagnetic core.

Once an external field H_a is applied to a PM, the resultant magnetic field H is:

$$H = H_a + H_d \tag{1.2}$$

where H_d is a potential that exists between the poles and is proportional to the intrinsic magnetization B_i . In fact, in a closed magnetic circuit, the magnetic field intensity which results from the intrinsic magnetization is $H_d = 0$. It is written in this way if the PM is removed from the magnet circuit:

$$H_d = -\frac{M_b B_i}{\mu_0} \tag{1.3}$$

where M_b is the coefficient of demagnetization dependent on geometry. Replacing B_i by $B_d - \mu_0 H_d$ in Equation 1.3, the relationship between magnetic flux density B_d , the self-demagnetizing field H_d and the magnet geometry is [60]:

$$\frac{B_d}{\mu_0 H_d} = 1 - \frac{1}{M_b}$$
(1.4)

PMs are characterized by many parameters. In order to deal with this thematic, a theoretical background is acquired.

• Saturation magnetic flux density B_{sat} and corresponding saturation magnetic field intensity H_{sat} :

The alignment of the magnetic moments of domains is in the direction of the external applied magnetic field at this point.

• Remanence or remanent magnetic flux density B_r :

It is the magnetic flux density when magnetic field intensity is equal to zero (H=0). High remanence means that the magnet is capable to support higher magnetic flux density in the air gap of the magnetic circuit.

• Coercivity or coercive field strength *H_c* :

It is the value of demagnetizing field intensity required to bring the magnetic flux density to zero in a previously magnetized material (the magnetization is symmetric and cyclic). High coercivity means that a thinner magnet can be used to support the demagnetization field.

• Intrinsic demagnetization curve : (see Figure 1.19)

It is the part of the $B_i = f(H)$ curve located in the upper left-hand quadrant where $B_i = B - \mu_0 H$ (Equation 1.1). For H = 0, the intrinsic magnetic flux density $B_i = B_r$.

• Intrinsic coercivity *H*_{*ic*} :

It is the magnetic field strength necessary to bring to zero the intrinsic magnetic flux density B_i of a magnetic material characterized by its $B_i = f(H)$ (H_c for $B_i = 0$). In the case of PMs, $H_{ic} \succ H_c$.

Recoil magnetic permeability µ_{rec}:

It is the ratio of the magnetic flux density to magnetic field intensity at any point on the demagnetization curve.

$$\mu_{rec} = \mu_0.\mu_{rrec} = \frac{\Delta B}{\Delta H} \tag{1.5}$$

where the relative recoil magnetic permeability $\mu_{rrec} = 1...3.5$.

• Maximum magnetic energy $(B.H)_{max}$:

It is the maximum magnetic energy produced by a PM is equal to the maximum magnetic energy density per volume:

$$w_{\rm max} = \frac{(B.H)_{\rm max}}{2} J.m^{-3} \tag{1.6}$$

where the product $(B.H)_{\text{max}}$ corresponds to the maximum energy density point on the demagnetization curve with coordinates B_{max} and H_{max} .

• Form factor of the demagnetization curve :

It characterizes the concave shape of the demagnetization curve.

$$\gamma = \frac{(B.H)_{\max}}{B_r.H_c} = \frac{B_{\max}.H_{\max}}{B_r.H_c}$$
(1.7)



FIGURE 1.19: Comparison of B - H and $B_i - H$ demagnetization curves and their variations with the temperature for sintered N48M NdFeB PMs (Courtesy of ShinEtsu, Japan) [57]

The most relevant types of PM materials are:

- Alnicos: (Al, Ni, Co, Fe),
- **Cermaics (ferrites) :** such as Barium ferrite $BaO \times 6Fe_2O_3$ and Strontium ferrite $SrO \times 6Fe_2O_3$,

• Rare earth materials : Samarium-Cobalt *SmCo* and Neodymium-Iron-Boron *NdFeB*.

Here is a short description of the previously cited types [61]. Firstly, Alnico magnets started to be commercialized in 1930 and are still used nowadays. This material is characterized by its high magnetic remanent flux density and its low temperature coefficients. It has a maximum service temperature equal to $520^{\circ}C$. These characteristics ensure a high air-gap magnetic flux density at high magnet temperature. Nevertheless, this material has numerous drawbacks like the low coercive force and the non-linear demagnetization curve allowing an easy magnetization and demagnetization of Alnicos.

Secondly, Ceramics also called ferrites (generally $BaFe_2O_3$ or $SrFe_2O_3$) started to be commercialized in 1950s and are still very popular due to their low cost. Compared to Alnico, Ceramic has a higher coercive force but a lower remanent magnetic flux density. Its maximum service temperature is $400^{\circ}C$ and has high temperature coefficients. Ferrites are known for these advantages: their low cost and their very high electric resistance, meaning the absence of eddy-current losses in the PM volume.

Thirdly, rare-earth materials are the most recent among three types. In fact, during the last three decades, the development of rare-earth PMs has ensured an important progress of the available energy density $(B.H)_{\text{max}}$. SmCo and NdFeB can be cited as rare-earth PMs as both of them are composed of rare-earth group of elements. From one hand, Samarium-Cobalt (SmCo) has multiple characteristics such as high energy product, high remanent magnetic flux density, high coercive force, linear demagnetization curve and low temperature coefficient. The range of its maximum service temperature is between $300^{\circ}C$ and $350^{\circ}C$. It has only one disadvantage which is its high cost resulting from supply restrictions of Sm and Co. From the other hand, Neodymium Iron Boron (general composition $Nd_2Fe_{14}B$, abbreviated NdFeB) is considered as the most recent PM material in the commerce. Indeed, it has the best properties compared to all PM materials at room temperature. Its maximum service temperature is $250^{\circ}C$ and its Curie temperature is $350^{\circ}C$. Moreover, the demagnetization temperature, which curves depend strongly on constitutes а magnetic-thermal coupling between the coercive force from one side and the temperature from the other side. Besides, the latest grades of this modern PM material offer higher remanent magnetic flux density and better thermal stability. The applications are wide and varied since rare-earth PMs are used in acoustic devices and magneto-mechanical devices (magnetic bearings, holding devices...). However, the major area of application remains *the electrical machines industry*.

To conclude, there are different obvious advantages of NdFeB PMs making them the most powerful PM materials commercially available [62] :

- High maximum energy product (*B*.*H*)_{max},
- High remanent magnetic flux density *B_r*,
- High coercive force *H*_c,
- Very high strength is spite of the small size of PMs,
- Low cost,
- Linear demagnetization curve,
- Ability to replace SmCo magnets in almost all cases especially when the operating temperature does not exceed 80°*C*,
- Possibility to be found in small sizes and different shapes (see Figure 1.20).



FIGURE 1.20: Different shapes of permanent magnets [61]

In general, the behaviour of some characteristics of PMs with linear demagnetization curve such as NdFeB atr room temperature is described here:

• The coercivity :

$$H_c = \frac{B_r}{\mu_0 \mu_{rrec}} \tag{1.8}$$

• The magnetic flux density produced in the air gap :

$$B_g \approx \frac{B_r}{1 + \mu_{rrec}g/h_{PM}} \tag{1.9}$$

where g is the air gap thickness and h_{PM} is the PM height.

The Ampère's circuital law for a simple PM circuit with rectangular cross section that consists of a PM with height per pole *h*_{PM}, width *w*_{PM} and *l*_{PM}, two mild steel yokes with average length 2*l*_{Fe} and an air gap thickness *g*:

$$2H_{PM}h_{PM} = H_gg + 2H_{Fe}l_{Fe} = H_gg\left(1 + \frac{2H_{Fe}l_{Fe}}{H_gg}\right)$$
(1.10)

where H_{g} , H_{Fe} and H_{PM} are the magnetic field intensities in the air gap, the mild steel yoke and the PM respectively.

• The magnetic flux balance equation :

$$\frac{V_{PM}}{2h_{PM}}\frac{1}{\sigma_{l_PM}}B_{PM} = \mu_0 H_g \frac{V_g}{g}$$
(1.11)

where $V_g = S_g g$ and $V_{PM} = 2h_{PM}S_{PM}$ are the volumes of the air gap and the PM respectively and σ_{l_PM} is the coefficient of leakage flux of the PM. (The fringing flux in the air gap is neglected).

• The air gap magnetic flux density :

$$H_{g} = \sqrt{\frac{1}{\mu_{0}} \frac{1}{\sigma_{l_{PM}}} \left(1 + \frac{2H_{Fe}l_{Fe}}{H_{g}g}\right)^{-1} \frac{V_{PM}}{V_{g}} B_{PM} H_{PM}}$$

$$\approx \sqrt{\frac{1}{\mu_{0}} \frac{V_{PM}}{V_{g}} B_{PM} H_{PM}}$$
(1.12)

Hence, the magnetic field strength of a PM circuit H_g in an air gap volume V_g is proportional to the square of the energy product $B_{PM}H_{PM}$ and the PM volume $V_PM = 2h_PMw_PMl_PM$.

b. Temperature dependence of permanent magnets

Despite their undeniable several key advantages, PM materials may present the risk of loosing their magnetic properties once they are heated to a certain temperature. Since PMs are often used in motors and generators, an overload or a short circuit can cause irreversible demagnetization because of temperature rise and magnetic field change. Hence, it is really important to evaluate demagnetization behaviour in order to make the right choice of PMs according to their properties and their ability to withstand demagnetization.

Under specific conditions such as armature reaction field and temperature rise, the PM magnetic properties notice the greatest changes. In fact, a PM may loose some or all of its magnetic properties. Moreover, the energy necessary to change these properties is different from one PM type to another. The irreversible demagnetization phenomenon (see Figure 1.21) is defined as *the loss in the magnetization by which the demagnetization curve of a PM is not recovered as original one when a demagnetizing field, such as a field*

weakening flux, is removed [63]. Its process is explained here [64]. If the working point a of a PM material goes below the knee point K after an external demagnetization field H_a is applied or under specific conditions such as temperature rise, even if H_a is reduced or removed, the working point does not belong anymore to the original B-H curve but it will lie along the recoil line L_a . The PM works along the recoil line L_a until a greater external demagnetization field H_b is applied. Hence, a new lower knee point b linked to a new recoil line L_b are established. Consequently, the part of the original demagnetization curve below b is cancelled as it is shown in Figure 1.21 by the dash lines.



FIGURE 1.21: Irreversible demagnetization due to working point below knee point [64]

In fact, demagnetization curves are sensitive to temperature as it is illustrated in Figure 1.22. Hence, there is a magnetic-thermal coupling between the remanence B_r and the coercivity H_c as magnetic properties and the functioning temperature. Indeed, both B_r and H_c decrease while the PM temperature increases [57, 61].

$$B_r = B_{r_{20}} \left[1 + \frac{\alpha_B}{100} (T_{PM} - 20) \right]$$
(1.13)

$$H_c = H_{c_{20}} \left[1 + \frac{\alpha_H}{100} (T_{PM} - 20) \right]$$
(1.14)

where:

- $B_{r_{20}}$ is the remanent magnetic flux density at $20^{\circ}C$,
- $H_{c_{20}}$ is the coercive force at $20^{\circ}C$,
- $\alpha_B \prec 0$ is the temperature coefficient for B_r in $[\%/^{\circ}C]$,
- $\alpha_H \prec 0$ is the temperature coefficient for H_c in $[\%/^{\circ}C]$,
- T_{PM} is the PM temperature.



The demagnetization models are multiple: linear models [65], hysteresis models [66, 67], parametric models [68], FE models [66, 69] or models based on single valued non-linear demagnetisation curves [70]. Some of these techniques are discussed below. Kang et al. [65] used a two-dimensional finite-element method (2D FEM) to analyse the irreversible demagnetization of ferrite PMs in a line-start synchronous motor by determining the worst load condition and applying it to the irreversible demagnetization. Indeed, they gathered various parameters such as the demagnetizing currents calculated from the transient analysis combination of voltage and mechanical dynamic equations, the peak currents and the

non-linear effect of the magnetic core. It is clear that this approach did not take into account the impact of demagnetization on circuit-based solutions. Hence, a disagreement between the worst working point found throughout this methodology and the true operating condition may be observed. The classical Preisach hysteresis approach was used by Rosu et al. [66] in modelling demagnetization aiming at studying the states of PMs in large synchronous motors during fault conditions. In 2010, Fu et al. [71] used a linear model built on normal B-H curve to model PMs' demagnetization. If this method is used, the working point of each element is required to be checked at every time step. In case that it is does not belong to the B-H curve, the remanence B_r has to be adjusted in such a manner it is back to the curve [72]. The identification of a new worst load point will definitely impact computation efficiency, modelling accuracy and convergence. These issues were not discussed by the different authors.

Both Equation 1.13 and Equation 1.14 were given directly in the book of Gieras et al. [57]. However, later on, there were further explanations about the different steps of the analytical demagnetization study and the details of the model development provided by Ruoho et al. [70], introduced a model based on an exponential function to take into consideration the temperature dependence of demagnetization. He discussed in his paper some simple demagnetization models that are quick and easy to implement for FE. In order to model the demagnetization of PMs, the relationship between B, H and M is required and is easily described throughout a B-H curve and Equation 1.15 which was already provided by Equation 1.1:

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \tag{1.15}$$

The hysteresis loop is able to be modelled with an analytic function:

$$\mathbf{B} = B_r + \mu_0 \mu_r \mathbf{H} + E e^{K_1 (K_2 + \mathbf{H})}$$
(1.16)

where E is a unit conversion factor equal to 1T. The parameter K_2 is calculated in this way :

$$K_2 = \frac{\ln\left[(B_r + (\mu_r - 1).\mu_0.H_{ic}).E^{-1}\right]}{K_1} - H_{ic}$$
(1.17)

The K_1 parameter is responsible for the shape of the knee point in the hysteresis loop. If a bigger value is used, the knee becomes sharper. A good agreement is found for multiple NdFeB PMs grades with a value of K_1 equal to $-1, 5.10^{-4} m/A$.

It is clear that the only material parameters required for the approximation of the B-H curve are the remanence and the coercivity. Since PM manufacturers usually provide the temperature coefficients α_B and α_H , it is possible to reproduce a B-H curve at any temperature by following both 1.13 and 1.14 equations.

In the same paper, Ruoho et al. [70] studied the temperature dependence of magnetic properties which are the remanence and the intrinsic coercivity. In fact, the remanence is not all linear in the range below Curie temperature T_c [73]. Because of this non-linearity, some manufacturers provide a temperature coefficient for each temperature range. Indeed, the authors made measurements on a NdFeB sample at different temperatures between room temperature and $120^{\circ}C$ (see Figure 1.23). For the remanence, there were average differences equal to 0,4% between the measured data points and the fitted first-order polynomial and second and equal to 0,2%between the measured data points and the fitted second-order polynomial. Therefore, it was concluded that for the whole measured temperature range it is convenient to use the first-order approximation for remanence temperature dependence. They expected also the linear temperature behaviour for higher temperatures but under $200^{\circ}C$. For the intrinsic coercivity, it is clear that its temperature dependence is linear.



FIGURE 1.23: Remanence (crosses) and intrinsic coercivity (circles) of NdFeB sample as a function of temperature [70]

In 2012, Zhou et al. [64], who noticed multiple shortages in the demagnetization models found in the literature, published a paper presenting an improved linear model handling at the same time the demagnetization curve and the temperature dependence of demagnetization behaviours. They proposed an algorithm that identifies a new worst working point from time to time throughout the transient solution process in case there is a working point below the knee point of the current recoil line. Here is a description of their temperature-dependent demagnetization model. Knowing that demagnetization curves present a high sensitivity to temperature, they consider that the first step is to describe the demagnetization curve by a function gathering two temperature depending parameters. These parameters are associated with $B_i - H$ curve included in the datasheets provided by the suppliers. [64] preferred working directly on intrinsic curve $B_i - H$ instead of B - H curve. They started with this equality found in Equation 1.1.

$$B = B_i + \mu_0 H \tag{1.18}$$

Then, they ensured that the parameters mentioned earlier are effectively B_r and H_ic and described them using arbitrary functions which use generally second order polynomial:

$$B_r(T) = B_r(T_0)(1 + \alpha_1(T - T_0) + \alpha_2(T - T_0)^2)$$

= $B_r(T_0)P(T)$ (1.19)

$$H_{ic}(T) = H_{ic}(T_0)(1 + \beta_1(T - T_0) + \beta_2(T - T_0)^2)$$

= $H_{ic}(T_0)Q(T)$ (1.20)

where T_0 is the reference temperature, α_1 , α_2 , β_1 and β_2 are coefficients provided by manufacturer datasheets.

According to Harrison [74], the $B_i - H$ curve can be described up to H_ic by this hyperbolic tangent function:

$$B_{i}(H,T) = P(T) \left(b_{0} \tanh\left(\frac{H + Q(T)H_{ic}(T_{0})}{Q(T)h_{0}}\right) + b_{1} \tanh\left(\frac{H + Q(T)H_{ic}(T_{0})}{Q(T)h_{1}}\right) \right)$$
(1.21)

where P(T) and Q(T) were already defined in equations 1.19 and 1.20. Therefore, the coefficients b_0 , h_0 , b_1 and h_1 are identified by a non-linear curve fitting relying on the input of the $B_i - H$ curve at T_0 .

