



**Study and Optimization of Materials
and Structures of Solenoids in Electro Valves**

João Rafael Fernandes

UMinho | 2022

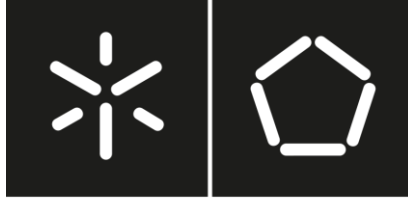


Universidade do Minho
Escola de Engenharia

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outubro de 2022



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and Structures of Solenoids in Electro Valves**

Dissertação de Mestrado
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Trabalho efetuado sob a orientação do
Professor Doutor Eurico Augusto Rodrigues de Seabra

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AGRADECIMENTOS

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Finalmente obrigado a todos os meus amigos que fizeram parte deste percurso e que estiveram lá nos momentos certos.

STATEMENT OF INTEGRITY

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ABSTRACT

Since magnetism is an area to be explored, the company felt the need to carry out a deeper study of the electromagnetic part of solenoid valves. With this being said, an action plan was created, which considered as an initial phase the creation of a theoretical basis.

For the next phase and in order to perform a benchmarking between the models developed internally, a library of models was created and with the purpose of being studied in order to find some patterns within it, and that is what happened. With the creation of a library that had more than 60 references, separated by 17 years, 10 sets of models were found with characteristics that were similar to each other and that were different from the other 9 sets.

That said, there was a need to understand how each difference affected the performance of each model, and for that, the need arose to perform electromagnetic simulations using the Maxwell software. For this, emerged the necessity of the adaptation of the models in order to reduce the number of variables during the study, and for that the coil used have been the same for all the 10 designs. Then was realized the study of the raw materials to be used in the simulation, and for that it was decided to use the same materials in all the models.

With the models ready and the material data fixed, simulations were performed for a set of 40 points for each model, counting this set of points with the combination of 10 gap distances between cores with 4 different current intensities.

That said, two practical tests were carried out using one of the models that was used as a reference, which did not undergo any adaptation. A practical test was then carried out using a tensile testing machine to measure the magnetic force. A practical test was also carried out using MagHyst and measuring the production of magnetic flux.

With the analysis of the results were obtained two different ranks, one where are presented the designs from the best to the worst suited for the proportional application and the other where the designs were also presented from the best to the worst, but in this case for the on/off application.

KEYWORDS

Hydraulic Solenoid Valves; Electromagnetism; Magnetic Simulation; Magnetic Force Evaluation; Magnetic Flux Evaluation.

RESUMO

Sendo o magnetismo uma área a explorar surgiu na empresa a necessidade de realizar um estudo mais aprofundado da parte eletromagnética das válvulas solenoides. Posto isto foi criado um plano de ação que considerou como fase inicial a criação de uma base teórica.

Para a fase seguinte e de modo a realizar um benchmarking entre os modelos desenvolvidos internamente foi criada uma biblioteca de modelos que pode ser estudada de modo a encontrar alguns padrões dentro desta, e foi isso que se sucedeu. Com a criação de uma biblioteca que contava com mais de 60 referências, separadas por 17 anos, foram encontrados 10 conjuntos de modelos com características que se assemelhavam dentre si e que se diferenciavam entre os outros 9 conjuntos.

Posto isto houve a necessidade de perceber como cada diferença afetava a performance de cada modelo, e para isso surgiu a necessidade de realizar simulações eletromagnéticas recorrendo ao software Maxwell. Para isso, surgiu a necessidade da adaptação dos modelos de modo a reduzir o número de variáveis durante o estudo, e para isso a bobina utilizada foi a mesma para todos os projetos. Após isto deu-se o estudo das matérias-primas a utilizar na simulação, e para isso decidiu-se utilizar os mesmos materiais em todos os modelos.

Com os modelos prontos e os dados dos materiais fixados foram realizadas simulações para um conjunto de 40 pontos para cada modelo, contando este conjunto de pontos com a combinação de 10 distâncias de folga entre núcleos com 4 diferentes intensidades de corrente.

Posto isto foram ainda realizados dois testes práticos recorrendo a um dos modelos que se utilizou como referência, sendo que este não sofreu qualquer adaptação. Realizou-se então um teste prático para medir a força magnética e outro para medir a produção de fluxo magnético.

Com a análise dos resultados foram obtidas duas classificações distintas, uma onde são apresentados os modelos do mais ou menos adequado para uma aplicação proporcional e a outra onde os modelos também foram apresentados do mais ao menos adequado, mas neste caso para a aplicação on/off.

PALAVRAS-CHAVE

Válvulas Solenoides Hidráulicas; Eletromagnetismo; Simulação Magnética; Análise da Força Magnética; Análise do Fluxo Magnético.

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LISTA DE ABREVIATURAS, SIGLAS E ACRÓNIMOS

SV – Solenoid Valve

H – Magnetic Field Strength [A.t/m]

mmf – Magneto-motive force [A.t]

N – Number of coil turns [t]

I – Current intensity [A]

l - Length of coil [m]

l – length of the magnetic circuit [m]

μ – magnetic permeability [H/m]

μ_0 – magnetic permeability of vacuum [H/m]

μ_r – magnetic permeability of material [H/m]

A – cross sectional area [m²]

$\Re$ - Reluctance [H^{-1}]

Φ_B or ϕ – Magnetic Flux [Wb]

λ – magnetic flux linkage [Wb.t]

B – Magnetic Field Density [T]

U - Energy

Δ - delta

F – Force [N]

dx – Gap between cores [mm]

B_r – Remanence [T]

C – Coercivity [A/m]

$\Delta \vec{E}$ – Divergence of the electric field

ϵ_0 – vacuum permittivity [F/m]

ρ – volume charge density [C / m^3]

$\Delta \vec{B}$ – Divergence of the magnetic field

U_i – Induced Voltage [H]

i – Electrical current intensity [A]

L – Inductance of the coil [H]

t – Time [s]

$I_{(t)}$ – electrical current on instant t [A]

V_s – voltage of the power supply [V]

V_L – voltage drop, across the inductor [V]

V_R – voltage drop, across the resistance [V]

R – resistance of the circuit [Ω]

I_0 – electrical current intensity on the instant before the switch off action [A]

τ – time constant of the inductor [s]

e – Natural logarithm

1. INTRODUCTION

In this chapter are presented the framing of the thesis theme and the motivation to pursue it. Being this such an interesting issue and being possible with this study to attain major developments in the evolution of the product that are the solenoid valves, the motivation for the research grows bigger.

The objectives are also presented here for a better organization and for the demonstration of the work that is planned to be developed.

1.1. Framing and Motivation

The automotive industry is continually developing technologies and strategies to increase fuel efficiency and reduce pollutant emissions [1]. The search for new solutions and the development of new technologies are a key aspect of this development. For these two aspects to be possible, companies need to dedicate resources to carry out research projects in the areas of technology they are dedicated to developing. This allocation of resources is an investment in the knowledge and improvement of technologies and products, an investment that can make a difference in the launch of more advanced and more competitive products on the market.

In the automotive field, solenoid valves are used as actuators and to control fluid pressure. Solenoid valve types that are used are 'idle speed control valves, shift control valves of automatic transmissions and control valves locked by a torque converter' [2]. The hydraulic circuits are controlled by solenoid valves through opening and closing for high pressure hydraulic fluid. Some examples of automotive applications include automatic transmission, brake system, boom control on an agricultural vehicle and hydraulic pump swash plate position control [3]

Many researchers have used parametric methods to optimize the shape of electromagnetic devices in their study [4, 5]. For example, Huang, N.B. et al. [6] studied the improvement of solenoid static electromagnetic forces and the reduction of open and closed response times of fuel injectors, optimizing the coil cross-section shape and the relative position of the coil and housing. However, the obvious disadvantages of parametric analysis methods could be found in previous studies, such as the large workload of the multi-objective and the limited number of optimization parameters. In addition, it

generally obtains a locally optimal result with lower performance than the results of global optimization algorithms. Therefore, a global optimization algorithm still needs to be used in the study of electromagnetic actuators[7]

The purpose of this work is to intensively study the designs and materials used in the automotive industry in the production of solenoids and deepen the knowledge of electromagnetism in order to find more efficient solutions for this product. The implementation of these aspects in a calculation method will also allow greater ease and optimization when developing a solenoid when it is requested by a customer with its own usage requirements. This optimization will bring advantages such as reducing the calculation time and the number of simulations needed to obtain the final solution.

1.2. Objectives

This work has as objectives the following points:

- Creation of an electromagnetism literature.
- Creation of state of art for solenoid valves.
- Creation of a solenoid valve library with the products developed by the company.
- Analysis of different coil designs used in solenoid valves in the automotive industry.
- Analysis of different materials used in solenoid valves in the automotive industry.
- Analysis of the calculation method for the solenoid valve development used by company.
- Optimization of the calculation method with the data obtained by the analysis.

1.3. Company Presentation

Bontaz started in 1965 in a small workshop in Marnaz, in the heart of the French Alps, and a few decades later had become the world leader in automotive hydraulic controls.

The company started when Yves Bontaz started making precision-turned parts at his family's house. He initially manufactured parts for local businesses and only then established direct business relationships with French automakers and parts manufacturers.

After 1980, Bontaz focused its strengths on manufacturing brake and engine subassemblies, primarily for the European automotive industry. At the same time strengthens its R&D department in France and became a trusted partner by developing assemblies.

Between 1995 and 2010, the company evolved into a tier 1 equipment manufacturer, supported its growing customers base and establishes foreign subsidiaries, notably in developing countries like Czech Republic, Brazil, China, US, Korea, Japan and Tunisia.

From 2010 to the present, Bontaz became the world leader in automotive hydraulic functions. It continues to expand in international markets while strengthening its local presence. New sites are created in India, Morocco and Portugal.

Across the world, affiliate companies became more and more multifaceted integrating various activities such as production, assembly, sales, R&D [8].

BCTP is an R&D site of Bontaz in Portugal, having 4 teams developing 2 kinds of products, Piston Cooling Jets and Hydraulic Solenoid Valves. The Portuguese site also has an industrialization team that develops the production lines that will then be mounted in production sites such as Tunisia and China for the mass production of the products developed.

BCTP also has a mechanic and injection department, which help with the prototype production. In the matters of support to the R&D, departments such as quality, simulation, metrology and laboratory tests are also part of the BCTP site.

2. THEORETICAL FOUNDATION

The main purpose of this paper is to study an electromagnetic mechanism that is the solenoid valve. For that the theoretical foundations behind the electromagnetism should be presented to develop the know-how needed to understand all the topics that are addressed here.

2.1. Magnetic Field

A magnetic field is a vector field in the neighbourhood of a magnet, electric current, or changing electric field, in which magnetic forces are observable. Magnetic fields such as that of Earth cause magnetic compass needles and other permanent magnets to line up in the direction of the field. Magnetic fields force moving electrically charged particles in a circular or helical path [9].

2.1.1. Permanent Magnet

Starting with a single magnet like a bar of iron, as represented in the Figure 1, is possible to say that a permanent magnet is a piece of material that can maintain his own permanent magnetic field. The magnetic field lines flow inside the material and through the surrounding environment connecting the north pole to the south pole and the magnetic field generated by the permanent magnet is identified as $\vec{B}$.

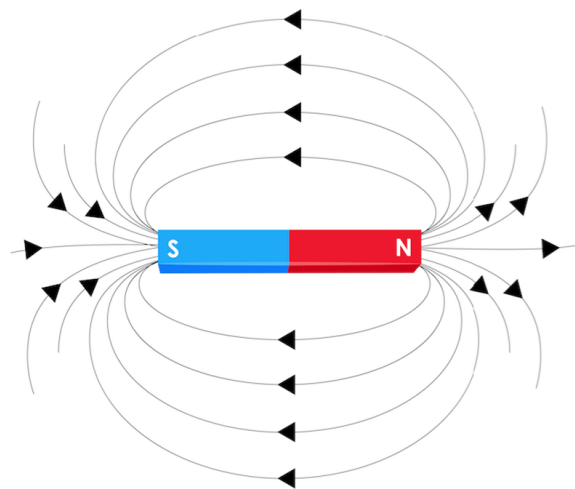


Figure 1 - Magnetic field lines on a bar magnet [10].

2.1.2. Solenoid

For a solenoid, that is usually a coil of wire like shown in the Figure 2, to have a magnetic field, a current must be flowing through the wire and only with this the magnetic field will be created around the coil.

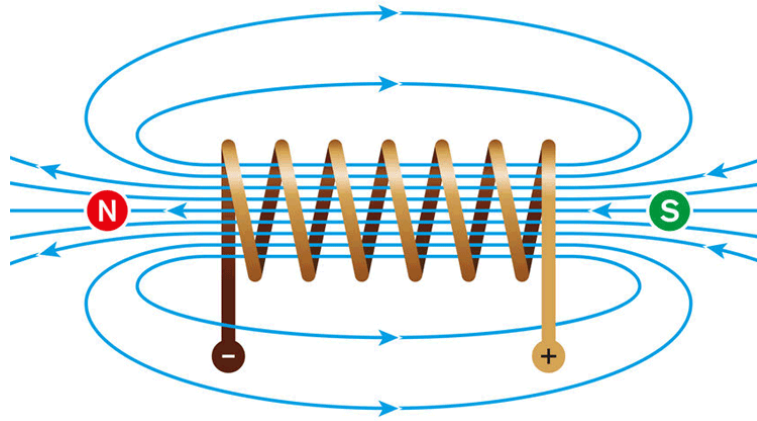


Figure 2 – Solenoid Scheme [11].

The magnetic field of the solenoid is also a B field, and the strength of this magnetic field is identified as $\vec{H}$ and is calculated by the following formula:

$$\vec{H} = \frac{\text{mmf}}{l} \quad (1)$$

$$\text{mmf} = N \cdot I \quad (2)$$

$$\vec{H} = \frac{N \cdot I}{l} \quad (3)$$

From the formula above, the magnetic field H generated by the coil depends on:

- Number of turns – More turns create a stronger magnetic field.
- Current intensity – Higher current intensity creates a stronger magnetic field.
- Length of coil – A shorter coil creates a stronger magnetic field.

It is important to notice that the MMF (magneto-motive force) is not a force in the classic Newtonian mechanic's concept. This "force" is just the amount of electrical charge that is going through the totality of the winding turns in the solenoid.

The magnetic field $\vec{B}$, can be related by the formula,

$$\vec{B} = \mu_0 \times \vec{H} \quad (4)$$

where appears a new variable, the μ which is the magnetic permeability. For the case of the solenoid the permeability that should be considered is the permeability of the vacuum once there isn't any material surrounding the coil.

2.1.3. Electromagnet

The concept of basis to the solenoid valve is the electromagnet where a metallic core is surrounded by a coil of wire as represented by the Figure 3. The core is usually made of a material with ferromagnetic properties. When activated, the coil generates a magnetic field that will align the domains inside this ferromagnetic material and turn the core into a magnet capable of emanate his own magnetic field. The properties of materials will be described in more detail after.