A simple verification demonstrates that Equation 1.21 satisfies the constraint provided by Equation 1.19.

$$B_i(0,T) = B_r(T)$$
 (1.22)

Thanks to this model, any $B_i - H$ can be constructed at a reference temperature T_0 . Added to this, the B - H curve in the second and third quadrants can be obtained via Equation 1.18.

Furthermore, one other magnetic parameter can be found thanks to equations 1.18 and 1.21 which is the magnetic permeability of the recoil line for a reference temperature T_0 .

$$\mu(T_0) = \frac{\partial B(H, T_0)}{\partial H}\Big|_{H=0}$$

= $\frac{\partial B_i(H, T_0)}{\partial H}\Big|_{H=0} + \mu_0$ (1.23)
= $\mu_i(T_0) + \mu_0$

Thus, the magnetic permeability of the recoil line for any temperature is written in this way:

$$\mu(T) = \frac{\partial B_i(H,T)}{\partial H} \Big|_{H=0} + \mu_0$$

$$= \frac{P(T)}{Q(T)} \mu_i(T_0) + \mu_0$$
(1.24)

Finally, the temperature dependent model is validated using a N4517 NdFeB PM. A comparison between the $B_i - H$ and B - H curves provided by the supplier datasheets and the ones obtained by applying the model (see shows a good agreement between them for the different temperatures (from $20^{\circ}C$ to $120^{\circ}C$).



FIGURE 1.24: Comparison between $B_i - H$ and B - H curves. (a) Provided by supplier datasheet. (b) Obtained by applying the proposed temperature dependent demagnetization model $(\alpha_1 = -0, 1, \alpha_2 = 0, \beta_1 = -0, 6 \text{ and } \beta_2 = 0)$ [64]

In summary, PM materials especially NdFeB have various and important applications such as motors, generators and sensors. They are known for their high remanence and coercivity and energy product. Moreover, they are very sensitive to temperature: many models provided by literature have been detailed here.

1.4 Conclusion

On the one hand, the mechatronic system design requires a concurrent life-cycle that ensures the collaboration between the different actors. Indeed, the common SysML language combined with an MBSE approach is able to support the conceptual design phase within an interdisciplinary environment to provide a selected architecture that fulfils the customers' requirements and includes geometrical and multi-physical (magnetic, electric, mechanic, etc.) performances thanks to the use of UML profiles/SysML extensions. In summary, the different types of life-cycles are described and the research works (metrics and simulations) related to the assessment of 3D architecture in the conceptual design are detailed.

On the other hand, since we focus on the magnetic-thermal coupling in permanent magnet materials, a general description of coupling and its different types and application fields is firstly presented. Secondly, the temperature dependence of the various parameters of permanent magnets is highlighted and many models are detailed. Furthermore, the theoretical background of the demagnetization of permanent magnets show a thermal-magnetic coupling. Indeed, the remanent magnetic flux density and the coercive field strength decrease while the temperature of the permanent magnets rises.

Chapter 2

Selection of multi-physical architecture generation approach

2.1 Introduction

The chapter 2 begins with defining the numerous industrial requirements. Firstly, it provides an overview of the conceptual design phase used usually in the system design process. Secondly, it proposes three different approaches that allow the system architecture selection under geometrical and multi-physical requirements since this deign step while enabling the effective collaboration between all the teams and hence the decrease of costs and design time caused by the late changes in the next modelling stages. Once described and compared, only one approach called SAMOS (Spatial Architecture based on Multi-physics and Organization of Systems) is retained because of the multiple advantages that it offers. [75] Thirdly, a detailed description and an implementation process of this platform are provided. Moreover, both geometrical and multi-physical extensions present in SAMOS are highlighted since they ensure the integration of these requirements in SysML. The different links between the SysML language, the 3D CAD tool and Modelica are detailed during all the process. An enrichment of the Modelica libraries with the thermal-magnetic coupling equation would be an advantage for the users working on multi-physical modelling and simulation.

2.2 Industrial requirements

Once the customers' needs are analysed, the first step consists in generating the requirements specification. Based on these requirements, the System Architects (SAs) provide a functional and logical system architecture after defining the concept, setting the performance objectives and performing the functional analysis. Then, they propose a physical architecture alternative to be assessed. Moreover, the Geometers (Gs) allocate an initial position and a volume for each component in the system.

Finally, the Simulation Teams (STs) gathering experts from different disciplines (mechanics, electronics, control, etc) verify the physical architecture through general analytical simulations. According to the simulations' results, SAs validate or not the physical architecture. In case some of the requirements are not satisfied, SAs propose an other physical architecture alternative. Hence, the iterative long and costly process is repeated until it converges to a convenient satisfactory architecture.

Therefore, the conceptual design has an important role in the system design since the selected 3D architecture responding to the "high level" requirements would be the basis of the work for different engineering teams during all the next design steps [76].

The industry field has lately known a tough competition between companies since all of them try more than ever to renovate their products and give to their clients the best of technology. Indeed, this has lead to a fast growing complexity of the produced systems and therefore higher costs and longer design time. In fact, the different engineering teams spend a lot of time during the embodiment and detailed design phases on long iterations and simulations of the physical behaviours affecting the systems.

Thus, the aim of the companies is to ensure not only, an interaction between different domains, disciplines and physics, but also a collaboration between all engineering teams while decreasing design time and consequently design costs. Hence, a MBSE approach seems necessary to meet these multiple purposes.

2.3 Conceptual design phase

2.3.1 General presentation

According to Guideline VDI 2221 [77], the design cycle consists in four main phases: the clarification of the task, the conceptual design, the embodiment design and the detailed design. The conceptual design phase also called *"Concept Development"* is decisive since the simulation teams (STs) pre-validate quickly the spatial architecture provided by the system architects (SAs).

It consists of three different parts shown and detailed in Table 2.1 :

- Needs analysis
- Concept exploration

• Concept definition

TABLE 2.1: Main parts of the conceptual design phase [78]

Step	Concept development		
	Needs analysis	Concept exploration	Concept definition
Requirements analysis	Analyze needs	Analyze operational requirements	Analyze performance requirements
Functional definition	Define system objectives	Define subsystem functions	Develop functional architecture component functions
Physical definition	Define system capabilities; visualize subsystems, ID technology	Define system concepts, visualize components	Develop physical architecture components
Design validation	Validate needs and feasibility	Validate operational requirements	Evaluate system capabilities

The different actors in the conceptual design are:

• System Architects (SAs) :

System Architects (SAs) are system engineers. Although system engineers focus on the whole system product in the different stages of the design life-cycle and work with the multiple technical teams, the most important role of the SAs is to develop the system architecture. In fact, they firstly design the initial system architecture after defining the concept, setting the performance objectives and performing the functional analysis. Secondly, they validate it based on the simulation realized by the simulation teams. In general, SAs have various activities such as data processing, meetings and discussions where they use different tools and methods to achieve them efficiently and to deal with complex systems (see Figure 2.1). Moreover, they ensure the collaboration and communication between the different teams working on the project. One of their major responsibilities is to divide systems into subsystems and subsystems into modules. Added to this, the SAs have to ensure a consistent design during the preliminary design stage [79]. If a parameter changes, they guarantee that the design parameters meet the customers' specifications and maintain the performances.

In summary, the role accomplished during the preliminary design by the SAs is crucial since the selected architecture following the "highlevel" goals would be the basis of the project for all the next design phases [76].



FIGURE 2.1: Activities of System Architects [79]

• Simulation Architects :

The simulations architects play the role at the interface between the systems architects and the simulation teams. In fact, they have to collaborate with both of teams. They specify to the simulation teams scenarios including the the simulation alternative physical architectures and the system's requirements provided by the SAs added to various geometrical constraints. Moreover, they, not only, assist the SAs when they select the most convenient architecture, but also, provide the simulation teams with a detailed description of the simulations to be carried out ensuring the adaptation between the simulation and the requirements. Therefore, the SAs validate or not an alternative architecture resulting from the simulation teams realized by the simulation teams and validated by the simulation architects.

• Simulation teams (STs) :

The Simulation Teams (STs) consist of groups of experts in different disciplines and physics (magnetics, mechanics, hardware/software, etc.). They have the responsibility of verifying by means of physical simulations that the behaviour of physical the architecture fulfils the spatial requirements and meets the performances.

• 3D architects :

The 3D architects provide the space allocation and the initial 3D architecture of the system's components according to the physical

architecture and the 3D design thanks to their expertise. They examine indeed the constraints of other disciplines and thus opt for the space allocation in the meetings with the different teams.

It is clear that the work environment is interdisciplinary and multi-physical. In fact, Kvan [80] proposed two collaboration processes : a close coupled design process and a loosely coupled design process which consists of both supervised and unsupervised processes. For every process, a technical solution is provided aiming at studying the data interoperability problem.

2.3.2 UML profiles/SysML extensions

Based on the SE approach (Figure 1.8) and the linked MBSE processes basically based on SysML, the aim of system-level modelling is to analyse the customers' needs and provide technical requirements [29, 81]. In order to respond to all these requirements, the geometrical and physical information should be taken into consideration in order to generate various possible physical architectures. In fact, a prevalent way is to use UML profiles or SysML extensions to enrich the system modelling. Some key definitions are provided here. According to Alhir [82], an UML profile provides a generic extension mechanism for customizing UML models for particular domains and platforms and extension mechanisms allow refining standard semantics in strictly additive manner, preventing them from contradicting standard semantics. Indeed, profiles are defined using stereotypes, tag definitions and constraints that are applied to specific model elements (meta-class), like Classes, Attributes, Operations and Activities. Moreover, a profile is a collection of such extensions that gathered together customize UML for one domain or platform. For Friedenthal et al. [32], a meta-class makes the description of the individual concepts of languages. Finally, the stereotypes allow designers to extend the UML vocabulary by giving to existing modelling elements (meta-class) specific properties that are suitable for a particular domain.

Some research works focused on the introduction of geometrical constraints since the first steps of design for a MBSE approach. In fact,

Baysal et al. [83] introduced a method for geometrical modelling and positioning linked to the tolerance analysis in SysML. However, the proposed positioning was not relative and did not integrate directly any constraint. Hence, this made the calculation of general positioning harder for designers. Besides, Albers et al. proposed the Contact & Channel-Approach [84] to build Contact & Channel-Models [85] through a SysML extension [86]. The provided modelling defined Working Surface Pairs as interface surfaces connected by physical components or volumes of liquid, gases or spaces, named Channel and Support Structures. Since their purpose was to represent engineering artefacts while taking into consideration physical flows between different components, their manner of modelling geometry was only based on the working interacting surfaces and did not enable to generate the whole components' volume and their relative positioning constraints. Moreover, Bohnke et al. [87] proposed an UML profile defining the 3D geometry of components, but without managing their assembly constraints. Indeed, the importation of geometries resulting from CATIA V5 designs in UML was not an efficient method as it did not allow the SAs to specify the geometrical parameters. They just linked the sections already represented by points and generated components' volumes. Hence, this method was not useful for conceptual design because it was more convenient for complex detailed geometries. At last, Warniez et al. [88] proposed a geometrical SysML extension including a library of simplified geometrical volumes in order to define physical integration metrics. Otherwise, neither the relative positioning between components nor the addition of a new geometry were managed by this extension.

In order to ensure the link between SysML/UML, simulation and 3D models, multiple profiles were already developed. There are two famous profiles linked with simulation which are: the SysML4Modelica extension [89, 90] and the ModelicaML UML profile [91, 92]. Because ModelicaML provided an UML environment to develop Modelica modelling which was not adapted for SAs as it was necessary to write the code required to perform a simulation in a Modelica environment, Schamai et al. [92] introduced SysML4Modelica, a SysML extension designed by artefacts where Modelica code was automatically generated from a diagram in SysML and did not have to be written directly in SysML. Nevertheless, SysML4Modelica did not include the definition of the components'

geometries required by STs in spite of its necessity to generate a 3D architecture.

Despite the advances made by UML profiles and SysML extensions, they did not include stereotypes for physics based on geometrical considerations. Moreover, a non-linked additional system view to the other modelling artefacts was proposed by many of these models. In summary, they are adequate to trace simulation data but not to specify them.

2.3.3 Integration of geometry

It is important to note that the sketches are required by the designers to have a preliminary vision of the system's geometry before using 3D CAD tools [93]. Even though they are used mostly for the detailed design, some of them were developed especially for the conceptual design stage such as the open VSP software used by Hahn [94] to design aircraft along this phase. This software is more convenient for 3D designers to visualize the system shape than for SAs who deal with components' pre-positioning since the Open VSP only provided the exterior surfaces.

Whereas different research works were interested by the integration of the geometrical data in the conceptual design and showed its importance for tolerancing [95], process planning [96] and assembly [97], a few number of them tried to implement them in the SE approach in order to evaluate the architecture.

2.3.4 3D physical architecture assessment

Once the customer requirements are translated into technical specifications and before moving to more detailed and more expensive analyses, the SAs evaluate different alternative architectures aiming at selecting the one corresponding to the customers' specifications. Thus, it is necessary to determine quantitatively the design parameters that meet the required performances by performing various initial physical behaviour simulations. Knowing that the physical behaviour is based on the orientation the distance between the components and the dimensional data, it is required to take geometry into consideration since the beginning of the design life cycle.

In order to evaluate 3D physical architectures, two approaches are mainly used : metrics and simulations.

• Metrics :

There are different models that can be mentioned. For eg., Warniez et al. [88] proposed the use of metrics in order to evaluate the physical integration of mechatronic systems. Based on alternative physical architectures in SysML, their metrics took only into consideration the component geometry to increase or decrease the space between components but clearly examined neither the relative components' positions nor their physical behaviour.

Other models were developed to fulfil assembly design objectives such as the model provided by Simpson et al. [98] using Design For Assembly (DFA) analysis to develop a cost metric depending on 3D architecture.

Moreover, Moullec et al. [99] developed metrics based on the components' positioning by generating an automatic generation of the 3D architecture throughout Bayesian networks and constraint satisfaction problem approach. In spite of its interesting 3D architecture automation, there were some faced problems such as the component geometry limited to a parallelepiped and its orientation limited to six positions. Besides, it was required to know all the geometrical specifications which were mostly unavailable at the design first steps.

• Simulations :

Different studies were made in order to evaluate a 3D physical architecture by simulating the physical behaviour utilizing the geometrical parameters provided by components. In fact, Qin et al. [100] presented a web-based framework to share and simulate the dynamic behaviour of a 3D conceptual architecture. Each component had a simplified representation of geometry while its position was calculated under various relative positioning constraints. Then, an external simulation tool calculated the relative orientation and positioning parameters that were not imposed by geometrical constraints. Hence, this process was useful as it proposed the verification of the dynamic components' positioning since the conceptual design. Nevertheless, the geometrical and physical modelling had to be programmed in JavaScript and only the kinematic movements were simulated.

Moreover, Komoto et al. [101] proposed a framework called System Architecting CAD (SA-CAD) including a geometric modeller for visualization, based on a Functional Behaviour Structure (FBS) framework. Firstly, they added the 3D modelling phase after the functional modelling. Secondly, they verified the requirements via the combined functional and geometrical parameters. The main obstacle was that all the relations had to be manually implemented without a solver; which made this method very long especially for a complex system.

According to Plateaux et al. [102], the paradigm "physics in geometry" would be more efficient that the common one "geometry in physics". Contrarily to usual simulation tools proposed a 2D object model hiding 3D geometrical parameters in the components, the authors represented the physical modelling in 3D in order to enrich the model with multiphysical constraints in an easy way. Hence, this paradigm allowed the geometrical objects to integrate their physical behaviour.

In summary, the conceptual design phase is a major phase in the MBSE context. Once geometrical and physical modelling is integrated through UML profiles/SysML extensions, the different actors collaborate together within an interdisciplinary environment in order to provide a system architecture enriched with geometrical and physical specifications that answers to customers' requirements and meets the performances.

2.4 Different approaches for concepts assessment with geometrical and physical constraints

As it was described in section 2.3, the traditional methodologies used in the conceptual design phase don't satisfy the high expectations of industrials. In this section, three different approaches are proposed aiming at exchanging suitable models between the engineering teams. Moreover, preventing the risks of late changes throughout including the multi-physical simulations taking place traditionally in the embodiment design phase in the conceptual design would make the physical architecture assessment more efficient. Therefore, not only, the components will have a simplified geometry, but also, the simulations will be analytical to satisfy the requirements of the conceptual design phase.

2.4.1 First approach

The first approach shown in Figure 2.2 proposes a platform based on a multi-physical architecture with facilitated interactions between the different actors.



FIGURE 2.2: Description of the first approach of 3D architecture generation

The process in described here. Firstly, SAs generate a potential architecture. which. Then, a System-3D model transformation transforms this architecture from a System model to a 3D model in order to ensure the volume allocation for each component by Gs. Indeed, Gs take into account all the geometrical requirements such as the form, the volume and the position of all the system components. Secondly, another transformation called M2M (Model to Model) has place ensuring the obtaining of a simulation model from the 3D model. In fact, this transformation is necessary to STs to make analytical simulations based on the multi-physical requirements. Thanks to the simulation results, STs can verify if the system architecture answers the different requirements or not. In this case, STs ask Gs to modify their spatial allocation or components' geometries or positions. Hence, the iterations can be long especially when realizing all the analytical multiphysical simulations each time. If the problem is not resolved where none of the proposed spatial allocation meets the physical requirements, SAs propose a new physical architecture. Then, the whole iterative process described earlier is repeated leading to time and cost losses.
Contrarily to traditional methods, the first approach provides an interactive support that gathers the different design information and facilitates the automatic exchange in real time between SAs, Gs and STs. Besides, it improves the design consistency thanks to the model transformation used in two different times in the process (between System model and 3D model and between 3D model and simulation model). However, this approach remains costly and time-consuming and the traceability is not ensured either.