The B-field of this electromagnet will now be much stronger than the one generated by the single coil.

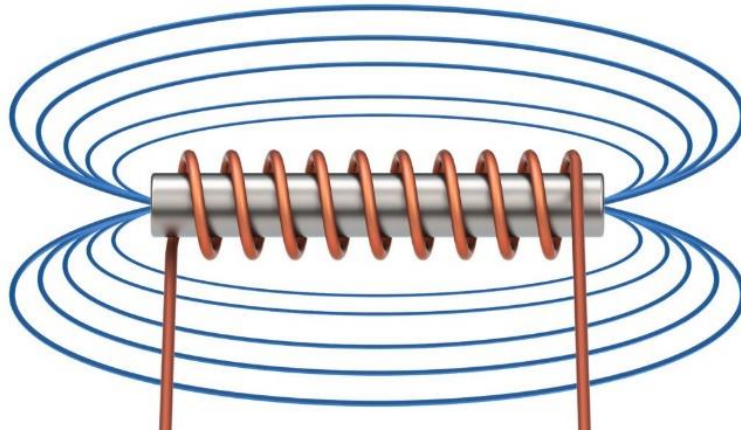


Figure 3 – Representation of a magnetic field flowing through a piece of metal using a coil of wire [12].

For this case, the formula that relates the magnetic field created by the electromagnet with the coil is,

$$\vec{B} = \mu \times \vec{H} \quad (5)$$

and is possible to notice that for this case the variable that changes is the permeability - μ that for this case must be related with the material of the core. For that, there is another equation that must be presented,

$$\mu = \mu_0 \times \mu_r \quad (6)$$

and with this equation is possible to see that the magnetic permeability used for this case must be the multiplication of the magnetic permeability of vacuum by the relative magnetic permeability, which is the indicator of the capability of the material to conduct magnetic fields. The increase of the magnetic field is due to the fact that a ferromagnetic material has a much higher permeability than the vacuum.

2.1.3.1. B-H Curve

Since the magnetic permeability has already been introduced, emerges the necessity to explain from where it comes and what is associated to it. The magnetic permeability of a material is obtained by his B-H Curve that is the result of a test realized on a sample. This test uses the concept of electromagnet and for that there is the need to use two solenoids instead of one. The first solenoid will be energized creating a magnetic field on the system and the second one will measure its intensity. So, the curve presented in the Figure 4 it's the result of this measurements along the increase of the electric current to a certain value. The relation of the B-field with the H-field, being the H related with the current as seen on the equation (3), will be the magnetic permeability of the material that has being measured as seen by the graph and by the equation (5).

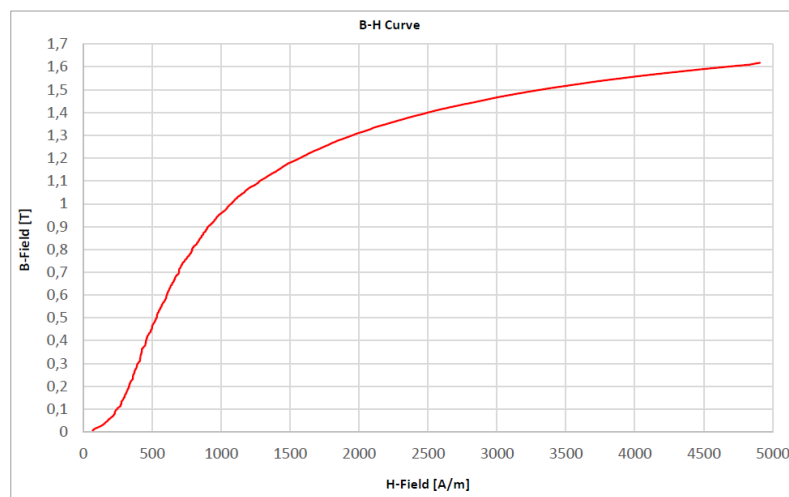


Figure 4 - B-H Curve of a magnetic Material

2.1.3.2. Magnetic Materials

Magnetic materials can be categorized as ferromagnetic, diamagnetic, or paramagnetic materials based on their reaction when placed in a magnetic field. The main difference between these materials is the way their domains line up when exposed to an external magnetic field.

Ferromagnetic materials have randomly aligned magnetic domains, as seen in the Figure 5 on left, that cancel each other out. When an external magnetic field is applied to ferromagnetic materials the individual domains are forced into alignment, as represented in Figure 5 on right, and in this moment this material is effectively a magnet emanating a magnetic field B [13].

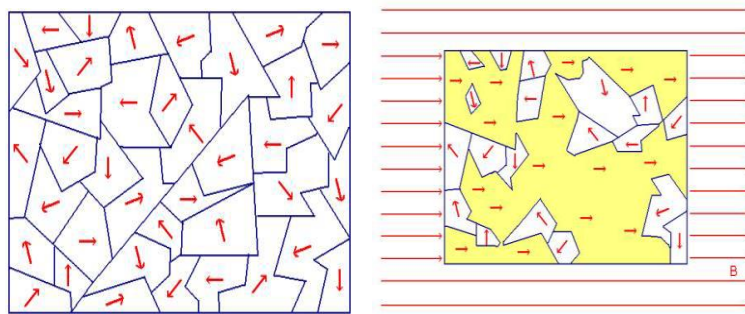


Figure 5 – Alignment of the domains inside a ferromagnetic material [14].

Diamagnetic materials have a weak, negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field and do not retain the magnetic properties when the external field is removed. In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom. Diamagnetic properties arise from the realignment of the electron paths under the influence of an external magnetic field. Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.

Paramagnetic materials have a small, positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field and do not retain the magnetic properties when the external field is removed. Paramagnetic properties are due to the presence of some unpaired electrons, and from the realignment of the electron paths caused by the external magnetic field. Paramagnetic materials include magnesium, molybdenum, lithium, and tantalum [15].

Magnetic materials can also be categorized as magnetically hard or magnetically soft materials. The magnetic soft materials are easily magnetized but the induced magnetism is usually temporary. For example, rubbing a permanent magnet on a nail, the nail will become temporarily magnetized and will emit their own weak magnetic field. Magnetic hard materials can be also magnetized by a strong external magnetic field, such as those generated by an electromagnet. The difference being that magnetically hard

materials will remain magnetized indefinitely unless they are demagnetized by an opposing magnetic field. Magnetically hard materials are used to create permanent magnets.

2.1.4. Solenoid Valve

The solenoid valve (SV), as is possible to see in the Figure 6, operates with the principle of the electromagnet presented before. When the SV is supplied with a certain amount of electric current, more precisely the copper coil wound on the bobbin, a magnetic field is created in the magnetic circuit composed by the shell, the mobile core, the fixed core, and plates, which are materials with ferromagnetic properties. Now these components became magnets, acquiring magnetic polarity, and attracting each other closing the air gaps between them. Being the mobile core the only component that is movable, the air gap that matters is the one between it and the fixed core, and the closing of this gap will move the mobile core. With the movement of the mobile core the needle will be pushed and consequently the piston will also move. The change in the position of the piston will affect the flow of the hydraulic circuits connected to the ports 1, 2 and 3, closing or opening these ports. Is important note that some solenoid valves can have 3 ports as the represented but can also have depending on the application.

When the SV is considered proportional the amount of electric current controls the displacement of the mobile core toward the fixed core and with these the piston opens more or less the ports. With these is also possible to control the amount of oil that is flowing through the ports.

When the SV is considered on/off the, with normally 2 ports, the purpose is to have an open or closed hydraulic circuit, so if the SV is normally open, with the activation of the SV the mobile core will move all the way toward the fixed core (maximum course) and close the circuit.

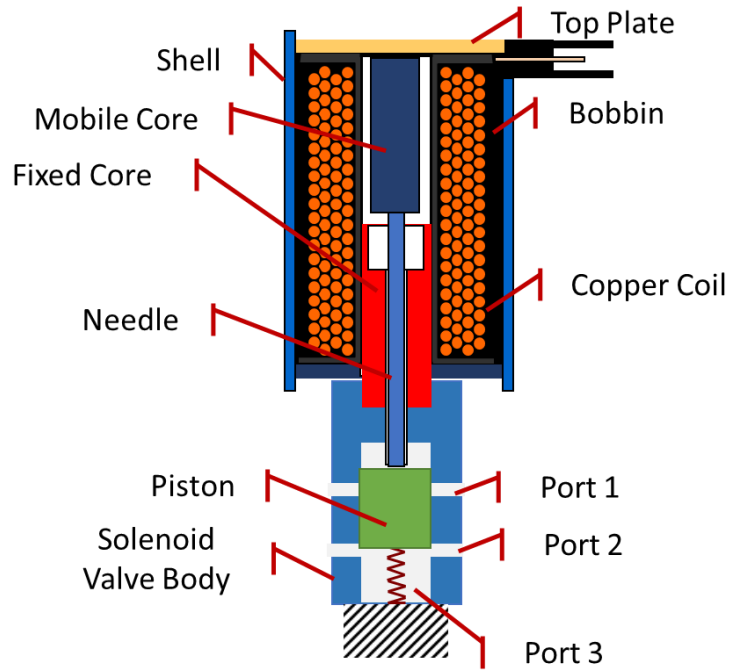


Figure 6 – Identification of the constituent parts of a solenoid valve

2.1.5. Magnetic Circuit

The magnetic circuit of the solenoid valve is only composed by the shell, the cores, and the plates, as well as by the copper coil.

2.1.5.1. Magnetic circuit vs Electric Circuit

For a better explanation of the magnetic circuit is presented the analogy with the electric circuit. Both schemes of the electric circuit and magnetic circuit are presented in the Figure 7.

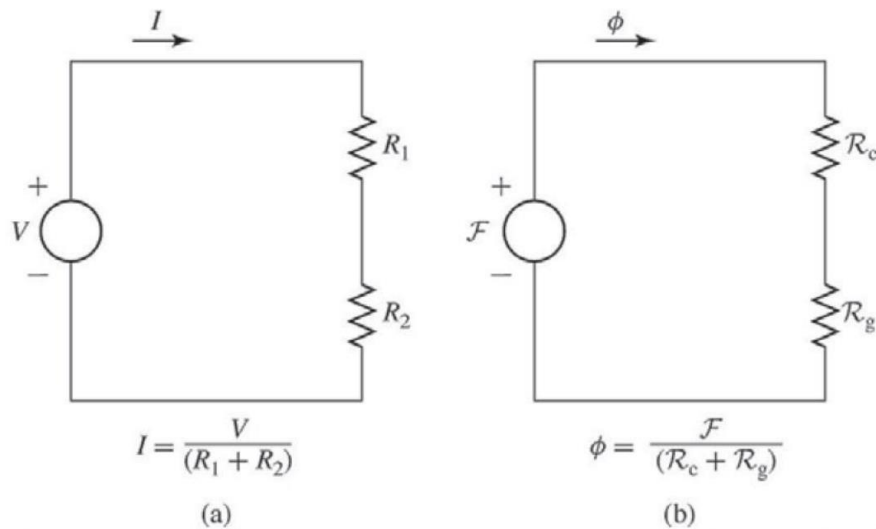


Figure 7 – Schematic representation of Electrical Circuit (a) and Magnetic Circuit (b)

In the Table 1 are presented the analogy between the variables for the analysis of electric circuits and for the analysis of the magnetic circuits.

Table 1 – Analogy between the variables of electric circuits vs magnetic circuits

Electric Circuit	Magnetic Circuit
Voltage [V]	Magneto Motive Force [$\mathcal{F}$] or [mmf]
Current [I]	Magnetic Flux [Φ_B]
Resistance [R]	Reluctance [$\mathfrak{R}$]
Conductivity [σ]	Permeability [μ]
Current Density [J]	Magnetic Flux Density [B]

In the Table 2 are presented the equations used for the analysis of electric circuits and analogously the equations used for the analysis of magnetic circuits.

Table 2 – Analogy between equations applied to electric circuits vs magnetic circuits

Electric Circuit	Magnetic Circuit
$V = R \cdot I$	$mmf = \Phi_B \cdot \mathfrak{R}$
$I = \frac{V}{R}$	$\Phi_B = \frac{mmf}{\mathfrak{R}}$
$R = \frac{l}{\sigma \cdot A}$	$\mathfrak{R} = \frac{l}{\mu \cdot A}$

With these analogies is possible to note that a magnetic circuit is not so different of an electric circuit being possible to understand one based on the other.

2.1.5.2. Magnetic Reluctance

Magnetic reluctance or magnetic resistance is a concept used on magnetic circuit analysis. It is defined as the ratio between the magnetomotive force (mmf) and the magnetic flux (Φ_B). It represents the opposition to the magnetic flux and depends on the geometry and composition of the object [16] In the case of the solenoid valve there are a set of parts that contribute to the total reluctance of the valve, as represented in the Figure 8.

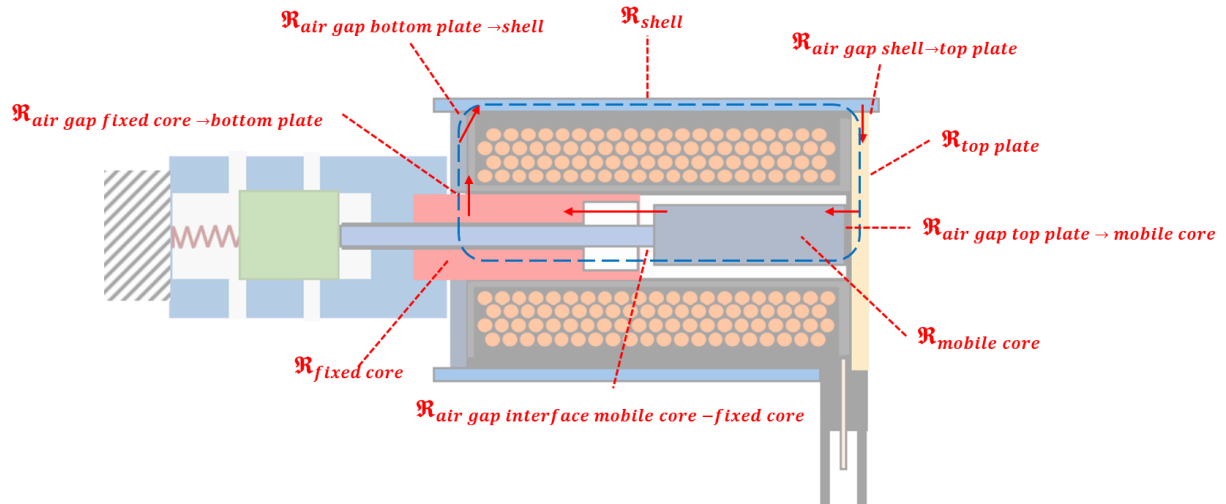


Figure 8 – Representation of the magnetic field circuit of a solenoid valve including the reluctances of the components involved.