Hence, a new approach reducing iterations and ensuring traceability is required.

2.4.2 Second approach

In order to ensure traceability, the second approach suggests to enrich System model with geometrical and multi-physical semantics.



architecture generation

Thanks to the enrichments made throughout System model geometrical and multi-physical semantics, the SAs are able to generate architectures with geometrical and multiphysical requirements since the beginning of the process. Then, a model transformation ensures a 3D element for each component integrating geometrical requirements. Moreover, the Gs finalize the spatial allocation in a 3D environment. After this, the reverse model transformation from the 3D model to the System model takes place and ensures the enrichment of the System model with geometrical information. This geometry-enriched architecture and the multi-physical requirements go once again through a model transformation in order to allow STs to make some multi-physical simulations. When the results are obtained, another model transformation takes place and the multiphysically-enriched 3D architecture is traced back to the System model to the SAs. If the results are satisfactory, the SAs validate the architecture. Otherwise, they have to decide whether to propose another physical architecture or to ask Gs to suggest another possible 3D architecture. The process is repeated until an enriched architecture meets the geometrical and multi-physical requirements.

It is clear that the second approach has an important advantage as Gs and STs can verify if the enriched 3D architecture fulfils all the geometrical and multiphysical requirements before making the model transformation back to SAs. Besides, the semantic geometrical and multiphysical enrichments ensure the traceability as SAs benefit from a single model where all the necessary information have place. The bidirectional model transformations used several times in this process are known to be quick too. In spite of all these benefits, this approach is not the most efficient as SA's intervention is required at each architecture modification. In fact, there is no real interaction between Gs and STs since the access to the design information is provided only via the System model. Hence, a third approach is proposed to solve this problem.

2.4.3 Third approach

In order to ensure the interaction between the Gs and the STs, the third approach presented in Figure 2.4 proposes to incorporate both of their missions in the same 3D multiphysical modeller environment.



IGURE 2.4: Description of the third approach of 3D architecture generation

The process is described here. Firstly, the SAs generate the physical architecture and the geometrical and multi-physical requirements which are automatically transferred into a 3D and simulation model using model transformations. Secondly, in the same 3D multi-physical modeller environment, the Gs make an initial volume allocation for the different components according to the previously specified geometrical requirements. Once a 3D architecture is convenient, the STs add the multi-physical requirements ensuring the physical modelling of the 3D proposed architecture. Indeed, they take into account different disciplines such as electromagnetics, mechanics and vibrations. Then, they make the necessary simulations in order to consider the impacts of the various physics on the provided architecture. If the results are satisfactory, the 3D architecture is traced back to the SAs through the reverse model transformation in the System model. Otherwise, the Gs collaborate with the STs to propose an other 3D architecture in order to meet the unsatisfactory constraints. Finally, if the Gs are not able to find a 3D architecture meeting the different requirements given by the SAs, the SAs are asked to modify the suggested

physical architecture.

Therefore, this platform called SAMOS (Spatial Architecture based on Multi-physics and Organization of Systems) allows the integration of the tasks realized by the Gs and the STs in the same environment in order to remove the need for two model transformations between their different environments. Moreover, it ensures the direct collaboration between the Gs ans the STs without needing the intervention of the SAs. Thus, SAMOS enables the decrease of time and costs resulting from long iterations.

To summarize, the most relevant advantages of this approach are:

- Only one physical 3D modeller environment that facilitates the collaboration between the Gs and the STs in order to quickly evaluate the 3D physical architecture without SAs' contribution.
- The unique bidirectional model transformation between the system model and the 3D and simulation model that allow both consistency and traceability of design models.
- The decrease of time spent on long iterations and hence design time.
- The reduction of costs.

Compared to both previous suggested approaches, SAMOS satisfies the different requirements. In fact, it ensures:

- 3D architecture assessment according to geometrical and multi-physical requirements,
- Data consistency,
- Traceability,
- Easy interactions between the different teams,
- Quick execution,

• Easy integration in the industrial design process.

Therefore, SAMOS framework has been selected to assess 3D architecture under geometrical and multiphysical constraints.

2.5 Implementation of the SAMOS framework

In order to ensure the implementation of the SAMOS process shown in Figure 2.5, multiple requirements linked to geometrical, multi-physical and 3D modelling have to be met. Moreover, the selection of the system modelling language and the model transformation process are based on other requirements explained in the paragraph below.



FIGURE 2.5: Implementation of the SAMOS platform

2.5.1 Selection of the system modelling language

Despite the unpopularity of SysML in the industry field, this language is, not only, well adapted for SE applications since SAs usually use it for MBSE approaches but also meets the different system modelling requirements to support SAMOS. In fact, it is able to:

- Include system geometrical and multi-physical enrichments by using extensions ⇒ Semantic enrichment
- Define semantic fields via stereotyped elements ⇒ Development facility
- Trace any modelling element to various requirements or allocate it to another ⇒ Traceability
- Allow data uniqueness \Rightarrow Data consistency
- Provide various graphical diagrams for user interface design ⇒ Graphical User Interface (GUI)
- Enhance the collaboration between the different engineering teams
- Ensure bidirectional model transformation
- Be easily used in the industrial design process
- Be adequate for any complex system including multi-physical couplings

As the semantic enrichment establishes one of the most important requirements to assess efficiently a 3D physical architecture, some details are provided. In fact, this requirement in SAMOS is ensured by SysML language throughout a multi-physical extension based on a geometrical extension as the physical behaviours are supposed to be relying on particular geometries of both 3D architecture components and physical phenomena.

It is true that the model transformation of the System model can be realized only throughout SysML language without the development of extensions which could complicate the transformation process. However, the tags and the stereotypes elaborated in the extensions facilitate the modelling process . Indeed, the extensions provide the different teams with the syntax elements required to establish an adequate architecture in order to create a System model functioning in the model transformation. Moreover, SAs construct a model that responds to the defined meta-model and Gs and STs add to it geometrical and multi-physical requirements and reverse the model transformation. Thus, the bidirectional transformation occurs from the System model into the 3D multi-physical model and vice versa. Consequently, the SysML enrichments of the semantics are essential to trace back all data in order to ensure efficient model transformation process.

Thus, the extensions are beneficial for the framework implementation since they allow the modification of the meta-model along the model transformation process and hence to guarantee the exchange of data between the various tools.

2.5.2 Selection of the model transformation process

Since the model transformation process is required to ensure bidirectional M2M transformation for both simplified geometry and different multi-physical phenomena while studying and analysing their equations in an acceptable short execution time, the method proposed by Kappel et al. [103] is convenient to implement the SAMOS platform. Indeed, its first phase named "Modelling" consists in developing an initial model with convenient syntax while its second phase named "Configuration & Generation" consists in creating an initial version of the transformation made thanks to the analysis of the initial and the updated models.

Hence, this approach is the most convenient as it meets the various required criteria.

2.5.3 Geometrical extension

The geometry modelling has a major place in the SAMOS framework elaboration as it affects both the system 3D architecture (components) and the multi-physical behaviours which are modelled by surface-flows. In fact, the geometrical extension ensures the model transformation between the SysML model and the 3D CAD model.

Since this work takes place in the conceptual design phase, the geometry is required to be simplified. The most convenient methodology to be used for this extension is the Technologically and Topologically Related Surfaces (TTRS) approach [104] which is a theory representing and classifying surfaces. As it is shown in TABLE 2.1, there are different TTRS classes according to the kinematic invariance degree and they are cited here: spherical, planar, cylindrical, helical, revolute, prismatic and complex. Moreover, a Minimal Reference Geometric Element (MRGE) can be associated to each TTRS. It is defined as the minimal combination of of these simple geometric objects: plane, line and point named Reduced Geometric Element (RGE). Thanks to the use of 13 constraints between two TTRSs, both positioning and orientation are ensured.

TTRS classes	Complex	Prismatic	Revolute	helicoid	cylinder	plan	spherical +
Invariance degree	0 (identity)	l translation	l rotation	l rotation & l translation combined	l rotation & l translation	1 rotation & 2 translations	3 rotations
	Point		Point	Point			Point
MGRE	Line	Line	Line	Line	Line		
	Plan	Plan				Plan	

TABLE 2.2: TTRS classes and associated MRGE

Thus, the TTRS theory has various advantages since:

• It allows the geometric modelling of the system components and the multi-physical behaviours

- It ensures the elaboration of any type of geometry no matter how complex it is.
- The GPS (Global Product Specifications) standards which build the basis of TTRS are implemented in different CAD software.

The TTRS is supported by a 3D CAD tool that especially meets the GUI (ergonomics) and is able to communicate with other tools.

2.5.4 Multi-physical extension

It is important to include the multi-physical requirements since the conceptual design phase. Since this phase does not support long FE simulations, preliminary approximate results provided by the analytical simulations are sufficient to allow the validation of the components' position and volume allocation in the 3D physical architecture. Moreover, the Modelica language is selected to make the analytical simulations since it:

- Is able to solve analytic equations
- Ensures the ease and the rapidity of development and use

Therefore, a library in Modelica containing the different analytical models dealing with multiple physics (electromagnetics, mechanics, vibrations, etc.) is essential since it would improve the process of selection and validation of the multi-physical 3D architecture. Indeed, the different engineering teams would fulfil their tasks more efficiently without additional time loss and cost rise.

The challenge is, not only, to develop an extension including the various physics, but also, to consider the couplings between them. In some applications, the physics are strongly or weakly coupled and hence should not be studied separately.

Thanks to the TTRS approach, a physical phenomenon can be modelled throughout both an emitting and a receptive devices having simplified geometries and a specific propagation mode of the physical behaviour which can be conducted or radiated. Indeed, Figure 2.6 shows a case where different devices are emitting and receiving multi-physical flows (magnetic, electric, thermal, etc). Thus, the modelling of the 3D multi-physical architecture via both a geometrical extension using TTRS approach and a multi-physical extension using analytical equations, not only represents an efficient way to have approximative physical behaviour results satisfactory for the conceptual design phase, but also ensures the avoidance of late changes in the system design caused by non-collaborative teams and inadequate simulation results in the embodiment design phase.



FIGURE 2.6: Logical scheme of the interaction between the components in the 3D multi-physical architecture

In this PhD work, a focus is made on magnetic constraints and magnetic-thermal coupling. Different studies of these phenomena are realized in chapter 3.

2.5.5 Description of the framework implementation

As it is illustrated in Figure 2.5, the framework is based on two SysML extensions ensuring the enrichment of SysML with geometrical and multi-physical semantics. In fact, the SysML language, the 3D CAD environment and the Modelica language are linked thanks to a System transformation platform in order to guarantee the different model transformation processes taking place during the multi-physical 3D sketcher as it is shown below:

- SysML geometrical extension \iff 3D CAD environment
- SysML multi-physical extension \iff 3D CAD environment
- SysML multi-physical extension ⇐⇒ Modelica language

Firstly, the SAs allocate the components of the system architecture in the SysML model. Secondly, they enrich them with the valuable geometrical information contained in the geometrical extension. Then, the geometrically-enriched System model is transformed using the System transformation platform to a 3D CAD model in the 3D CAD environment. At this stage, the Gs are able to make changes on the components' geometry and spatial allocation (such as positioning). Then, the 3D CAD model is traced back using the same transformation platform to the System model in the geometrical extension. Moreover, the SAs are able to validate or not the recent changes made on the architecture. If the updated model is not validated, the SAs return to the beginning of the process and change the geometrical requirements or the components' geometry and positioning. Otherwise, this part of the process is complete.

Secondly, the SAs precise the multi-physical requirements in the System model thanks to the multi-physical extension. Hence, the System model is transformed using the model transformation platform to a Modelica model in Modelica language. Moreover, the STs make analytical simulations. Indeed, the Modelica tool gathers different models of multiple physics. Since the SysML geometrical extension is included in the SysML multi-physical extension, all the steps described earlier are repeated. Regarding the Modelica tool, it represents a library of multi-physical analytical models allowing the STs to efficiently and quickly validate the architecture under the multi-physical constraints at the conceptual design phase. If the results are adequate with the multi-physical requirements, the Modelica model is traced back to a System model from Modelica language to SysML. Thus, the architecture meets the different requirements and is validated. Otherwise, the Modelica model is transformed to a 3D CAD model in the 3D CAD environment in order to ensure the modification of the components' geometry and spatial allocation until its Modelica model meets all the requirements. Hence, the System model is validated. However, the SAs change the requirements in the SysML model.

2.6 Implementation of the thermal-magnetic coupling model in Modelica/Dymola

2.6.1 Description of Dymola [105]

Dymola is an integrated environment dedicated for both developing models in the Modelica language and simulating them in order to perform experiments. It ensures the modelling and the simulation of large and complex systems such as complete vehicles including chassis, engine and transmission [106]. Moreover, Dymola uses a hierarchical object-oriented modelling aiming at describing the systems, subsystems and components of a specific model. The physical couplings are modelled through the definition of physical connectors and graphically connecting submodels.

Dymola contains different kinds of libraries varying from basic to more specific dealing with many fields such as electronics, thermodynamics, hydraulics and control systems. The user can modify pre-defined libraries or develop new libraries according to his modelling and simulation requirements.

a. Dymola architecture

- **Modelling level:** The models are developed using the standard libraries found in Dymola and other ones created by the user for specific requirements. They can be composed of primitive components or described through equations.
- **Simulation level:** Dymola enables the transformation of the models into simulation codes. It provides an efficient simulation environment

able of performing experiments such as multi-physical behaviours.

• **Visualization and analysis:** The visualization and analysis are provided by the plotting and animation features of Dymola. The experiments are documented in HTML format including images and animations in VRML (Virtual Reality Modelling Language).

b. Dymola graphical user interface

Dymola provides different layers of information as it is shown through the tool bar in in Figure 2.7. An example of a quad-rotor propeller model is illustrated for the three different cases.



FIGURE 2.7: Navigation tools

• *Icon layer:* Dymola has a graphical editor where an icon of the model can be established which facilitates the modelling when connecting multiple models. (see Figure 2.8)



FIGURE 2.8: Propeller icon

The representation of a model icon can be created thanks to drawing tools shown in Figure 2.9. Hence, the user can insert lines, rectangles, polygons, text and can import images.



FIGURE 2.9: Drawing tools

• *Diagram layer:* The user uses this layer to gather components and connect them. (see Figure 2.10)



FIGURE 2.10: Propeller diagram

• *Modelica text layer:* This layer contains the modelling code. (see Figure 2.11)

```
boddl propeller!Modelica. Mechanics. NultiBody. Interfaces. Frame_al<br/>"Coordinate system fixed to the component with one cut-force and cut-torque"<br/>";parameter Real 100.337//Yhrust moment constant<br/>";Modelica. Mechanics. Notational. Interfaces. Frame_al<br/>"Coordinate system fixed to the component with one cut-force and cut-torque"<br/>";parameter Real 100.337//Yhrust distance between CoG and propeller<br/>parameter Real Ph0.0587/Vertical distance between CoG and propeller<br/>diameter=0.01;Modelica. Mechanics. NultiBody. Parts. BodyCylinder bodyCylinder (<br/>distance frame_al)<br/>";Modelica. Mechanics. NultiBody. Parts. BodyCylinder (<br/>distance frame_al)<br/>";Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Modelica. Mechanics. NultiBody. Parts. BodyCylinder (<br/>distance frame_al)<br/>";Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Connect (forculated. frame_al) *;Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Connect (forculated. frame_al) *;Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Connect (forculated. frame_al) *;Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Connect (forculated. frame_al) *;Modelica. Mechanics. NultiBody. Parts. BodyBox bodyBox(<br/>distance frame_al)<br/>";Connect (forculated. frame_al) *;Mo
```

FIGURE 2.11: Propeller Modelica text

2.6.2 Implementation

In this paragraph, the Equation 1.13 modelling the coupling between the magnetic flux density and the temperature for NdFeB permanent magnets is implemented in Dymola in order to be used for different cases and hence determine the magnetic flux density for any NdFeB permanent magnet at any temperature while knowing the initial temperature before the heating process T_0 , the initial magnetic flux density $B_{r_{T_0}}$ and the temperature coefficient α_B .

$$B_r(T_{PM}) = B_{r_{T_0}} \left[1 + \frac{\alpha_B}{100} (T_{PM} - T_0) \right]$$
(2.1)

Thanks to the drawing tools a rectangle is drawn in the icon layer and **Thermal Magnetic Coupling** is written on it. Two blocks enable the development of both input $B_{r_{T_0}}$ and output $B_r(T_{PM})$ of the model as it is shown in Figure 2.12. The other parameters T_0 , α_B and T_{PM} are the variables of this model which can be changed by the used depending on the case.