The magnetic reluctance is represented by $\mathfrak{R}$ and the equation used is the following:

$$\mathfrak{R} = \frac{l}{\mu A} \quad (7)$$

As seen in the Figure 8, the magnetic reluctance for a solenoid valve is the sum of all the magnetic reluctances of the different parts in the circuit. This can be represented by the equation:

$$\mathfrak{R}_{solenoid\ valve} = \sum \mathfrak{R}_{air\ gaps\ between\ components} + \mathfrak{R}_{components} \quad (8)$$

2.1.5.3. Magnetic Flux

The magnetic field created by the current in a solenoid valve can be represented as in the Figure

9.

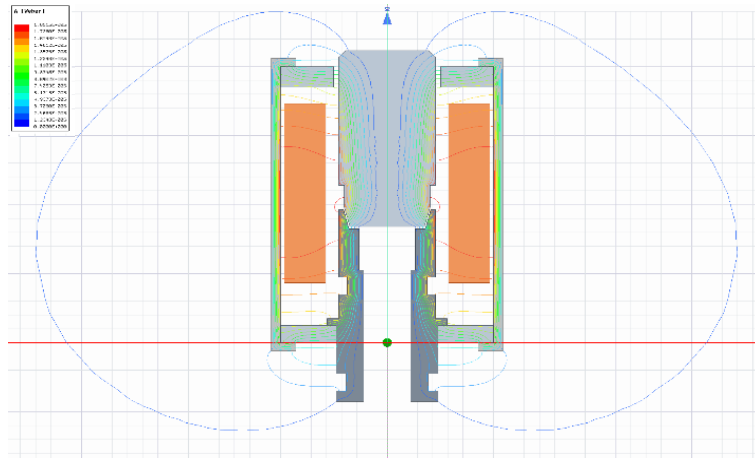


Figure 9 – Magnetic field of a solenoid valve obtained by simulation.

The magnetic flux of this field is given by Φ_B and this is obtained by the following equation:

$$\Phi_B = \frac{mmf}{\mathfrak{R}} \quad (9)$$

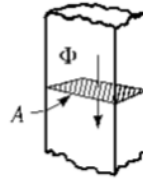


Figure 10 – Scheme representative of the magnetic reluctance.

As the magnetic field Φ_B is dependent on the geometry cross-section of the component it can also be calculated for each part of the magnetic circuit and the equation used for that is:

$$\Phi_B = B * A_m \quad (10)$$

The magnetic flux is constant along the circuit and this principle can be represented by the Figure 11. In this representation is possible to observe that the amount of field lines in the cross-section a-a' is equal to the amount of field lines in the cross-section b-b'. The variable that is changing in these two cross-sections is the magnetic density B, because once the cross section is bigger for the same amount of field lines the magnetic density B will also be bigger for this section.

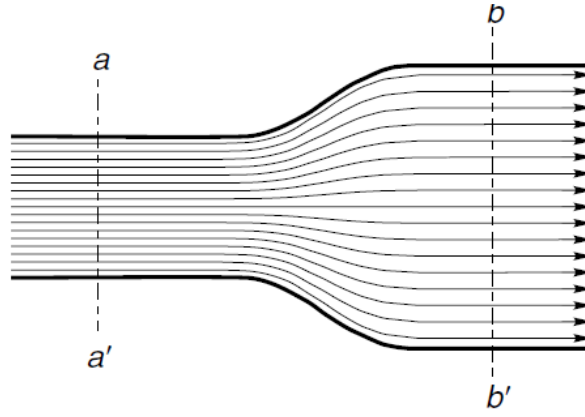


Figure 11 – Representation of the magnetic field density

2.1.6. Magnetic Force deduction based on the energy variation of the magnetic field

Based on energy conservation is possible to obtain an approximation of how much force can a solenoid exert. When the solenoid is empty the equation for the energy exerted by the magnetic field is:

$$U = (volume)(magnetic\ energy\ density) \quad (11)$$

$$U = (volume) \left(\frac{B^2}{2\mu_0} \right) \quad (12)$$

When the solenoid is filled with some kind of material, the magnetic permeability of it must be considered to calculate the energy of the magnetic field and the equation that reflects it is:

$$U = (volume) \left(\frac{B^2}{2\mu_0} \right) \left(\frac{\mu_r}{\mu_0} \right) \quad (13)$$

On the solenoid valves is possible to consider the air gap between the mobile core and the fixed core as an empty space where the magnetic force will be exerted. For that the Equation (13) is the one that will be most suitable for this application once the attraction force developed in the space between the cores is the force that will be relevant for the development of the solenoid valves. Considering that the cores are also inside the solenoid, is questionable how the material properties influence this method, but

With this being said is possible to calculate the magnetic force similarly to the gravitational force as represented in the Figure 12. Once the gravitational force of a body can be calculated for a specific height relative to the earth surface (height = 0 m) based on the potential energy variation, also the magnetic force can be calculated for a specific distance between the mobile core and the fixed core considering analogously the fixed core surface as the earth surface ($dx = 0$ m).

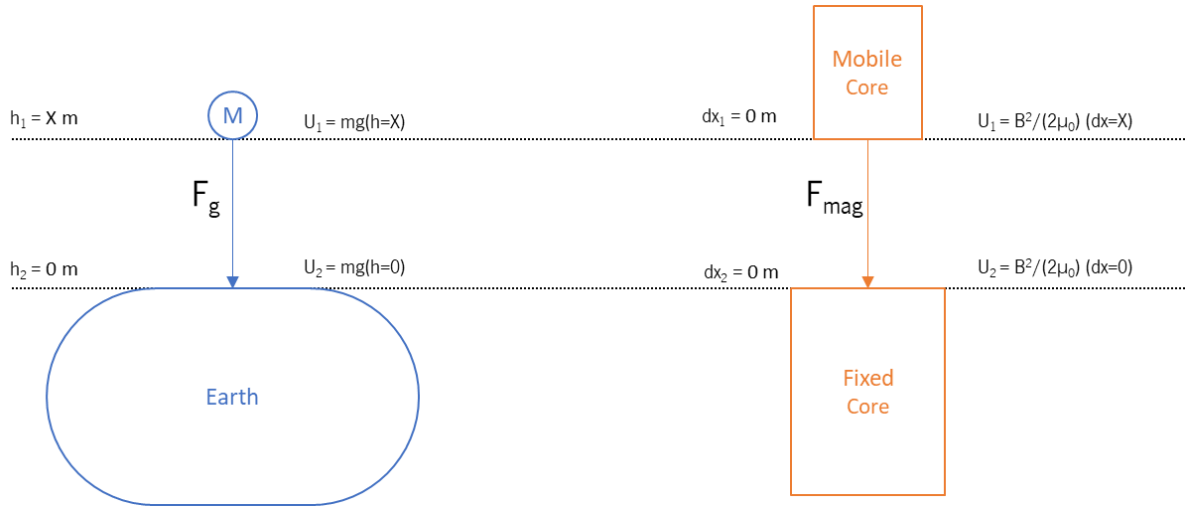


Figure 12 – Comparative Scheme between gravitational force and magnetic force

For the calculation of a force recurring to the energy variation the equation that needs to be used is:

$$F_g = \frac{\Delta U}{dx} \quad (14)$$

where the ΔU represents the energy variation and the dx the displacement, or position variation.

So, for the gravitational force is possible to consider that the U_2 is 0 once the $h = 0$ m. Considering that the height will be the same displacement dx is possible to cut both of them from the equation and assuming the final equation for the force calculation as:

$$F_g = mg \quad (15)$$

Analogously for the magnetic force, the U_2 will also be 0 once the dx for the final position is 0, considering here the dx as the same dx of the equation 14, they can also both be cut from the final equation which in this case will be:

$$F_{mag} = \frac{B^2 A}{2\mu_0} \quad (16)$$

For the purpose of better understanding the equation 16 is transformed to work not with the magnetic density but instead with the magnetic flux and this equation will be:

$$F_{mag} = \frac{\Phi^2}{2\mu_0 A} \quad (17)$$

and this is the equation that allows the calculation of the magnetic force of attraction between two opposite poles inside a solenoid.

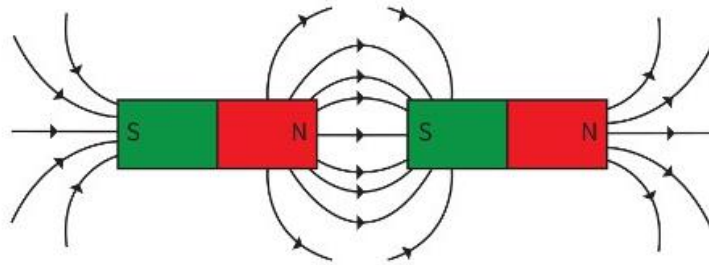


Figure 13 – Attraction between opposite poles [17]

In the Appendix I is presented the complete deduction of the magnetic force used for the solenoid valves.

2.1.7. Magnetic Properties

In this chapter are presented the magnetic properties of the magnetic materials.

2.1.7.1. Remanence and Coercivity

The plot represented in the Figure 14 is an example of the Hysteresis Curve of a material and is also obtained from a magnetic analysis. With this curve is possible to see that when a ferromagnetic material is subject to the action of a magnetic field **H**, a magnetic field **B** develops in it and the material is transformed into a magnet (point **a** in the graph).

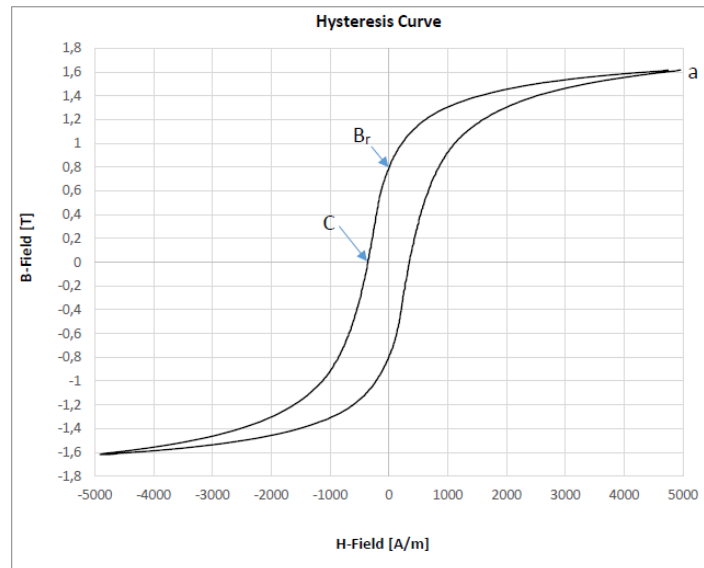


Figure 14 – Hysteresis Curve of a magnetic material

Theoretically the expected is that when the magnetic field $\mathbf{H}$ is removed (coil switched off), the material would went back to its initial state, that is the point (0,0) in the graph, but the reality is a little bit different and when the magnetic field $\mathbf{H}$ is removed, a residual magnetic field $\mathbf{B}$ remains in the material, this residual magnetic field it's represented in the graph by the point $\mathbf{B}_r$ (intersection of the curve with the positive branch of the “Y” axis) and the value of the curve at this point is denominated as the Remanence value of the material.

The other property that is represented in the graph by the point $\mathbf{C}$ (intersection of the curve with the negative branch of the “X” axis) is the Coercivity. The value of the coercivity of a material is the amount of $\mathbf{H}$ -field necessary to apply to a material in order to reduce the residual magnetization to null.

An important note is that the residual magnetization is more prone to exist in areas with higher $\mathbf{B}$ -field values.

2.1.8. Maxwell's Equations

After all the things that have been studied in the previous chapters it can be summarized in the four fundamental Maxwell's Equations.

$$\text{(Gauss's Law)} \quad \nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad (19)$$

$$\text{(Gauss's Law for Magnetism)} \quad \nabla \cdot \vec{B} = 0 \quad (20)$$

$$\text{(Faraday's Law)} \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (21)$$

$$\text{(Ampere's Law)} \quad \nabla \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (22)$$

The first of the four of Maxwell's Equations is based on concepts developed by Carl Friedrich Gauss, and it is a formula that explains how electrical charges create electrical fields. It basically says that if there is an electrical charge there will be an electrical field emanating from it. The strength of this electrical field is possible to calculate with this equation and it's proportional to the constant epsilon, the vacuum permittivity, which in other words can be explained as the resistance of free space against the formation of an electrical field.

The second is the Gauss's Law for Magnetism and it says that there are no magnetic charges in the universe, in other words there no magnetic monopoles, a piece of metal always have the two magnetic poles no matter how small it is.

In the third equation says that if a magnetic field is changing with the time an electrical field will be created by this movement. In simple words if a magnet is moving, an electrical field will be created, and this is what happens on an electrical generator, when large magnets are put in movement around a coil of wire, this movement create an electrical field in the wire that consequently generates an electrical current in this same wire.

The fourth and last Maxwell's Equation explains that if there is a moving charge flowing through a wire, a magnetic field is generated. This equation allows the calculation of the magnetic field strength. So, if there is a current flowing through a wire, and the objective is to know how strong the magnetic field would be one meter away of the wire, will be required a constant called μ_0 , known by the permeability of

the vacuum that is the ability of free space to allow magnetic lines through it. But this explanation is only for the first term of the equation, the second term says that the moving electric fields can also create a magnetic field, and this was the Maxwell's addition to Ampere's Law[18].

3. STATE OF ART

In this chapter is presented initially the history of the solenoid valves and his operation. The applications of solenoid valves on the various systems are also exposed in this chapter and with that is possible to understand the versatility of the product on the automotive industry.

3.1. Solenoid Valves

The solenoid valves are used nowadays for the control of other systems in the many different areas of the industry. In this paper the study will be focused on the solenoid valves used in the automotive industry.

3.1.1. History

The first solenoid valves (SVs) appeared with the solenoid control valve, produced, and sold in 1910. In 1950, the manufacturers started producing SVs moulded in plastic. The change for the plastic made the SVs more efficient, reliable, and resistant to the corrosion and to chemical products.

That improvement trend continued to the final of the 20th century. By example, since the 70's, the manufacturers started producing SVs of automatic shutdown, which are safer and easier to operate than the valves with manual control of shutdown.

In the 90's, governs of all worlds, as well as independent companies, started to create standardizations for SVs, what enabled a greater frequency of international trade, facilitate the cooperation between companies and facilitate the maintenance. Today, the newest patterns also restrict the use of dangerous substances in the making of the valves, to improve their compatibility with the environment. Nowadays. The bigger part of the manufacturing and the innovation of the valves its focused-on health and sustainability [19].

3.1.2. Operation

A solenoid valve is a device where a magnetic field is generated by the passage of an electric current, and with this, a magnetic force moves a mechanism to regulate the opening or the closing of a fluid (liquid or gas) flow in a circuit. Then it is an electromechanically device possible to represent by the scheme of Figure 15.