FIGURE 2.12: Thermal-magnetic coupling model icon

In the Modelica text layer, the Equation 2.1 is written in the Modelica code as it is illustrated in Figure 2.13.

```
model TMCoupling
  parameter Real alphaB( unit="%/°C") "the temperature coefficient for Br";
  parameter Real T0( unit="°C")
    "The initial temperature of the permanent magnet before the heating process";
  parameter Real TPM( unit="°C")
       "The temperature of the permanent magnet after the heating process";
  Modelica.Blocks.Interfaces.RealInput BrT0( unit="mT")
       "The remanent magnetic flux density at TO
   ∎;
  Modelica.Blocks.Interfaces.RealOutput BrTPM( unit="mT")
"The remanent magnetic flux density at TPM"
    a;
equation
BrTPM = BrT0 * (1+((alphaB / 100) * (TPM - T0)));
  annotation (Diagram(coordinateSystem(preserveAspectRatio=false, extent={{-100,
-100}, {100,100}})), Icon(coordinateSystem(preserveAspectRatio=false,
extent={{-100,-100}, {100,100}}), graphics={Rectangle(
extent={{-68,38}, {52,-38}},
linecolor={28,108,200},
               fillColor={63,38,255},
              fillPattern=FillPattern.Solid), Text(
extent={(-58,12}, {40,-14}},
              lineColor={0,0,0},
fillColor={63,38,255},
               fillPattern=FillPattern.Solid,
               textString="Thermal Magnetic Coupling",
textStyle={TextStyle.Bold})}));
end TMCoupling;
```

FIGURE 2.13: Modelica text of the magnetic-thermal coupling model

Thus, Dymola is enriched by this implementation and the thermal-magnetic coupling model can be used in order to solve multiple cases with various initial conditions. Hence, this model can be used as a component dealing with the thermal-magnetic coupling for NdFeB permanent magnets. Once it is imported in the diagram layer of a new component, with a double-click, all the variables can be changed for the specific case the user is working on like it is shown in Figure 2.14.

tMCouplir	ng in Coupling.e	ex				Ę	3	×
General	Add modifiers							
Component						Icc	n	
Name tMCoupling								
Comment Thermal Magnetic Coupling for NdFeB permanent magnets								•
Model								
Path Comment	Coupling.TMCou	pling						
Parameters								
alphaB	-0.12 • %/°C	the temper	ature coeffic	cient for	Br			
T0	27 • °C	The initial the heating	temperature 9 process	of the p	permaner	nt magne	et befo	ore
ТРМ	41 · °C	The tempe heating pro	rature of the ocess	e perma	nent mag	net after	⁻ the	
BrT0	401 · mT	The reman	ient magneti	ic flux d	ensity at	то		
		(ОК		Info		Cano	cel

FIGURE 2.14: The magnetic-thermal coupling component

2.7 Conclusion

The chapter 2 proposes different approaches of 3D multi-physical architecture generation in the conceptual design phase unlike the traditional deign cycles. In fact, the third platform called SAMOS based on an effective collaboration between the different engineering teams in order to assess the concept architecture under geometrical and multi-physical requirements is selected. This approach allows the decrease of time and costs caused by the late changes in the modelling process thanks to a geometrical and a multi-physical extensions. Furthermore, it is essential to gather all the multi-physical analytical models in the Modelica environment. Hence, a library containing all the information dealing with different physics is elaborated and would certainly facilitate the architecture generation, validation and verification. Besides, the thermal-magnetic model is implemented in Dymola and hence it enriches the different multi-physical Modelica libraries.

In summary, the SAMOS platform is an effective tool to find a system concept architecture under the various geometrical and multi-physical requirements while reducing time and costs.

Chapter 3

Study of magnetic and thermal constraints

3.1 Introduction

The chapter 3 provides an overview of permanent magnet motors which are the application case of this PhD work. Indeed, the impact of temperature on both PMSM parameters and performances in different functioning conditions is discussed in order to demonstrate the thermal-magnetic coupling for this type of devices. Then, this chapter provides a description of all the tools used in the upcoming experimental studies. Moreover, it deals with two types of studies. Firstly, the magnetic constraints of some systems such as coils and permanent magnets are studied through simple analytical models and compared to results given by FE tools in order to validate the multiphysical 3D architecture verify and through approximative simulation results. Secondly, the thermal-magnetic coupling of permanent magnets is studied through analytical models and experiments.

3.2 Permanent magnet brushless motors (PMBMs)

3.2.1 General presentation

In the last three decades, because of the advances in electronics and PM quality, the Permanent magnet motors (PMMs) have been increasingly used in multiple fields such as industry (compressors, pumps, machine tools, robots, automation processes...), public life (air conditioning systems, catering equipment, autobank machines, amusement park equipment...), domestic life (dish-washers, washing machines, clothes dryers...), information and office equipment (printers, scanners, audiovisual aids...), automobiles with combustion engines, transportation (elevators, electric road vehicles, aircraft flight control surface actuation...), defence forces (radar systems, missiles...), aerospace (rockets, satellites...), medical and healthcare equipment (electric wheelchairs, air compressors...), power tools (drills, polishers...), renewable energy systems and research and exploration equipment. The largest market area is located in Japan, China, South Korea, America and Europe. The PMMs can have small or large power for a power range starting from some mWs and reaching hundreds KWs. Otherwise, the rare-earth PMMs exceed these values and can reach more than 1 MW.

In comparison with the induction motors, the PMMs have better properties. In fact, they have higher efficiency because they do not pose electrical losses by the field excitation. Besides, they have higher torque, higher output power, higher magnetic flux density in the air gap, better dynamic performance, easier maintenance and simple construction [62].

Generally, PMMs are classified into :

- DC commutator motors,
- DC brushless motors,
- AC synchronous motors.

Gieras et al. [57] made a detailed description of the three types. Indeed, there is a similarity in the construction of a PM DC commutator motor and a DC motor with the replacement of the electromagnetic excitation by PMs. Besides, the designs of PM DC motors and AC PM motors are almost the same with a polyphase stator and PMs on the rotor. Only one difference exists and it is about the shape and the control of the excitation voltage. While a PM AC synchronous motor functions with sinusoidal waveforms producing a rotating magnetic field, a PM DC brushless motor functions with trapezoidal waveforms. For Y connection, two phase windings conduct simultaneously the current and there is a synchronization between the switching pattern and the rotor angular position (electronic commutation). PM DC commutator motors are used in big quantities in the car industry [107] while PM brushless motors are the most adequate propulsion motors for electric and hybrid road vehicles [108] because of their hight torque density, high power factor, wide field weakening area and low acoustic noise [109, 110]. For the three mentioned types, different constructions have been developed. constructions. For PM DC commutator motors, there are motors with conventional slotted rotors, motors with slotless (surface-wound) rotors, motors with moving coil rotors (outside field type, inside field type). For both others, they can be designed as motors with conventional slotted stators, motors with slotless (surface-wound) stators, cylindrical type, disk type (single-sided or double-sided).

The PM brushless motors have two main advantages:

- The armature current is not transmitted through brushes which require usually maintenance,
- The power losses occur in the stator where heat transfer conditions are noticed to be good.

Thanks to these advantages, the power density is increased when compared to PM DC commutator motors. Added to this, since the rotor has a low inertia, the air gap magnetic flux density is high and there is no limitation concerning speed-dependent current, significant improvements in dynamics can be reached. Consequently, the volume of a PM DC brushless motor is able to be reduced by more than 40% while keeping the same rating as a PM DC commutator motor (see Figure 3.1) [111].



FIGURE 3.1: Comparison between PM brushless and PM DC commutator motors [57]

3.2.2 Fundamental equations

The fundamental equations of a DC PMBM are :

• The terminal voltage :

For a three-phase bridge inverter with six solid state switches and Yconnected motor, two phase windings are always connected in series during conduction period. For phases A and B:

$$v_1 = (e_{fA} - e_{fB}) + 2R_p h i_a + 2L_S \frac{di_a}{dt}$$
(3.1)

where R_{ph} is the armature resistance per phase, i_a is the armature instantaneous current, L_S is the synchronous inductance per phase which includes both the leakage and armature reaction inductances and $e_{fA} - e_{fB} = e_{fAB}$ is the line-to-line EMF called generally e_{fL_L} . (e_f is defined as the instantaneous value of the EMF induced in a single phase armature winding by the PM excitation system)

• The instantaneous current :

If these assumptions are taken into account: $L_S \approx 0$ and the zero-impedance solid state switches $v_1 = V_{DC}$ where V_{DC} is the

inverter input DC voltage, the instantaneous armature current is written :

- for Y-connected windings and half-wave operation

$$i_a(t) = \frac{V_{DC} - e_f}{R_{ph}} \tag{3.2}$$

- for Y-connected windings and full-wave operation

$$i_a(t) = \frac{V_{DC} - e_{fL-L}}{2R_{ph}}$$
 (3.3)

where e_{fL-L} is the line-to-line EMF induced in two series connected phase windings.

If L_S is included and $e_{fL-L} = E_{fL-L} = cte$ (trapezoidal EMF), Equation 3.3 for the conduction period is written as :

$$i_a(t) = \frac{V_{DC} - E_{fL-L}}{2R_{ph}} (1 - e^{(R_1/L_S)t}) + I_{a_0} e^{(R_{ph}/L_S)t}$$
(3.4)

where I_{a_0} is the armature current at t=0. Since $V_{DC} \succ E_{fL-L}$, the motor is under-excited.

• The EMF :

The EMF is simply expressed as a function of the rotor speed n_r as:

$$E_{fL-L} = c_E \phi_f n_r = k_E \phi_f n_r \tag{3.5}$$

where c_E or k_E is the EMF constant called also the armature constant and ϕ_f is the magnetic field excitation flux. For PM excitation and negligible armature reaction, $\phi_f \approx cte$.

• The electromagnetic torque :

$$T_{EM} = c_T \ _{DC}\phi_f I_a = k_T \ _{DC}I_a \tag{3.6}$$

where k_{T_DC} and c_{T_DC} are torque constants.

• The linear and rotational speed :

The linear speed is the full angle of rotation or 2τ divided by the period of full rotation $T = \frac{1}{pn_r}$ is:

$$\upsilon = \frac{2\tau}{T} = 2\tau p n_r \tag{3.7}$$

where τ is the pole pitch, p is the number of pole pairs and n_r is the rotational speed.

3.2.3 Permanent magnet demagnetization in permanent magnet motors

The main focus here is to study the thermal aspects of Permanent magnet brushless motors PMBM or PMSM taking into consideration the different parameters impacting its functioning.

The thermal analysis of PMBM is a challenging area of study since in terms of model development ease and reaching good accuracy. Because of thermal stress and high faulty electric loads, the PM materials may be irreversibly demagnetized. In fact, the thermal stress is created by the losses dissipated in the motor. Therefore, high torque density and harsh ambient temperature combined with limited space ensure a coupling between both electromagnetic and thermal fields in different working conditions of the PMBM. Many publications have been lately focused on the demagnetization phenomenon as it was mentioned in subsection 1.3.3. Some models were used to study the motor behaviour under the demagnetization risk such as parametric model [68] and FE model [66]. Besides, there were several comparisons [112] and optimizations **69** of motors against demagnetization. Some authors tried to make diagnostics aiming to detect demagnetization [113]. There were even models developed for motors using various PM grades [114]. Ruoho et al. [72] remarked the absence of a complete study gathering demagnetization, loading and temperature-rise in a PMSM. Hence, they proposed this diagram shown in Figure 3.2 in order to explain the coupled phenomena present in a PMSM. If a PMSM loaded with a constant torque is partially demagnetized, it starts to draw more current in order to produce the required torque. Hence, this increased current may

cause more demagnetization; which raises again the current. More copper losses result from the current increase causing the rise of temperature, the PMs' intrinsic coercivity dropping; which make them more susceptible to demagnetization. The authors underlined the importance of studying if this repetitive process make the PMSM stall. Along their paper, they modelled demagnetization in several situations (constant speed, single run, including mechanical model). For accurate and real results, it was concluded that a thermal model must be used because of the temperature rise caused by demagnetization.



FIGURE 3.2: A diagram representing the dynamics of demagnetization of the PMs in a PMSM loaded with a constant torque [72]

From another hand, Sebastian [115] dedicated a paper dealing only with the reversible demagnetization. Indeed, he studied the temperature effects on the torque production capability and on the efficiency of NdFeB PM motors. He demonstrated that there is a variation of the maximum torque capability over a wide temperature range (from $-40^{\circ}C$ to $150^{\circ}C$) depending on motors' designs; which is due, not only, to PMs temperature but also to the stator resistance and the magnetic saturation. Moreover, a higher efficiency motor has a positive slope to the torque temperature characteristics and vice versa. The motor efficiency decreases when the temperature rises (influenced by magnetic saturation too). Hence, in order to obtain a constant torque for a wide temperature range, temperature is required to be compensated to adjust the current.

3.2.4 Losses analysis

In order to make a study of different phenomena present in the BPMM, a detailed description of the losses is required. Indeed, there are several loss models proposed in the literature such as 2D FEA [116, 117], 3D FEA [116, 118], multislice FEA [119, 120], analytical method [121, 122, 123].

In their paper, Popescu et al. [124] provided the main loss mechanisms of a BPMM and proposed efficient cooling systems. The thermal study was made using analytical tools (lumped thermal networks) combined with numerical methods (FEA and CFD) in order to possibly improve the performances of the BPMM. Finally, an experimental validation took place with different examples of BPMMs.

In summary, there are different types of losses in a PMM [125] :

- Stator loss : contains copper loss and iron loss.
- *Rotor eddy-current loss :* is generated by induced eddy current in the steel shaft and permanent magnets. Besides, it has no significance compared with the total machine loss.

$$P_{rotor_eddy} = \int_{V} \sigma E^2 dV = \int_{V} \frac{J_e^2}{\sigma} dV$$
(3.8)

where σ is the material conductivity, *E* is the electric field, J_e is the eddy current density and *V* is the material volume.

• *Windage loss* (mechanical loss present often for high speed PMMs) : it is a generated heat due to the relative motion of the fluid flowing between the rotor and the stator. Besides, it is a function of shaft rotational speed and fluid properties (temperature, pressure, density, and temperature gradients at stator and rotor walls). The work of

Vrancik [126] estimated it by the system of these equations:

– Shaft rotational speed :

$$\omega = \frac{2\pi N}{60} \tag{3.9}$$

– Reynolds number :

$$Re = \omega r \frac{\rho}{\mu} \varphi \tag{3.10}$$

- Skin friction coefficient for turbulent flow :

$$\frac{1}{\sqrt{C_d}} = 2,04 + 1,768\ln(\text{Re}\sqrt{C_d})$$
(3.11)

- Windage

$$W = C_d \pi \rho \omega^3 r^4 \lambda \tag{3.12}$$

where ω is the angular frequency of the current, *N* is the rotational speed of rotor (in rpm), ρ is the density of fluid the (in $Kg.m^{-3}$), μ is the kinematic viscosity of cooling media (in $m^2.s^{-1}$), *r* is the rotor radius (in *m*), φ is the radial gap between both rotor and stator (in *m*) and λ is the rotor length (in *m*). Besides, two other factors have to be included which are surface roughness of the stator tooth and rotor surface since they impact windage loss.

However, the main losses in a BPMM are : stator copper losses, iron losses and magnet losses.

- Stator copper losses : include conventional *I*²*R* loss and stray load loss caused by skin and proximity effects. In general, the most relevant loss component in a BPMM is the stator winding copper loss. Indeed, it is a function of current and stator winding resistance.
 - Conventional I^2R loss :

$$P_{cu} = n_{ph} I_a^{\ 2} R \tag{3.13}$$

where n_{ph} is the number of phases, I_a is the armature current and R is the stator winding resistance. In a BPMM, both the electrical resistivity of the stator winding material and the required current to deliver a certain torque are affected by the temperature. Hence, in this case, the copper loss depends on temperature. Because of the increase of the winding resistance, the I^2R loss increases while the copper stray load loss decreases with increasing temperature. In fact, the increase in winding temperature results in an increase of copper resistivity shown by this formula:

$$\rho_{copper} = \rho_{copper_0} \left[1 + \alpha \left(T - T_0 \right) \right] \tag{3.14}$$

where ρ_{copper} and ρ_{copper_0} are the copper resistivity at temperatures T and T_0 respectively and α is the temperature coefficient of resistivity.

- The skin effect : is due to electromagnetic induction in the conducting material. In fact, the skin depth is given by

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \tag{3.15}$$

where σ is the electrical conductivity of the conducting material.

 The proximity effect : has place in parallel paths made for coil turns which are located in the slot top and the slot bottom because of leakage. For high speed motors, it is estimated based on this equation [127] :

$$P_{stray} = P_{cu}(k_d - 1)$$
 (3.16)

where:

$$k_d = \varphi(\xi) + \left[\frac{m^2 - 1}{3} - \left(\frac{m}{2}\sin\left(\frac{\gamma}{2}\right)\right)^2\right]\psi(\xi)$$
(3.17)

$$\varphi(\xi) = \xi \frac{\sinh(2\xi) + \sin(2\xi)}{\cosh(2\xi) + \cos(2\xi)}$$
(3.18)

$$\psi(\xi) = 2\xi \frac{\sinh(\xi) - \sin(\xi)}{\cosh(\xi) + \cos(\xi)}$$
(3.19)

and ξ is the relative height of a conductor (the ratio of its height to the effective skin depth considering insulation), γ is the phase angle between the upper layer and lower layer currents for a twolayer case, *m* is the total number of identical conductors in layers, and k_d is the average resistance coefficient, which is the ratio of effective AC resistance against DC resistance.