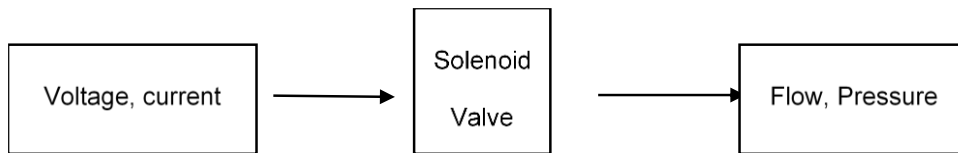


Figure 15 - Solenoid Valve Operation Scheme

There are different types of solenoid valves, and they can be characterized relatively to the control or the arrangement of the SV.

In the control we have two kinds of SV, the ON/OFF and the proportional. Regarding the arrangement they can be normally forward or normally backward.

The ON/OFF opens or closes completely depending on the arrangement when is supplied with electrical power. The proportional variates the opening or the closing according the effective current and voltage applied.

3.1.3. Applications

Some of the applications of the solenoid valves in the automotive industry are exposed in this sub-chapter. The understanding of these applications is relevant to acquire a better know-how of the solenoid valve's operation when applied to certain systems.

3.1.3.1. Oil Pump

One of the various applications of the solenoid valves are the oil pumps, most precisely the variable displacement oil pumps. This type of pump provides an active control over gallery oil pressure. An illustration of this pumps is shown in Figure 16. When the engine starts, the oil pressure needs to be built as quickly as possible, so since no pressure is applied yet to the control surface, the control spring pushes the adjustment ring against the full flow stop. As the spaces between the vanes on the suction and pressure sides are fully open, the oil pump delivers the maximum oil quantity for the respective engine speed to the oil circuit [20].

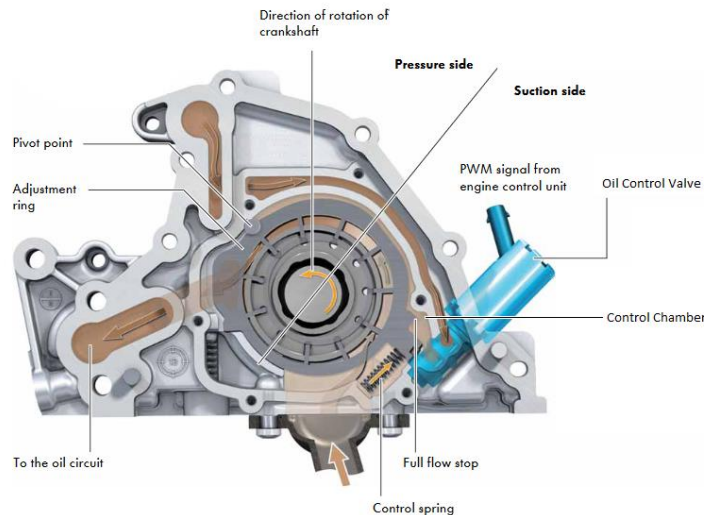


Figure 16 – Representation of an oil pump with a solenoid valve integrated [20].

While the engine is running, the oil pressure is continuously variably controlled in relation to the load, engine speed and oil temperature by means of a map. The valve for oil pressure control is activated with PWM (Pulse Width Modulation) signal and opens the corresponding flow cross-section for the oil from the oil circuit. The oil reaches the control surface, turns the adjustment ring and adjusts the oil pressure accordingly [20].

When the oil pump is reducing the oil delivery quantity and oil pressure as can be seen in the Figure 17 - (b), the oil control valve is activated by the engine control unit using a PWM signal with a large pulse width. A larger flow cross-section is opened to the control surface on the adjustment ring. The oil pressure acts on the control surface and the resulting force is greater than that of the control spring and turns the adjustment ring clockwise to the centre of the cane-type oil pump. The delivery chamber on the suction and pressure sides becomes smaller and less oil is delivered to the oil circuit [20].

Otherwise, when the oil quantity and pressure need to be increased, the oil control valve is activated by the engine control unit using a PWM signal with a small pulse width or can even be totally deactivated. This way the flow cross section to the control surface of the adjustment ring is reduced and a lower oil pressure acts on the control surface. In this moment the resulting force is smaller than that of the control spring and turns the adjustment ring anti-clockwise towards the full stop. The delivery chamber on the suction and pressure sides becomes larger and the oil pump delivers a larger quantity of oil to the oil circuit [20].

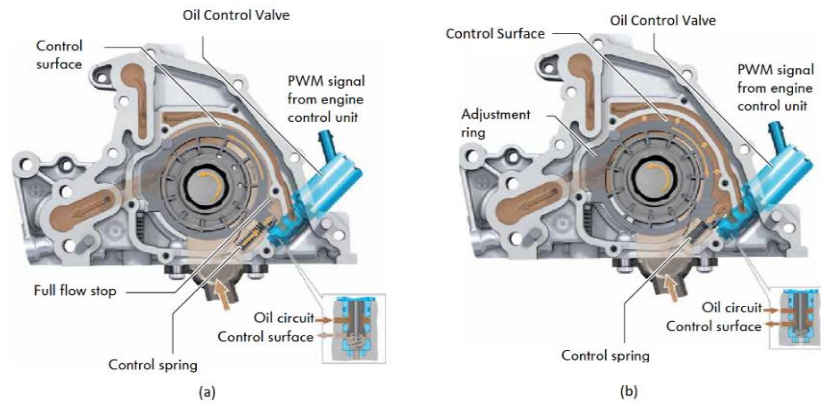


Figure 17 – Operation of the oil pump controlled by the solenoid valve [20].

If for some reason there is no signal to activate the oil control valve, this has a fail-safe mode that will allow the valve to control the oil pressure delivered by the oil pump without current. This Fail-Safe Mode (or Second Level Regulation) operates like a safety for the system and allows it to operate only hydraulically. When the oil quantity and pressure delivered by the oil pump is too high, the valve detects the high pressure and relieves part of that pressure to another chamber. This way the oil pump decreases the oil pressure and quantity delivered.

3.1.3.2. Piston Cooling Jet

Nowadays piston cooling jets (PCJ) are used in more and more engines, to spray lubrication under pistons to cool down, improve mechanical and thermal properties, as seen in the Figure 18. Explosion in the engine needs lubrication, cooling and temperature regulation. Due to that and having the piston the highest lubrication oil demand in the engine, about 40% of the oil flow, the PCJ plays a very important role in the engine temperature management, being the main goal to have the right temperature all the time. PCJ management will also allow to reduce the oil consumption and to attain the main goal that is to downsize the lubrication system.

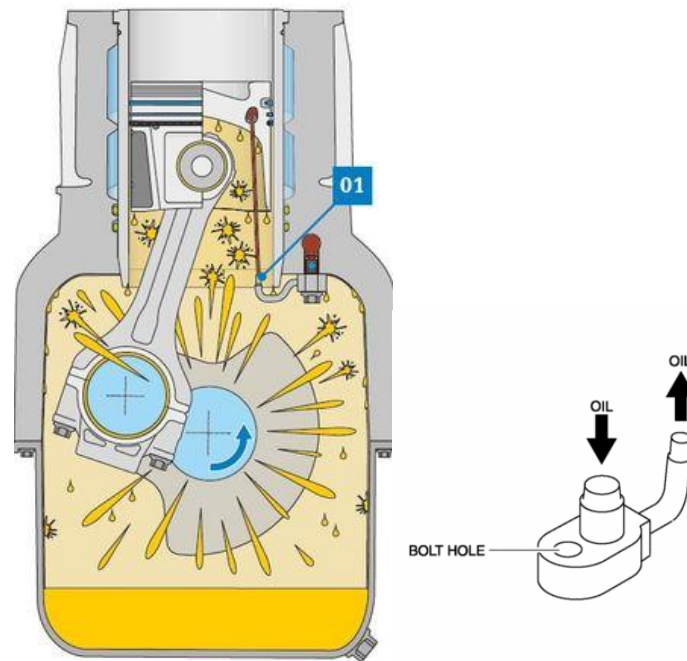


Figure 18 – Representation of the function of a Piston Cooling Jet [21], [22].