- Iron losses : The non-sinusoidal (PWM) voltage waveform of power electronic converters causes the rise of losses in the lamination steel. In a BPMM, the iron losses result from the variation in the magnetic field caused by the permanent magnet rotation and the pulsations in the stator winding magnetic field. The highest value of iron loss density has place in the stator laminated teeth region and on the rotor surface. Besides, the iron losses are separated into two components :
 - Hysteresis loss (static loss) : is caused by a form of intermolecular friction when a varying magnetic field is applied to the magnetic material.
 - Eddy-current loss (dynamic loss) : The eddy-current is explained by circulating electric currents which are induced in a sheet of a conducting material when it is subjected to alternating magnetic field. At higher frequencies, this loss component becomes the most dominant iron loss [128] (the magnetic properties change with frequency and induction).

In spite of the various models provided by the literature under a physical or an engineering approach [129, 130], there is still no definitive estimation of iron losses under different working conditions. A good methodology presented in the works of Ionel et al. [131] and Popescu et al. [132] is shown in Equation 3.20.

$$P_{Fe} = P_{hys} + P_{eddy} = k_h(f, B_m) \cdot f B_m^2 + k_e(f, B_m) \cdot (f B_m)^2$$
(3.20)

where *f* is the frequency, B_m is the peak flux density and k_h and k_e are the loss coefficients determined using 3^{rd} order polynomial functions.

The current time harmonics generated by PWM inverters and the manufacturing process are additional factors increasing iron losses in BPMMs. Gathered with the stator copper losses, these losses constitute the biggest amount of losses in a BPMM; which are present in the stator volume limited by the air gap area. The heat generated by them has to be extracted or dissipated.

• Magnet losses : are generated by high energy permanent magnets such as NdFeB an SmCo. In fact, they are created by eddy-currents generated by dips in the air-gap flux density resulting from slotting, current time and space harmonics which are more significant in a BPM with DC operation. These losses may be significant even for low speed applications because of its dependence on the number of slots/pole and the winding configuration. Even though the variation of the electrical resistivity for sintered rare-earth PMs was usually neglected, recent studies [133] showed that the resistivity follows a linear temperature dependence for Sm_2Co_{17} while it has a nonlinear behaviour against temperature for some NdFeB samples at the temperature range between $-40^{\circ}C$ and $150^{\circ}C$ for both transversal and axial directions.

In spite of the big number of publications made in this field, a very few of them dealt with the PMSM losses calculation with skewed slot [123, 122]. In order to respond to this requirement, Deng [134] proposed an improved method that calculates iron loss with skewed slot shown in Equation 3.21.

$$P_{statot-skew} = \left(k_{h}fB_{tm}^{\alpha} + \frac{4}{\pi}\frac{f^{2}B_{tm}^{2}k_{e}}{\alpha_{tt} + \sigma_{t}} \times \left(2 - \frac{\pi - \beta_{m}}{\alpha_{tt} + \sigma_{t}}\right) + \left(\frac{4}{\pi}\frac{k_{exc}}{\alpha_{tt} + \sigma_{t}}\right)^{\frac{3}{4}}f^{1,5}B_{tm}^{1,5} \times \left(2 - \frac{\pi - \beta_{m}}{\alpha_{tt} + \sigma_{t}}\right)\right) * W_{t}$$

$$+ \left(k_{h}fB_{ym}^{\alpha} + \frac{8}{\pi}\frac{f^{2}B_{ym}^{2}k_{e}}{\beta_{m}} + \left(\frac{8}{\pi}\frac{k_{exc}}{\beta_{m}}\right)^{\frac{3}{4}}f^{1,5}B_{ym}^{1,5}\right) * W_{y}$$
(3.21)

where $k_e = \frac{\sigma \pi^2 d^2}{6\rho_{fe}}$ is the eddy-current coefficient in which σ , ρ_{fe} and d are respectively the conductivity, density, and thickness of steel lamination, k_h and k_{exc} are hysteresis and excess coefficients, B_{ym} and B_{tm} are peak values of flux density, respectively, in tooth and yoke, W_t and W_y are weights of stator teeth and stator yoke, α_{tt} , β_m and σ_t are, respectively, the electrical angle of the effective tooth arc, pole width and skew angle as shown in Figure 3.3.



FIGURE 3.3: Stator tooth average flux density analysis. (a) Skewed tooth model. (b) Tooth average flux density. [135]

However, Zhang et al. [135] explained that the assumption (the linear relationship between the flux density in the stator and time) on which was based Equation 3.21 is changed because of skewed slot. Indeed, they expressed this variation by the red line shown in Figure 3.3. Hence, they divided the skewed tooth into three parts where flux density rises linearly with time in each part. Finally, they established this improved formula of

the core losses in the skewed-slot stator shown in Equation 3.22 :

$$P_{statot-skew} = \left(k_{h}fB_{tm}^{\alpha} + \frac{2f^{2}B_{tm}^{2}k_{e}}{\pi} \times \left(\frac{2 - \frac{\pi - \beta_{m}}{\alpha_{tt} - \sigma_{t}}}{\alpha_{tt} - \sigma_{t}} + \frac{2 - \frac{\pi - \beta_{m}}{\alpha_{tt} + \sigma_{t}}}{\alpha_{tt} + \sigma_{t}}\right) + \left(\frac{4k_{exc}}{\pi}\right)^{\frac{3}{4}}f^{1,5}B_{tm}^{1,5} \times \frac{1}{2}\left(\left(\frac{1}{\alpha_{tt} - \sigma_{t}}\right)^{\frac{3}{4}}\left(2 - \frac{\pi - \beta_{m}}{\alpha_{tt} - \sigma_{t}}\right) + \left(\frac{1}{\alpha_{tt} + \sigma_{t}}\right)^{\frac{3}{4}}\left(2 - \frac{\pi - \beta_{m}}{\alpha_{tt} + \sigma_{t}}\right)\right)\right) + W_{t} + \left(k_{h}fB_{ym}^{\alpha} + \frac{8}{\pi}\frac{f^{2}B_{ym}^{2}k_{e}}{\beta_{m}} + \left(\frac{8}{\pi}\frac{k_{exc}}{\beta_{m}}\right)^{\frac{3}{4}}f^{1,5}B_{ym}^{1,5}\right) * W_{y}$$
(3.22)

3.2.5 Thermal-magnetic coupling

In order to study the thermal-magnetic coupling present in PMMs, we have to focus on various models provided by the literature concerning different types and applications of PMMs taking into account the interactions between magnetic and thermal constraints. Among the most used PMMs, we mention Permanent magnet brushless motors (PMBMs) also called Permanent magnet synchronous motors (PMSMs).

In fact, in the field of electric vehicles (EVs), Vong et al. [136] proposed a weak electromagnetic-thermal coupling model showing that a possible resolution can be made using time-harmonic and time-transient methods for the electromagnetic and thermal problems respectively. Some works combined finite-element analysis (FEA) with thermal resistance network (TRN) to predict the performance of PMSMs [137, 138]. Moreover, in order to predict accurately the PMSM's performance, some papers [139, 140] employed numerical methods like FEA and computational fluid dynamic in electromagnetic-thermal coupling. In fact, Vese et al. [140] coupled a 2D electromagnetic field with a 3D thermal field proving that multiphysics numerical field analysis is an effective method to investigate the performance of a PMM. Moreover, Wang et al. [141] studied the impact of temperature and PM material (various grades) on different magnetic characteristics and interior PM motor performances (IPMM) (iron losses, torque, total losses, efficiency) ensuring a valuable design guidance based on all the detailed investigations.

In summary, almost all researches based their studies on numerical methods. However, Zhang et al. [135] increased the calculation efficiency of coupling analysis method by introducing the improved $(\mu + 1)$ evolution strategy (ES) which consists in an intelligent algorithm using mechanisms known from natural evolution like mutation, recombination and selection. Indeed, they combined electromagnetic FEA with thermal resistance network TRN and study the PMSM's performances under different working conditions (no load, under rated load) via their method. Finally, they verified the accuracy of their strategy by experiments on a 36 kW PMSM prototype cooled by water. To test the temperature, some thermal test papers were pasted on the rotor core surface. They plotted curves of self-inductance, mutual inductance, back-EMF depending on rotor position for both experimental and ES calculation cases. Besides, they measured the temperature in different parts of the motor (stator teeth, stator York, end-winding, end-cap) and compared the values to the ones obtained through calculation. They ended the verification by comparing between the calculated and the experimental results of temperature and torque when the PMSM is excited one time by different currents under rated speed and one time by the same current under different speeds. Thus, all the comparisons showed a good agreement between calculated and measured PMSM performance, which means that this method is an efficient tool to predict magnetic-thermal coupling.



FIGURE 3.4: Experimental platform [135]

In the case of axial flux permanent magnet synchronous machines known for their compact design and and their high power density, there were firstly analytical thermal models such as lumped parameters models used to understand heat transfer. In the 1990s, ameliorated thermal networks appeared [142]. In spite of the detailed study of radial flux machines , there were only few published experiments validating the models [143, 144, 145]. In 2012, Verez et al. [146] presented a 3D analytical (nodal) thermal model where they subdivided the axial flux PMs machine into small homogeneous and isotherm volumes. Then, they calculated all the parameters (heat capacities and thermal conductivities) and solved the heat equation. Finally, they compared the simulations in Matlab with the ones obtained via a FEM and found a good agreement between them for both transient ans steady-state cases. The proposed model can be applied to any axial flux PMS machine with any number of air gaps, any rotor position and any physical dimensions.

For high-speed PMMs supported by active magnetic bearings (AMB), the loss distribution, where the rotor air friction losses provided by Equation 3.23 are the most important loss component, differs form conventional standard motors. However, the overtemperature remains one of the biggest problems able to cause irreversible demagnetization.

$$P_{air_friction} = kC_f \pi \rho \omega^3 r^4 l \tag{3.23}$$

where *k* is the roughness coefficient, ρ is the fluid density, *l* is the length of the cylinder and *r* is the rotor radius.

Working on a 100 KW, 32 Kr/min high speed PMM, Huang et al. [147] used a fluid-temperature coupling to evaluate the influence of the stator core temperature on rotor thermal performance. They concluded that from a thermal perspective, the most critical parts of the high-speed PMM are the rotor PMs and the stator winding because of the rotor heating. Thanks to proposed ways of cooling, they could make the impact of the stator core surface temperature on rotor surface temperature minor when the axial cooling air is satisfactory. Finally, they concluded that the best way to cool the rotor is the pressurized air in air gap.

For a PMBM using NdFeB PMs and having a DC functioning (PM

motor with trapezoidal back EMF), [148] studied the effects of the temperature on some parameters such as torque and efficiency at an operating temperature range of $20^{\circ}C$ to $140^{\circ}C$. Indeed, they ensured that the impact of temperature rise on demagnetization is to degrade the performance of the motor: firstly, by decreasing the remanent magnetic flux density and thus the torque; secondly, by limiting the functioning current since the change of the knee-point. Furthermore, the authors used the magnetic-coupling to rewrite the formulas of the back EMF and the armature winding resistance when they depend on temperature.

$$e_{L-L} = \frac{B_{r20}}{1 + \frac{\mu_{rrec}g}{h_{PM}}} \left[1 + \frac{\alpha_B}{100} (T_{PM} - 20) \right]$$
(3.24)

$$R_{ph} = R_{ph20} \left[1 + \varsigma \left(T_w - 20 \right) \right]$$
(3.25)

where ς is the resistance temperature coefficient and T_w is the winding temperature.

Moreover, the copper and the PM have the same temperature only for motors operating at a very low duty cycle, but mostly the copper temperature is higher. As the armature heats up, the current has to be reduced in order to avoid exceeding the rated armature dissipation. In fact, the "hot" current is found by :

$$i_{a_hot}^{(sq)} = \frac{i_a^{(sq)}}{\sqrt{1 + \varsigma_{Cu} \left(T_w - 20\right)}}$$
(3.26)

where $i_a^{(sq)}$ is the flat-topped value of the square-wave current equal to the inverter input current and ς_{Cu} is the resistance temperature coefficient of copper. Hence, they concluded that starting from the formula of the per unit gap torque at rated speed given by:

$$T_{EM_g} = e_{L-L} i_a^{(sq)} = \frac{e_{L-L}}{2R_{ph}} \left(V_{DC} - e_{L-L} \right)$$
(3.27)

They can calculate the ratio a "hot" torque to a "cold" torque:

$$\frac{T_{EM_g}^{(hot)}}{T_{EM_g}^{(cold)}} = \frac{1 + \frac{\alpha_B}{100}(T_{PM} - 20)}{\sqrt{1 + \varsigma_{Cu}(T_w - 20)}}$$
(3.28)

Hence, for higher efficiencies, the motor has a positive slope to the
torque-temperature characteristics. The efficiency decreases with the temperature too and this variation is influenced by the magnetic saturation. Also, a temperature compensation is required to obtain a constant torque. Finally, this study may be applied on other types of the PM motors.

In summary, the thermal-magnetic coupling for PMBMs is taken into consideration. The different parameters, application fields and models are already described. Besides, the risks of the irreversible demagnetization and its impacts on the functioning of PMBMs are discussed. Hence, it is shown that the motors' performances are deteriorated when the temperature reaches very high values.

3.3 Experiment tools

3.3.1 Measuring equipment

In the upcoming sections, several experiments will take place in order to study the magnetic constraints and the thermal-magnetic constraints. The equipment required to realize these measurements is described here.

a. Permanent magnets

The permanent magnets are already described in chapter 1. Even though, some explanations have to take place such as the dimensions of each PM and its physical data. In fact, each PM has a specific grade that contains the residual magnetism, the coercive field strength, the energy product and the maximum operational temperature. All these information are provided in Appendix B and Appendix C.

b. Gauss-meter

Concerning the Gauss-meter, it is a magnetic device that measures the magnetic flux density. The selected Gauss-meter for the next experiments is shown in Figure 3.5. It has four different ranges going from 0 to more than 3 Tesla. Furthermore, the measurements can be made in Tesla, Gauss, $A.m^{-1}$ or Oersted. The whole data sheet is provided in Appendix D.



FIGURE 3.5: Gauss-meter

c. Hall effect sensor

The chosen Hall effect sensor (Allegro 1324) is a linear Hall effect sensor that provides a voltage output proportional to the magnetic flux density. As it is shown in Figure 3.6, it is a 3-pin ultra-mini SIP $1.5 \times 4 \times 3$ mm (suffix UA). Moreover, this temperature-stable device has a sensitivity equal to 5 mV/G. Thanks to its low-noise output, it allows good accuracy. The operating characteristics are provided in Appendix E.



FIGURE 3.6: Hall effect sensor

d. Thermal imaging camera

The operating principle of a thermal camera is to create a visible image depicting infra-red radiation that is contrarily invisible to the human eye. Both the thermal image and the corresponding temperature are displayed on the camera screen in real time. For more precision, the ambient temperature, the relative humidity, the distance and the emissivity can be entered. Moreover, the images can be frozen and saved in the camera thanks to its micro SD memory card. Then, they can be viewed on the device or on a PC and can be edited through a specific software. The selected camera is shown in Figure 3.7. All the characteristics are available in Appendix F.



FIGURE 3.7: Thermal imaging camera

e. Heat gun

The heat gun shown in Figure 3.8 allows to heat some devices in the experiment through a stream of hot air. The temperature of the emitted air can be varied. Moreover, this device is essential to study the relation between the variation of temperature and the magnetic flux density of permanent magnets.



FIGURE 3.8: Heat gun

3.3.2 Finite Element tool

In order to validate the analytical and experimental results, the selected FE tool that ensures the different simulations is COMSOL Multiphysics. [149] In fact, it is a simulation platform dealing with multiple disciplines and physical phenomena. Moreover, the modelling workflow beginning with developing the geometries, defining the material properties and selecting the physics to be studied and ending with meshing, solving and postprocessing the models provides accurate and precise results. COMSOL Multiphysics has a graphical user interface (GUI) that allows to input user-defined physical phenomena through equations and expressions and to easily realize couplings of a wide range of physics such as acoustics, mechanics, heat transfer, fluid flow and electromagnetics.

3.4 Study of magnetic constraints

In order to study the magnetic constraints in the conceptual design phase, simple models are selected to compare the results issued from the analytical models, the FE simulations and the experiments. Hence, STs are able to verify and validate the multiphysical 3D system architecture using these analytical models without employing FE tools which are inadequate in the conceptual design phase. In fact, two cases are selected: coils and permanent magnets.

3.4.1 First case: Coils

In order to realize this experiment, three coils having the same diameter equal to 20 mm and the same length equal to 100 mm but with different copper wire diameters are built. The magnetic flux density is measured through a Gauss-meter and a Hall effect sensor.

The current is varied according to the copper wire diameter for each coil.

• For coil 1, the wire diameter is equal to 0.4 mm.

- For coil 2, the wire diameter is equal to 0.71 mm.
- For coil 3, the wire diameter is equal to 1 mm.

This experiment is shown below in Figure 3.9.



FIGURE 3.9: Measurement of magnetic field for different coils

Each one of the tables below is a comparison between the values of magnetic field found by:

- Hall effect sensor measurement,
- Gaussmeter measurement,
- FE simulations,
- Theory which calculates the magnitude of the magnetic field inside the solenoid. It is concentrated into a nearly uniform field in the center of the coil and it is approximately constant at all points far from its ends. This formula is : B = μ₀.n.I (T) n = N/1 : the number of turns per unit μ₀ = 4.π.10⁻⁷ H.m⁻¹

For Coil 1, $n = \frac{250}{0.1} = 2500$.

	Magnetic Flux Density (T)										
Current (A)	Hall effect sensor	Gaussmeter	Simulations	Theory							
0,5	$1,26.10^{-}3$	$1,51.10^{-3}$	$1,54.10^{-3}$	$1,57.10^{-3}$							
1	$2,52.10^{-3}$	$2,72.10^{-3}$	$3,08.10^{-}3$	$3, 14.10^{-3}$							
1.5	$3,78.10^{-}3$	$3,85.10^{-3}$	$4,61.10^{-3}$	$4,71.10^{-3}$							
2	$5,06.10^{-3}$	$5,22.10^{-3}$	$6, 15.10^{-3}$	$6,28.10^{-3}$							

TABLE 3.1: B-field of Coil 1





For Coil 2, $n = \frac{140}{0.1} = 1400$.

TABLE 3.2:	B-field	of Coil 2
------------	---------	-----------

	Magnetic Flux Density (T)									
Current (A)	Hall effect sensor	Gaussmeter	Simulations	Theory						
1	$1,26.10^{-}3$	$1,57.10^{-}3$	$1,69.10^{-}3$	$1,76.10^{-3}$						
2	$2,52.10^{-}3$	$2,97.10^{-}3$	$3, 38.10^{-}3$	$3, 52.10^{-3}$						
3	$3,78.10^{-}3$	$4,38.10^{-}3$	$5,07.10^{-3}$	$5,28.10^{-3}$						
4	$5,04.10^{-}3$	$5,85.10^{-3}$	$6,76.10^{-3}$	$7,04.10^{-3}$						
5	$6, 30.10^{-3}$	$7,29.10^{-3}$	8,44.10-3	8,80.10-3						



FIGURE 3.11: Magnetic flux density of Coil 2

For Coil 3, $n = \frac{100}{0.1} = 1000$.

	Magnetic Flux Density (T)									
Current (A)	Hall effect sensor	Gaussmeter	Simulations	Theory						
1	$8,40.10^{-4}$	$9, 2.10^{-4}$	$1, 2.10^{-3}$	$1,26.10^{-3}$						
2	$1,64.10^{-3}$	$1,96.10^{-}3$	$2,41.10^{-3}$	$2,51.10^{-3}$						
3	$2,52.10^{-3}$	$2,91.10^{-3}$	$3,61.10^{-}3$	$3,77.10^{-3}$						
4	$3, 3.10^{-}3$	$3, 9.10^{-}3$	$4,81.10^{-}3$	$5,03.10^{-3}$						
5	$4, 14.10^{-3}$	$4, 9.10^{-3}$	$6,01.10^{-3}$	$6,28.10^{-3}$						
6	$4,94.10^{-3}$	$5,86.10^{-3}$	$7,22.10^{-3}$	$7,54.10^{-3}$						
7	$5,74.10^{-3}$	$6,91.10^{-}3$	$8,42.10^{-3}$	$8,80.10^{-3}$						
8	$6, 66.10^{-3}$	$7,85.10^{-3}$	$9,62.10^{-}3$	$1,01.10^{-2}$						
9	$7, 5.10^{-3}$	$8,93.10^{-3}$	10-2	$1, 13.10^{-2}$						

TABLE 3.3: B-field of Coil 3



FIGURE 3.12: Magnetic flux density of Coil 3

Thanks to these comparisons, it is clear that the different results are in accordance with the experiments. Concerning the simulations, the different models are developed in COMSOL Multihysics. An example of a solved model showing the magnetic field lines of the coil is illustrated in Figure 3.13.



FIGURE 3.13: Coil simulation in COMSOL

(The material properties of NdFeB defined in COMSOL are provided in Appendix A.)

3.4.2 Second case: Permanent magnets

In this case, different permanent magnets having various dimensions and shapes (disc, cylinder, parallelepiped, cube, ball, ring, cone) are used. The magnetic flux density is firstly studied in the air then in a magnetic circuit. In fact, it is important to study both cases in order to emphasise the impact of the magnetic circuit on the PM magnetic flux density.

a. In the air

Since the STs require analytical models in order to study the magnetic phenomenon, the Table 3.4 summarizes the magnetic flux density equations of PMs calculated in the air according to the different shapes such as cylinder, sphere or ball.

PM geometry	Magnetic flux density (T)
z R N S D	$B = \frac{B_r}{2} \left(\frac{D+z}{\sqrt{R^2 + (D+z)^2}} - \frac{z}{\sqrt{R^2 + z^2}} \right)$
Z N S L	$B = \frac{B_r}{\pi} \cdot \left(\arctan\left(\frac{L \cdot W}{2z\sqrt{4z^2 + L^2 + W^2}}\right) - \arctan\left(\frac{L \cdot W}{2(D+z)\sqrt{4(D+z)^2 + L^2 + W^2}}\right) \right)$
z - N R S	$B = B_r \frac{2}{3} \frac{R^3}{\left(z+R\right)^3}$
z R, R, D	$B = \frac{B_r}{2} \left[\frac{D+z}{\sqrt{R_a^2 + (D+z)^2}} - \frac{z}{\sqrt{R_a^2 + z^2}} - \left(\frac{D+z}{\sqrt{R_i^2 + (D+z)^2}} - \frac{z}{\sqrt{R_i^2 + z^2}} \right) \right]$

TABLE 3.4: Magnetic flux density equations according to PM shapes

Then, the Table 3.5 gathers the theoretical, simulated and measured values of PM magnetic flux density. Indeed, COMSOL multiphysics and measures are both used to validate the analytical results.

All the information linked to the PMs (dimensions, shape, magnetic grade) are found in Appendix B and Appendix C.

Magnetic Flux Density (T)								
PM	Gaussmeter	Simulations	Theory					
S-08-06-N52-N	0,424	1, 15	0,588					
S-45-30-N	0,490	1,05	0,528					
S-08-30-N	0,513	1,02	0,636					
S-10-40-N	0,560	0,99	0,623					
S-12-60-N	0,565	1,09	0,605					
Q-10-05-03-N	0,320	0,91	0,341					
Q-19-13-06-N	0,354	0,72	0,345					
Q-25-25-13-N	0,386	0,85	0,411					
Q-60-30-15-N	0,345	0,91	0,346					
W-10-N	0,471	0,84	0,495					
W-12-N	0,544	0,88	0,538					
K-10-C	0,460	0,83	0,830					
K-19-C	0,670	0,8	0,808					
K-26-C	0,690	0,8	0,810					

TABLE 3.5: Theoretical, simulated and measured values of PM magnetic flux density

Furthermore, Figure 3.14 illustrates an example of a cylindrical permanent magnet simulation developed in COMSOL multiphysics.



FIGURE 3.14: PM simulation in the air

b. In a magnetic circuit

In this part of the experiment, each PM is placed in a magnetic circuit composed of iron plate having these dimensions:

- Length: 10,5cm
- Width: 10cm
- Thickness: 5mm

Since the magnetic flux density of each PM is measured using a Gaussmeter, a thin plate is inserted between the permanent magnet and the iron plate having a groove with the same dimensions of the Gaussmeter probe. The measurements are made for two thin plates of these materials:

- Brass
- Aluminium

The length and the width of the thin plate are the same as the iron plate whereas the thickness is 1mm for both brass and aluminium plates.

The groove has these dimensions:

- Length: 6,3cm
- Width: 4,5mm (the width of the probe)
- Thickness: 1mm (the thickness of the probe)

The measurements are made only on permanent magnets that have dimensions more important than the probe dimension, otherwise the measurement is not possible. This experiment is illustrated by Figure 3.15.



FIGURE 3.15: Magnetic flux density of PMs in a magnetic circuit

The Table 3.6 below summarizes all the measurements of the magnetic flux density for different thin plates materials.

	Magnetic Flux Density (T)								
	Br	ass	Aluminium						
PM	Gaussmeter	Simulations	Gaussmeter	Simulations					
S-08-06-N52-N	0,852	1,06	0,858	1,06					
S-45-30-N	1,015	1,7	1,027	1,69					
S-08-30-N	0,976	1,03	0,979	1,03					
S-10-40-N	1,008	1,02	1,022	1,01					
S-12-60-N	1,038	1,03	1,045	1,01					
Q-10-05-03-N	-10-05-03-N 0,664		0,673	0,91					
Q-19-13-06-LN	0,988	1,04	0,994	1,05					
Q-19-13-06-N	0,727	0,9	0,734	0,9					
Q-25-25-13-N	0,835	1,05	0,818	1,04					
Q-60-30-15-N	0,725	1,22	0,715	1,21					
W-10-N	0,889	0,98	0,893	0,98					
W-12-N	1,032	1,06	1,035	1,05					
K-10-C	1,039	1,14	1,048	1,15					
K-19-C	1,353	1,27	1,280	1,27					
K-26-C	1,358	1,34	1,390	1,35					
R-10-04-05-N	0,648	1,16	0,664	1,18					
R-15-06-06-N	0,711	0,99	0,700	1,09					
R-25-04-04-N	0,609	1,07	0,612	1,09					
R-40-23-06-N	0,652	0,88	0,666	0,88					

TABLE 3.6: Magnetic flux density influenced by brass and aluminium

Figure 3.16 represents an example of a parallelepiped PM model in a magnetic circuit elaborated in COMSOL Multiphysics.



Surface: Magnetic flux density norm (T) Streamline: Magnetic flux density

FIGURE 3.16: PM simulation in a magnetic circuit

In general, the differences noticed between the measures, the simulations and the analytical results may be caused by these factors:

- **Measurement errors:** The Gaussmeter can provide imprecise measures if its probe is not placed exactly in the surface center of the PM's north pole.
- **Simulation inaccuracy:** Although the FE tools are known to provide efficient simulation results, the model elaborated in COMSOL Multiphysics may lead to some errors. Since the air has to be modelled as a geometry (parallelepiped, cube, ball, etc.) having the physical properties of the air, any modification of the type of the geometry (dimensions or shape) is capable to modify the results. Moreover, the air is present in all the room where the measures are made. Hence, this incompatibility can cause some errors. In our case, a ball with a

sufficiently important diameter is defined in COMSOL to represent the air. However, this alternative may not be enough to prevent this risk.

3.5 Study of magnetic-thermal coupling

3.5.1 First case: Permanent magnets

a. Analytical study

The permanent magnets are known to be sensitive to the heat. In fact, if the temperature increases, the magnetic flux density decreases and vice versa. As it is already described in chapter 1, the analytical equation of this coupling (Equation 1.13) is given by the equation shown below:

$$B_r = B_{r_{20}} \left[1 + \frac{\alpha_B}{100} (T_{PM} - 20) \right]$$
(3.29)

In general, the $20^{\circ}C$ temperature can be substituted by T_0 which represents the room temperature (the initial temperature of the PM before the heating process). Hence, Equation 1.13 can be rewritten in Equation 3.30 :

$$B_r(T_{PM}) = B_{r_{T_0}} \left[1 + \frac{\alpha_B}{100} (T_{PM} - T_0) \right]$$
(3.30)

Since the temperature coefficient α of remanent induction B_r for NdFeB permanent magnets is generally equal to $-0, 12\%/^{\circ}C$, the different values of remanent induction can be determined at any temperature below the maximum operating temperature. However, a range of $-0, 08\%/^{\circ}C$ to $-0, 12\%/^{\circ}C$ is possible depending on the NdFeB grade.

b. Description of the experiment

In order to validate the analytical proposed model, a series of measures takes place. In fact, the used PM is a parallelepiped having these dimensions (40 * 20 * 5mm) and a maximum operating temperature equal to

 $80^{\circ}C$. The principle of this experiment is to firstly heat the PM thanks to the hot air provided by the heat gun. Secondly, the magnetic flux density is measured through the Gauss-meter until the maximum operating temperature is reached. Thirdly, other measures take place during the cooling process back down to room temperature. In fact, the PM is put in the fresh air until it regains its original temperature.

Since the used PM has a Nickel (Ni-Cu-Ni) coating which is necessary to protect the NdFeB material and to prevent its oxidation, the first step in this experiment is to deal with the Nickel emissivity. In fact, the emissivity describes the energy radiation of a material. It depends on the factors cited below:

- Material composition
- Surface condition
- Temperature

In theory, the emissivity value can be between 0,01 and 1. A material having a dark and matt surface is assumed to have a high emissivity. However, the emissivity decreases if the surface is brighter and smoother. The higher the surface emissivity is, the more precise the temperature measurement becomes since reflections are neglected.

In our case, polished Nickel has approximately an emissivity equal to 0,05 at $25^{\circ}C$ since it is a shiny material. Hence, the reflections would prevent efficient measures. In order to tackle this problem, the PM is coloured with black, which would make the emissivity high without any other impact. Once this problem is solved, the measures can be made.

c. Results

Based on the magnetic-thermal coupling overview and the manufacturer information, the PM (40 * 20 * 5mm) can be heated up to $80^{\circ}C$. Even though, the measures show that the PM looses some of its magnetic flux density

when it is cooled to room temperature if heated up to this temperature. Hence, a series of measures are made to find out the heating temperature that allows a reversible demagnetization. All the results of the measurements and the analytical models are gathered in Table 3.7 and Table 3.8 below where:

- $B_{r_{ana}}$ is the remanent flux density for the analytical case.
- $B_{r_{exp}}$ is the remanent flux density for the experimental case.

TABLE 3.7: Variation of remanent flux density with temperature for the heating process

T (° C)	27	28	33	34	35	36	37	39	41	42	44	46	47	49	50,5
$B_{r_{ana}}$ (mT)	401	400,52	398,11	397,63	397,15	396,67	396,19	395,22	394,26	393,78	392,82	391,86	391,38	390,41	389,7
$B_{r_{exp}}$ (mT)	401	400	397	396	395	394	393	392	391	390	389	388	387	386	385

TABLE	3.8:	Variation	of	remanent	flux	density	with
		temperature	for	the cooling	proces	s	

T (° C)	44	42	39	37	35	34	33	31	30	28	27
B_{rana} (mT)	392,82	393,78	395,22	396,19	397,15	397,36	398,11	399,1	399,56	400,52	401
$B_{r_{exp}}$ (mT)	388	390	392	393	395	396	397	398	399	400	401

The obtained measures result in both graphs below : the first is dedicated for heating and the second for cooling.







The graphs show that there is no important error between the experimental and the analytical variation of remanent flux density with temperature. This error is may be linked to the range of the temperature coefficient that can be included between $-0,08\%/^{\circ}C$ and $-0,12\%/^{\circ}C$. Hence, the measures validate the analytical models only up to $50^{\circ}C$ since below this temperature, the PM looses an amount of its strength once it is cooled to room temperature. Consequently, $50^{\circ}C$ is the experimental maximum operating temperature.

In general, once the operating point moves down to the non-linear part of the demagnetization curve, the irreversible demagnetization has place. Therefore, the flux density will not come back to its original value when the temperature is reduced. The critical temperature at which the irreversible demagnetization occurs is a function of both the magnet and its operating load line. However, in this case, the irreversible demagnetization has place at a lower temperature than the maximum operating temperature indicated by the manufacturer. When $50^{\circ}C$ are exceeded, the magnetic flux density does not come back to its original value when the PM is cooled to room temperature. Hence, other factors have an impact on both the maximum operating temperature and the irreversible demagnetization. Indeed, after a heating and cooling process, some PMs with different shapes and dimensions have lost an amount of their magnetizations starting from various temperatures in spite of having the same magnetic grade. Consequently, the maximum operating temperatures may be influenced by the geometry and the dimensions of the PMs. This assumption is discussed in the next paragraph.

d. Conclusion

In order to study the coupling between the magnetic and the thermal constraints for a PM, two key temperatures have to be listed:

- **Curie temperature:** At this temperature, the PM looses all its magnetization.
- **Maximum operating temperature:** Starting from this temperature, the PM looses irreversibly some of its magnetization.

According to Figure 3.19, between the maximum operating temperature

and the Curie temperature, some of the magnetization is irreversibly lost. Hence, three different types of losses are distinguished:

- **Reversible losses:** Some losses of PM magnetic strength take place up to the maximum operating temperature. They are small, within 5 to 10 percent. Once the PM is back down to its initial temperature (room temperature), it returns to its original magnetic strength.
- Irreversible losses: Once the maximum operating temperature is exceeded, some of the PM magnetization is lost. When its temperature is back down to room temperature, the PM is weaker than it was before the heating. The amount of lost magnetization is more important if the PM temperature is close to the Curie temperature. Theoretically, a PM having irreversible losses can theoretically be re-magnetized to its original strength or very close to it.
- Permanent losses: Above the Curie temperature, structural changes have place resulting in a permanent total demagnetization of the PM. There is no sufficient external magnetic field able to bring the PM strength back. For NdFeB PMs, this temperature is generally above 900°C.



FIGURE 3.19: Different types of demagnetization according to temperature

In order to know the loss amount of the magnetic strength for a PM at a specific temperature, the maximum operating temperature has to be studied. In fact, this temperature depends on how the PM is used in the

magnetic circuit. Hence, if the PM is in free space, this temperature depends on the PM shape. The measure of the shape is called the *Permeance coefficient* P_c (*B*/*H*). It is also called the load-line, *B*/*H* or "the operating slope" of a PM (the line on the demagnetization curve where a PM operates). In fact, it depends on the PM shape and its environment (circuit). Practically, it is a number that describes how hard it is for the magnetic field lines to go from the PM north pole to reach its south pole. For example, a short PM such as a thin disc has a low P_c unlike a tall PM that has a high P_c . In order to tackle this problem, some manufacturers have developed their own calculators which can calculate P_c for common shapes in free space. Nevertheless, the ferromagnetic materials present in the PM environment can change the P_c value. In the free space, Figure 3.20 and Figure 3.21 show the variation of P_c with the NdFeB PM dimensions for both shapes: axially magnetized cylinders and parallelepipeds. [150] (M is the magnetization or the intrinsic induction or the polarization)



FIGURE 3.20: P_c or B/H for axially-magnetized cylindrical rare-earth PMs



FIGURE 3.21: P_c or B/H for parallelipipedic rare-earth PMs

It is important to note that for the previously discussed phenomena, the PMs are in free space where no external demagnetizing field is present and their B/H operating slope is constant.

Furthermore, a good way to find all the necessary information linked to a heated PM and to its new magnetic strength is to efficiently analyse and use its BH curves. The BH curves of N42 PMs are shown in Figure 3.22.



FIGURE 3.22: BH curves of N42 PM grade

There are five key elements coloured in Figure 3.22 with different colours:

- Normal curve: Since this curve describes the PM performance, it is the most referred to for design purposes. Moreover, it is used for the fixed operating temperature of the PM in order to determine the amount of flux a PM is capable to produce. The linear part of this curve has a slope which is sometimes called the Recoil permeability. In the case of NdFeB PMs, this slope is generally 1,05.
- **The knee:** The knee consists in the normal curve portion where it bends down and becomes a vertical line.
- Intrinsic curve: This curve is derived from the normal curve and vice versa. It is useful when the PM's reaction to an external magnetic field is studied.
- Load line: Also called the operating line, it is a line from the origin having a slope equal to the PM permeance coefficient *P*_c. Indeed, it can be drawn from the origin to *P*_c shown around the edges of the graph.
- **Operating point:** The intersection of the load line with the normal curve represents the operating point of the PM.

Here is an example illustrating how tu use these curves in order to determine the lost magnetization of the PM taking place after the heating process. [151] At $20^{\circ}C$ and in free space, a PM is supposed to have a N42 grade and a P_c equal to 0,61. The first step is to draw the load line between the origin (0,0) and the value of P_c . This line is coloured in green in Figure 3.23. The operating point coloured in blue is the result of the intersection of the load line and the normal curve at $20^{\circ}C$. It is clear that at $80^{\circ}C$ the operating point would be at the normal curve knee as it is shown below by the purple circle. Hence, $80^{\circ}C$ represents the maximum operating temperature.



FIGURE 3.23: PM at $20^{\circ}C$

At this step, the PM is supposed to be heated up to $100^{\circ}C$. Thus, the PM looses irreversibly some amount of its magnetization since $100^{\circ}C$ is more important than the maximum operating temperature. The blue point shown below in Figure 3.24 represents the new operating point as it the intersection of the load line and the $100^{\circ}C$ normal curve. It is located below the knee of the normal curve. This point drops down by a "B" distance as it is shown in Figure 3.24. Once the PM cools back to $20^{\circ}C$, it does not climb the knee. Indeed, it drops by an amount shown below as "A" (A=B). Hence, the red point is the new operating point at $20^{\circ}C$ after the heating and cooling processes. In fact, the lost magnetization amount at $100^{\circ}C$ drops the operating point from the $20^{\circ}C$ normal curve.



FIGURE 3.24: PM at $100^{\circ}C$

A simple calculation provides the lost pull strength which is close to the product B * H. Using the absolute value of H, this product is calculated for both operating points at $20^{\circ}C$ (blue point in Figure 3.23) and after the heating process (red point in Figure 3.24). For Figure 3.23, B * H is approximately equal to 38 MGOe. However, B * H is equal to 26 MGOe for Figure 3.24. Consequently, the pull strength drops to 68% of its original value approximately.

3.5.2 Second case: Permanent magnet motor

The last few decades have known several technological developments especially with the emergence of permanent magnet motors. As it is already described in subsection 3.2.1, this innovative type of motors offers several benefits. In fact, PMMs have revolutionized many fields thanks to their high efficiency, better dynamic performance, their high output power capable to reach 1 MW in the case of rare-earth permanent magnets.

Since it represents an important device used in multiple fields and for different applications, the permanent magnet motor is selected to be the second case to study the magnetic-thermal coupling. Moreover, the heat is able to impact the performances of the PMMs according to the literature. Hence, an experimental bench is elaborated in order to make all the required measures for this study.

a. Description of the experimental bench

This experimental bench shown in Figure 3.25 mainly consists of the devices cited below.



FIGURE 3.25: Experimental bench

• Permanent magnet motor

The selected motor is a BLDC motor designed for direct drive para-glide, hang glider and other applications using 1,3 m propeller. Furthermore, it is able to provide a continuous power equal to 15 kW and 18 KW only for a short time because of its small dimensions and its high torque. The motor has integral temperature and Hall sensors. The motor properties can be found in Appendix G.

The motor is shown in Figure 3.26.



FIGURE 3.26: BLDC motor

• BLDC motor controller

A BLDC motor controller is required. In fact, it ensures the variation of the motor speed by adjusting the timing of pulses of the delivered current to the several windings of the motor.

• Thermal imaging camera

It is essential to measure the temperature of the motor. It is already described in subsubsection d..

The development of this experimental bench has required different efforts and solid multi-disciplinary knowledge.

b. Description of the experiment

The aim of this experiment is to study the magnetic-thermal coupling by analysing the impact of the temperature on the motor performances especially when it works at very high speeds. Using the controller, the speed can be varied from low up to high. Several measures can be made on the BLDC motor with and without load. In fact, among these series of measures, we can cite:

- The variation of the temperature with the motor speed.
- The variation of the magnetic flux density provided by the permanent magnets with the temperature.
- The variation of the intrinsic coercivity of the permanent magnets with the temperature.

Identically to the studies found in the literature, if the motor loaded with a constant torque is partially demagnetized, it starts to draw more current in order to produce the required torque. However, this current rise is able to lead to more demagnetization. Furthermore, the demagnetization increases again the current. Hence, more copper losses result from the increased current leading to the rise of temperature. This decreases the intrinsic coercivity of the permanent magnets and exposes them increasingly to the demagnetization. Consequently, it is necessary to prevent the demagnetization by using the motor under accurate working conditions. Otherwise, the motor performances may be worsened until it finally stalls. (Figure 3.2)

This phenomenon illustrates the strong coupling between the temperature and the intrinsic coercivity of the permanent magnets.

c. Validation

The different results can be validated using the coupling between Maxwell Designs and ANSYS Thermal via Workbench. In fact, Maxwell is the leading electromagnetic field simulation software for the design and analysis of electric motors, actuators and various electromagnetic and electromechanical devices [152]. Moreover, ANSYS Workbench is a finite element software used to simulate different physical behaviours such as the temperature [153].

The different steps of this process are described below.

- 1. Firstly, the process begins with importing a Maxwell 2D or 3D design to the *Workbench* schematic.
- 2. Secondly, a *Steady-State Thermal* system is inserted in 2D or 3D according to the Maxwell design type.
- 3. Thirdly, the *Steady-State Thermal* system's geometry is set up by exporting the Maxwell geometry (sat or step format) and importing the file via the *Geometry* module.
- 4. Once the *Model* cell of the *Steady-State Thermal* system is refreshed, the geometry mode of the *Steady-State Thermal* system is able to be changed through ANSYS *Mechanical* user interface.
- 5. Then, the coupling is set up by dragging the *Solution* cell of the Maxwell system and dropping it on the setup cell of the *Steady-State Thermal* system.
- 6. After updating the Maxwell *Solution* and refreshing the *Steady-State Thermal Setup*, the coupling setup can be finished by launching ANSYS *Mechanical*.
- 7. At this stage, an *Imported Load* is inserted. The user can select it to view its *Details* providing information about the way of temperature result exportation and the most adequate mesh mapping.
- 8. An *imported Heat Generation* or an *imported Heat Flux* have to be inserted.
- 9. The electromagnetic loss can be imported from the *Maxwell Solution*.
- 10. Once the *Import Heat Generation* becomes a folder, it shows a plot of the imported load if selected.
- 11. The user creates a specific thermal boundary such as *Convection* which once selected changes the *Film Coefficient* through the *Detail* window.

- 12. Finally, the model can be solved by right-clicking on the *Solution* tree.
- 13. Plots of temperature can be obtained and the results are able to be evaluated.
- 14. The thermal result can be exported to Maxwell.
- 15. The user is able to use the automation capabilities of ANSYS in order to ensure a continuous interaction between Maxwell and Thermal simulations from the Workbench schematic.

3.6 Conclusion

The chapter 3 studies the magnetic constraints and the magnetic-thermal coupling for some specific cases. The purpose is to validate analytical models based on simplified geometries in order to allow the different engineering teams to quickly validate the 3D multi-physical architecture in the conceptual design phase. Indeed, the magnetic flux density models of both coils and permanent magnets are validated through FE simulations and measures. Moreover, the magnetic-thermal coupling model is studied and validated. Hence, if a permanent magnet is heated, its remanent flux density decreases and vice versa. Nevertheless, it is possible that it looses an amount of its remanence once it is cooled to room temperature even if the heating did not exceed the maximum operating temperature. Many factors impact the permanent magnet demagnetization especially the permeance coefficient. Besides, some key elements to read and efficiently use the BH curves are provided. Finally, the permanent magnet experimental bench is described. The impact of the temperature on the different performances of the motor is highlighted. Hence, there is a strong coupling between the thermal and magnetic constraints for a permanent magnet motor. Concerning the validation, the different steps required to develop a coupling between Mawell Designs and ANSYS Thermal through Workbench are detailed in order to provide magnetic-thermal FE simulations.

Conclusions and perspectives

The rising complexity of the systems usually leads to an important increase of costs and time during the embodiment and detailed design phases. In fact, many interactions take place between the different engineering teams dealing with various disciplines resulting in multiple and long iterations. Moreover, the verification of the multi-physical and multi-disciplinary behaviours does not take place until the embodiment and detailed design phases throughout long FE (Finite Element) simulations. The unsatisfactory simulation results at this design level can result in additional iterations and time loss. Besides, the conceptual design phase lacks different elements necessary for system architects to assess the proposed architectures under the various requirements. In order to tackle these issues, a MBSE (Model Based Systems Engineering) approach is required to ensure, on the one hand, the decrease of costs and design time and the management of consistency and traceability on the other hand.

In this PhD work, an early evaluation of the proposed system architectures according to the geometrical and multi-physical constraints is suggested since the conceptual design phase. In fact, three different approaches for architecture assessment are provided in order to allow efficient collaboration between the different actors. Considering all its advantages in comparison with the first two approaches, the third process called SAMOS (Spatial Architecture based on Multi-physics and Organization of Systems) is selected to ensure the verification of the 3D multi-physical system architecture since the conceptual design phase. Indeed, a unique 3D and simulation environment gathers the tasks realized by the geometers and the simulation teams who respectively allocate volumes and positions of the system components and add different multi-physical constraints to the initial architecture provided initially by the system architects. Once the simulation results meet the different geometrical

and multi-physical requirements, the system architects can choose the most convenient 3D multi-physical architecture.

Then, the importance of the development of a geometrical and a multi-physical SysML extensions is highlighted since they ensure the enrichment of the mechatronic system architecture with geometrical and multi-physical requirements. Moreover, the specification of geometry is based on the TTRS (Technologically and Topologically Related Surfaces) theory since simplified geometries are sufficient in the conceptual design phase. Regarding the multi-physical extension, the results provided by the analytical simulations allow the validation of the 3D architecture. During this process, model transformations at each step between the system model in SysML, the 3D model in 3D CAD and the multi-physical model in the Modelica language different are described.

A focus on the magnetic phenomenon and its coupling with the temperature is realized in this PhD work. On the one hand, we provided magnetic flux density analytical equations of NdFeB permanent magnets having different shapes such as cylinder and sphere and we validated them with experimental measurements and FE simulations. Hence, these analytical equations can be integrated in the magnetic SysML extension and more specifically in Modelica in order to enrich the 3D architecture with magnetic information. On the other hand, we studied the magnetic-thermal coupling of permanent magnets and permanent magnet motors. Indeed, the NdFeB permanent magnets' demagnetization curves are sensitive to temperature. Hence, the remanent magnetic flux density and the coercive force decrease while the permanent magnet temperature increases. Once the permanent magnet is heated then cooled back to room temperature, it may loose irreversibly some of its remanent magnetic field even though the heating temperature does not exceed the maximum operating temperature. One of the equations coupling the temperature with the magnetic flux density is implemented in Dymola in order to enrich the standard libraries

The measures provided by the thermal imaging camera are most of the time in accordance with the analytical models. However, other factors may impact the demagnetization process such as the permeance coefficient which depends directly on the shape of the permanent magnet. Moreover, the temperature impacts permanent magnet motors by the decrease of the remanent magnetic flux density and thus the torque and by limiting the functioning current made because of the change of the knee-point in the demagnetization curve. Besides, the risks of the irreversible demagnetization and its impacts on the functioning of this type of motors are discussed. Hence, it is shown that the motors' performances are deteriorated when the temperature reaches very high values.

This PhD work offers multiple perspectives.

- For the magnetic field, other application cases can be studied in order to possibly include their analytical equations in the Modelica language and enrich consequently the SysML magnetic extension.
- Besides, other physical behaviours and their resulting couplings can be studied in order to build new SysML extensions dealing with other disciplines such as mechanics.
- Finally, all these extensions may efficiently enable the system architects to select the most convenient 3D multi-physical architecture since the conceptual design phase. Thus, a complete multi-physical sketcher is built based on these enrichments linked to all the multiple physical phenomena.

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Appendix A

NdFeB properties

- Type of magnetisation : anisotropic
- Grade : each PM has a specific grade (exact values under physical permanent magnet data)
- Density: $7, 4 7, 6g.cm^{-3}$
- Electrical resistance $\mathbf{R}: 1, 4 1, 6\mu\Omega m$
- Relative permeability: 1,05
- Hardness: 570 HV

Appendix **B**

Dimensions and grades of permanent magnets

In this appendix :

- Ø: Diameter
- L : Length
- W : Width
- H : Height
- L_e : Length of edge

TABLE B.1: Dimensions and grades of Disc PMs

Reference Grade		Dimensions(mm)
S-01-01-N	N45	Ø=1, H=1
S-05-02-N52N	N52	Ø=5, H=2
S-08-06-N52N	N52	Ø=8, H=6
S-20-10-N	N42	Ø=20, H=10
S-45-30-N	N45	Ø=45, H=30

Reference Grade		Dimensions(mm)	
S-04-10-AN	N45	Ø=4, H=10	
S-04-10-N N45		Ø=4, H=10	
S-08-30-N N42 S-10-40-N N40		Ø=8, H=30	
		Ø=10, H=40	
S-12-60-N	N38	Ø=12, H=60	

TABLE B.2: Dimensions and grades of Cylinder PMs

TABLE B.3: Dimensions and grades of Parallelepiped PMs

Reference	Grade	Dimensions(mm)
Q-05-2,5-02-HN	44H	L=5, W=2,5, H=2
Q-10-05-03-N	N45	L=10, W=5, H=3
Q-19-13-06-LN	N42	L=19, W=13, H=6
Q-19-13-06-N	N42	L=19, W=13, H=6
Q-25-06-02-SN	45SH	L=25, W=6, H=2
Q-25-25-13-N	N40	L=25, W=25, H=13
Q-60-30-15-N	N40	L=60, W=30, H=15

TABLE B.4: Dimensions and grades of Cube PM

Reference	Grade	Dimensions(mm)
W-03-N	N45	<i>L</i> _e =3
W-05-N	N42	<i>L_e</i> =5
W-10-N	N42	$L_e=10$
W-12-N	N48	<i>L_e</i> =12

TABLE B.5: Dimensions and grades of Ball PMs

Reference	Grade	Dimensions(mm)
K-05-C	N42	Ø=5
K-10-C	N40	Ø=10
K-19-C	N38	Ø=19
K-26-C	N38	Ø=26

Reference	Grade	Dimensions(mm)
R-10-04-05-N	N42	Ø=10/4, H=5
R-10-07-03-DN	N45	Ø=10/7, H=3
R-15-06-06-N	N42	Ø=15/6, H=6
R-25-04-05-N	N45	Ø=25/4, H=5
R-40-23-06-N	N42	Ø=40/23, H=6

TABLE B.6: Dimensions and grades of Ring PMs

TABLE B.7: Dimensions	s and grades of Cone PM	s
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Reference	Grade	Dimensions(mm)
CN-10-05-04-N	N45	Ø=10/5, H=4
CN-15-08-06-N	N42	Ø=15/8, H=6
CN-20-10-08-N	N38	Ø=20/10, H=8
CN-25-13-10-N	N38	Ø=25/13, H=10

Appendix C

Physical permanent magnet data

All the physical data of used permanent magnets are shown in the table below. They are provided by the manufacturer.

https://www.supermagnete.de/eng/data_table.php

Grade	Remanence	Coercive field strength		Energy product	Maximum operational temperature
	Br (T)	bHc (kA. m^{-1})	iHc (kA. m^{-1})	BxHmax (kJ. m^{-3})	Tmax (°C)
N38	1,22-1,26	860-915	≥955	287-303	≤ 80
N40	1.26-1.29	860-955	≥955	303-318	≤80
N42	1.29-1.32	860-955	≥955	318-334	≤ 80
N45	1.32-1.37	860-995	≥955	342-358	≤80
N48	1.37-1.42	860-995	≥955	358-382	≤ 80
N50	1.40-1.46	860-995	≥955	374-406	≤ 80
N52	1.42-1.47	860-995	≥955	380-422	≤80
44H	1.32-1.36	860-1035	≥1353	334-350	≤ 120
45SH	1.32-1.37	860-955	≥1592	342-358	≤150

TABLE C.1: Physical magnet data

Appendix D

Gauss-meter data sheet

The data sheet can be found on: https://fr.rs-online.com/web/p/gaussmetres/6212063/



HIRST

Magnetic Instruments Ltd.

Introduction

The GM07 and GM08 Gaussmeters have been designed and manufactured by Hist Magnetic Instruments Ud, a company with more than 40 years experience in Magnetic Measurement. This experience and aurestensive knowledge of the magnetics markethas enabled us to design an instrument incorporating all of the measurement functions a user's likely to need. The GM07/08 is controlled via a simple menu and is suppled with a thin semi-flexible Transverse Hall Probe suitable for all but the very smallest of applications.

The GM07/08 incorporates an analogue peak detector for the D.C and AC peak functions. This, coupled with the micropocessor operation means fast response is possible with digital stability (fast pulses / no droop in readings).

Measurement functions

The GM07/08 can measure >

DC	DC magnetic field measurement.
DC PEAK	Maximum pasitive peak reading of the DC field.
AC RMS	True RMS (Rootmean Square) of inputsignal.
AC RMS MAX	Maximum true RMS.
AC PEAK	Maximum pasitive peak value.

Utilities

The GM07/08 has a number of UTIL/TES options allowing the operator to disable or select various times for the automatic POWER DOWN. Also nullingroutines can be selected.

The GM07/08 disc has the facility to operate its menu structure in English, French German, Italian, Spanish and Portuguese.

Calbration

The GM07/08 is calibrated to standards traceable to the National Physical Laboratories.

During manufacture, the accuracy of nuclear magnetic esonance (NMR)susad to determine the inegularities and name conformities of the GM07/08 and its Hall Probe. This is stored and used mathematically to automatically correctinearing staken by the GM07/08.

Measurement units

The GM07/08 can measure magnetic flux density or magnetic field strength. The menu system enables the operator to easily choose between Tesla, Amps/m(SI Units), Gauss or Oersted (ogs units).

Datacapture

The GM07/08 can HOLD measured values by pressing the Hall Prabe button. Pressing the button again releases HOLD (when enabled).

The GM07/08 can also SIORE measured values. These values can later be RECALLED, either an the meter or via RS232/US8 with the GM08.

Applications

The GM07 is labal for inspection and measurement of magnetic flux density of magnets and magnetic assembles in both goods inward and Quality Assurance environments.

Where individual measurements need to be recorded the GMD8 will store and upload not only the measured values, polarity, measurement units and measurement function, but also the time at which the measurementwastoles. Applications include: Computer Disk Drive Actuatos, Loudspeaker Air Gaps, Electric Motor air gaps(including pancake and Permanent Magnets), Transformer Stray Field measurements, Magnetiser and Demagnetiser Field measurements, Bending Magnets, Non-Destructive Testing (Magnetic), Goods Inward and Quality Assurance Inspection, automated magnet calibration, etc.

GM08 Communications

The GM08 features all of the functions of the GM07 plus:

An interface to provide RS232 and USB communication for uploading measurement data to a host computer. The GM08 can also be remotely controlable via this link.

A full driver suff is available as an aptional extra. This includes sample programs with full source code (Marosoft Visual C++.NET) for the 2000 operating system, XP and later. A Labview ¹ VI is included. Linux is also supported.

The GM08 also incorporates a non volatile memory to enable the retention of stored values even when switched off.

The GM08 also includes a time keeping device to record the time data is stored and an external DC power supply socket for bench top applications.



Screen shot from within Microsoft Excel



Magnetic Instruments Ltd.

GM07 & GM08 Hall probes

HIRST

Both the GM07 and the Gm08 are supplied with a transverse Hall probe asstandard (Tp002).

The design of the Hall probe is critical to the satisfactory operation of any gaussmeter. For the GMOS and GMO2 we have used our experience to pockace altransverse Hall probe which is semi-flexible and only 1 mm thick by 4 mm wide. This enables operators to take measurements in fight spaces and narrow alt gaps. In addition the sensitive Hall element is clearly visible so the user knows exactly where the measurement is being made...

The probe is fitted with a push button enabling the operator to HOLD and STORE measuments and orientate the probe for polarity readings.



All transverse and axial probes are fully interchangeable with Hist Magnetic instruments Lid's GM04, Gm05, VGM01, BGM01, GM07 and GM08 gaussmeters

Axial and transverse probes are also available with langer cable lengths. If you require a lang cable or a custom probe please contact the sales office for more information

Hall Effect Theory

In an Ideal world, a Halt Element consists of a small slab of semiconductormaterial. Current passes from one end of the slab to the other and the voltage an each edge of the slab is the same when no magnetic field is present. If a magnetic field is now applied through the top to botham surfaces of the slab, a voltage appears across the slabs/of the slab which is directly proportional to the Magnetic Fux Denrity or Magnetic Field Strength. In reality, all practical Hall Robe elements are only linear within certain limits, normally 1%-2%. The more accurate and thinner the probes, the greater the expense. Most Gaussnetter manufactures approach this problem by selecting current and Hall Probe load resistance to minimise these non-linearity errors.

The Hall Probes are connected to Gaussmeters, the Gaussmeters are designed to be linear to make the best use of the non-linear Hall Pobles.

The philosophy behind the design of the GM04 is that both the Probe and the Gaussmeter will contain non-linearities and errors. The difference between a theoretical, perfect Hall Robe and that of an Individual Hall Probe is measured and the difference recorded in an E2promicocated in the Hall probe socket (this memory device also contains other information such as selicin umber and calibration date).

The perfect Hall Probe is in fact a calibration process using a technique known as Nuclear Magnetic Resonance (NMR) which gives very high accuracy.

Transverse Probes



The errors between the GM07/08 and an ideal electronic clicuit are measured and recorded in its internal E2pram.

When a measurement is taken the voltage generated by the Hail Probe element is amplified by the GM07/08 electronic dircuit and digitised in an Analogue to Digital converter.

The software of the GM07/08 then automatically conects this data mathematically, fistly with the Hall Robe calibration information and then with the GM07/08 calibration information.

This technique gives superb results and enables calibration of the Gaussmetter to be carried out in software rather than "select on test" resistor values. The GM07/08 includes other innovative techniques which further improve and give additional ang termstability.

The GM07/08 also includes a linear analogue circuit for peak detection. This declarated circuit enables the accurate capture of transient events without the inherent delays of Analogue to Digital Converter sampling times.

Although this captured voltage level will decay, in the analogue circuit, it is converted and alsplayed from a digital storage giving zero droop digital storage.

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GM07/08 SPECIFICATION

AUTO RANGING AND MANUAL RANGING

Range 1 0 to more than 3 Testa resolution 1 millTesta

Range 2 0 - 299.9 milliTesta resolution 100 microTelsa

Range 3 0 - 29.99 millTelsa resolution of 10 microTesia

Range 4 0 - 2.999 milliTesia resolution of 2 microTesia

Measurements can be made in Tesla, Gaus, Amps/m or Oersted.

(1 mT = 10 Gauss = 0.796 kAm)

Accuracy (at 20 degC +/- 1%

(DC) Traceable NPL

Reproducibility

Temperature Coefficient Better than +/- 0.1 % of reading / degC Including probe.

+/- 0.5%

Requency Range DC and 15Hz to 10kHz

Averaging Time Constant 100 milliseconds

Functions

DC, DC Peak, AC RMS, AC RMS MAX, AC PEAK

LCD graphics display monochrame.

Display Sampling rate 3 / second (approx)

Facilities

State and Recall on 0. 99 samples. Hold facility. Analogue peak with digital statage. Auto and manual ranges. Automatic reading conversion between different units. Operating setup at time of power down is stored and recalled automatically at poweron. Functions are selected with an easy to use menu.

Operating Temperature Range 0 degC to +50 degC

Storage Temperature Range -20 degC to +70 degC Battery Type 4 of Longille1.5V Alkaline AA cells.

Battery Life Battery Life of 15 hours continuous operation. Auto power down after 1, 4 or 10 minutes or can be disabled, all under menu control.

Dimensions Length 175mm Width 89mm Height 40mm

Weight

430 g (not including probe)

Standard Accessaries Transverse Hall Probe, Zero Flux Chamber and Carry Case.

Optional Accessories

Avid Probe Ref AP002. Replacement Transverse Probe Ref TP002. Reference Magnets Avial and Transverse contact factory for details.

GM08 ADDITIONAL FEATURES

RS232 and US8 Used for data transfer and remote control. Software handshaking, US8 1.1 Compliant.

Analogue Output +/- 3 Volts full scale.

Non volatile memory

The GM07 and GM08 will retain stored measurements when the instrument is switched off.

Time Keeping

The GM08 has a time keeping device so that the time that measurements were taken can also be recarded.

External PSJ Socket

An external PSU (not supplied) may be used to power the GM08 when used in bench top applications.

ADDITIONAL STAND AND ACCESSORES

Software

Windows communication software is supplied with the GM08. This allows the user to download readings stored data and control, the instrument remotely.

The Hat Probe

Both the GM07 and GM08 are supplied with a transverse Hall probe as standard.

The design of the hall probe is critical to the satisfactory operation of any gaussmeller. For the GM07 and GM08 we have used our extensive industrial experience to produce a transverse Hall probe which is semi-flexible and only Imm thick by 4mm wide. This enables operators to take measurements in light spaces and narow at gaps. In addition thesenstitve Hall element is clearly visible so that the user knows exactly where the measurement is being made.

The probe is fitted with a push button enabling the operator to HOLD and STORE measurements and orientate the probe for polarity readings.

An axial probe is also available as an option of extra. This is only 5mm in diameter and also incorporates a push button for HOLD and STORE functions.

All transverse and axial probes are fully interchangeable on both the GM07 and GM08 without the need for re-calibration.

Compatibility

The probes of GM04 and GM05 meters are directly compatible with the GM07 and GM08 and fully interchangeable.

The software interface (RS232) is also compatible. A GM08 can directly replace a GM05 in service.

RoHS Compliance

Both the GM07 ,GM08 meters, probes and accessories are RoHS compliant.

Hist Magnetic Instruments Ltd. also manufactures wide ranges of magnetic Instruments, magnetisers, demagnetisers, precision demagnetisers and special magnetic systems.

Due to a process of continual improvement, Hist Magnetic instruments Ltd. reserve the right to change any specifications without notice.

Document

Hirst Magnetic Instruments Etd

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Appendix E

Operating characteristics of Hall effect sensors

The whole data sheet of the chosen Hall effect sensor (Allegro 1324) is available in:

http://docs-europe.electrocomponents.com/webdocs/106a/ 0900766b8106a158.pdf

Only the operating characteristics are provided here.

Characteristics	Symbol	Test Conditions	Min.	Typ.	Max.	Unit ¹
Electrical Characteristics	oymoor				muxi	Unit
Supply Voltage	Vee		4.5	50	5.5	v
Supply Current	100	No load on VOUT	-	6.9	9	mA
Power-On Time ²	teo	$T_A = 25^{\circ}C_C (PROBE) = 10 \text{ pF}$	-	32	_	us
Supply Zener Clamp Voltage	- 40 V7	$T_{A} = 25^{\circ}C_{100} = 12 \text{ mA}$	6	8.3	-	V
Internal Bandwidth	BW:	Small signal. –3 dB	_	17	_	kHz
Chopping Frequency ³	fc	$T_A = 25^{\circ}C$	-	400	-	kHz
Output Characteristics						
Quiescent Voltage Output	V _{OUT(Q)}	B = 0 G, T _A = 25°C	2.425	2.500	2.575	V
		A1324, T _A = 25°C, C _{BYPASS} = 0.1 µF	-	7.0	-	mV _(p-p)
Output Referred Noise	VN	A1325, T _A = 25°C, C _{BYPASS} = 0.1 μF	-	4.4	-	mV _(p-p)
-		A1326, T _A = 25°C, C _{BYPASS} = 0.1 µF	-	3.5	-	mV _(p-p)
Input Referred RMS Noise Density	V _{NRMS}	T _A = 25°C, C _{BYPASS} = open, no load on VOUT, f << BW _i	-	1.3	-	mG/√Hz
DC Output Resistance	R _{OUT}		-	< 1	-	Ω
Output Land Deviation		VOUT to VCC	4.7	-	-	kΩ
Output Load Resistance	RL	VOUT to GND	4.7	-	-	kΩ
Output Load Capacitance	CL	VOUT to GND	-	-	10	nF
Outrast Optimation Mathema	Vour(sat)HIGH	$R_{PULLDOWN} = 4.7 \text{ k}\Omega, V_{CC} = 5 \text{ V}$	4.7	-	-	V
Output Saturation voltage	V _{OUT(sat)LOW}	R _{PULLUP} = 4.7 kΩ, V _{CC} = 5 V	-	-	0.30	V
Magnetic Characteristics						
		A1324, T _A = 25°C	4.750	5.000	5.250	mV/G
Sensitivity	Sens	A1325, T _A = 25°C	2.969	3.125	3.281	mV/G
		A1326, T _A = 25°C	2.375	2.500	2.625	mV/G
Constituity Temperature Coefficient	TO	LH package; programmed at T _A = 150°C, calculated relative to Sens at 25°C	-	0	-	%/°C
Sensitivity temperature Coefficient	CSens	UA package; programmed at T _A = 150°C, calculated relative to Sens at 25°C	-	0.03	-	%/°C
Error Components						
Sensitivity Drift at Maximum Ambient	4Cone	LH package; from hot to room temperature	-5	-	5	%
Operating Temperature	Doens(TAmax)	UA package; from hot to room temperature	-2.5	-	7.5	%
Sensitivity Drift at Minimum Ambient	A Cono	LH package; from cold to room temperature	-3.5	-	8.5	%
Operating Temperature	(TAmin)	UA package; from cold to room temperature	-6	-	4	%

OPERATING CHARACTERISTICS Valid throughout T_A range, C_{BYPASS} = 0.1 µF, V_{CC} = 5 V; unless otherwise noted

Characteristics	Symbol	Test Conditions	Min.	Тур.	Max.	Unit ¹
Error Components (continued)						
Quiescent Voltage Output Drift Through Temperature Range	ΔV _{OUT(Q)}	Defined in terms of magnetic flux density, B	-10	-	10	G
Linearity Sensitivity Error	Lin _{ERR}		-1.5	-	1.5	%
Symmetry Sensitivity Error	Sym _{ERR}		-1.5	-	1.5	%
Ratiometry Quiescent Voltage Output Error ⁴	Rat _{VOUT(Q)}	Throughout guaranteed supply voltage range (relative to V_{CC} = 5 V)	-1.3	-	1.3	%
Patiamata (Canaitivity Error4	Bot	Throughout guaranteed supply voltage range (relative to V_{CC} = 5 V), T_A = 25°C and 150°C	-1.5	-	1.5	%
Rationeu y Sensitivity Error	RaiSens	Throughout guaranteed supply voltage range (relative to V_{CC} = 5 V), T_A = -40°C	-2	-	2	%
Sensitivity Drift Due to Package Hysteresis	∆Sens _{PKG}	T _A = 25°C, after temperature cycling	-	±2	-	%

 $\label{eq:gauss} \begin{array}{l} \texttt{16} \ (\texttt{gauss}) = 0.1 \ \texttt{mT} \ (\texttt{millitesla}). \\ \texttt{2See Characteristic Definitions section.} \\ \texttt{3f}_{\texttt{C}} \ \texttt{varies up to approximately } \texttt{±20\% over the full operating ambient temperature range and process.} \\ \texttt{4Percent change from actual value at } \mathsf{V}_{\texttt{CC}} = \texttt{5} \ \texttt{V}, \ \texttt{for a given temperature.} \end{array}$

Appendix F

Thermal imaging camera data sheet

The data sheet of the thermal imaging camera is available here:

https://fr.trotec.com/fileadmin/downloads/Temperatur/ IC085LV_IC125LV/TRT-BA-IC085LV-IC125LV-TC-001-EN.pdf

Appendix G

Selected BLDC motor characteristics

The different characteristics of the motor are gathered in the table below.

Туре	REX 30
Turn	4
Voltage (V)	63
Continuous current / max (kW)	8-20
Working rotation	1800
Weight (g)	5200
RPM/V (1)	40

TABLE G.1: BLDC motor characteristics



FIGURE G.1: Technical drawing

Further information and photos can be found on the manufacturer website:

http:

//www.rotexelectric.eu/products/bldc-motors/rex-series/