PCJ management can be attained using solenoid valves that are going to manage the oil flow of PCJ with higher efficiency, with this the lubrication will be optimized and complemented with the right temperature the fuel consumption will be reduced. The maintenance of the engine temperature will also reduce the emission level of the engine.[23]

3.1.3.3. Water Regulation / Coolant Switch Valves

Coolant switch valves control the coolant flow in side-flow cooling circuits of the powertrain and in the heating circuits of the passenger compartments. In hybrid and electric vehicles, they can be used for coolant flow distribution, e.g., for cooling the battery and power electronics. They increase comfort, optimize performance, and reduce CO_2 emissions [24].

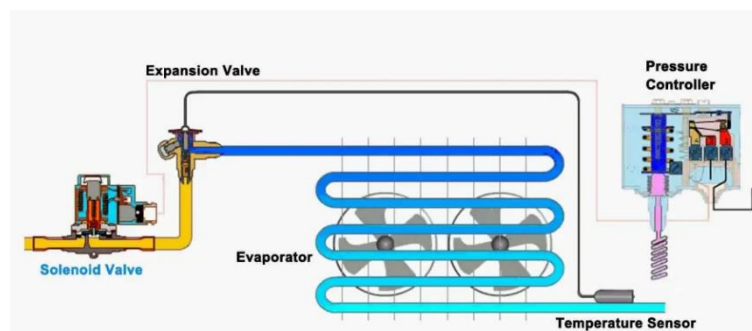


Figure 19 – Representation of a water-cooling system that uses a solenoid valve for control [25].

3.1.3.4. Engine Brake System

Another application of the solenoid valves is in engine brake systems. In a specific engine break mechanism called Jake Brake system, name which refers to the Jacobs brand of engine brakes, the solenoid valves are used to control the oil flow to the circuit represented in the Figure 20.

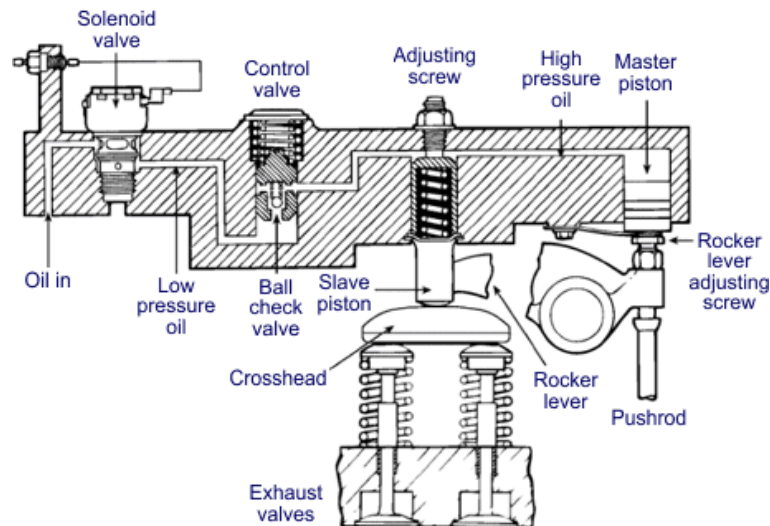


Figure 20 – Application of a solenoid valve in the engine brake system [26].

The typical compression release engine brake, as originally developed, uses an add-on hydraulic system using engine oil. When activated, the motion of the fuel injector rocker arm is transferred to the engine exhaust valve(s). This occurs very near the engine's "top dead centre" (or TDC) and releases the compressed air in the cylinder so that the energy is not returned to the crankshaft. Energy is instead expelled out the exhaust system rather than being retained in the drivetrain. If used properly, a compression release brake can assist a vehicle to maintain speed or even slow it with little or no use of the service brakes. The power of this type can be around the same as the engine power [27].

3.1.3.5. Automatic Gearbox

The solenoid valves used in an automatic transmission, control the flow of a proper transmission fluid into and through the transmission. In modern transmissions, the transmission solenoid generally comes in a pack which is installed in the transmission control unit, the transmission control module, or a transmission valve body, as represented in the Figure 21. Transmission fluid is critical to the function of the transmission. If its flow is impeded or hindered, your transmission cannot operate properly.

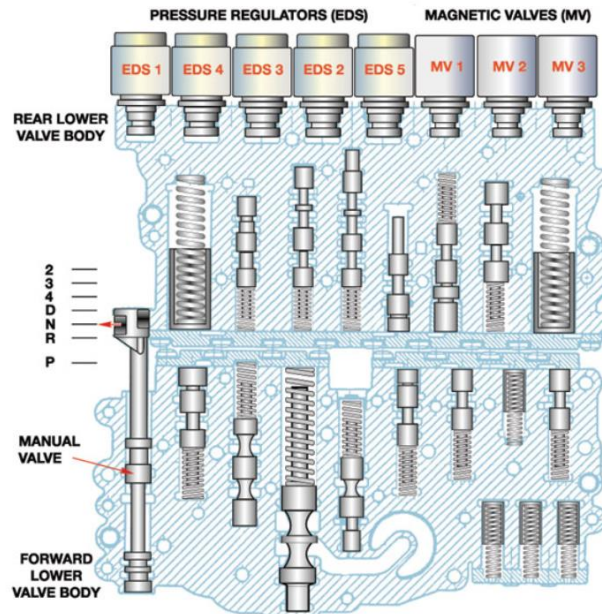


Figure 21 – Application of solenoid valves in order to control an automatic gearbox.[28]

Transmission solenoids are powered by an electrical current supplied by the transmission controller or computer. This is how it works: the transmission computer sends out instructions to the individual transmission solenoids in the pack which then direct transmission fluid to specific clutch packs or servo valves in order to control gear shifting to suit given driving conditions and engine requirements [29]

4. BONTAZ SOLENOID VALVE LIBRARY

To compare the coil designs, a deep study of all the projects developed by the company was made. From this study a chronologic organization was made to see the evolution of this product since the first developments. All the different specifications as materials, coil resistance, magneto motive force and others were collected into this library which allows the comparison between the different projects developed.

After the information was collected the different solenoid valves were evaluated and separated in ten different types based on the structure that is more relevant to the magnetic circuit.

5. EXPERIMENTAL PROCEDURE

In this chapter are presented all the procedures for the tests and analysis requested for this dissertation.

5.1. Magnetic Test Procedure for Material Evaluation

Magnetic properties are a lacking point on materials datasheets. In the case of the hard magnetic materials, as magnets, it could not be true, but for the soft magnetic materials usually ferromagnetic steels that can also become magnetic it is. For the magnetic simulations the B-H Curve of the material, where the magnetic permeability can be obtained, is the essential data that is needed to create a real-life approximated simulation, and most of the times is not present in the material datasheet.

The purpose of the magnetic test realized with the Maghyst represented in the Figure 22 is to measure the magnetic permeability of materials. The output curves of this test are the B-H curve and the magnetization hysteresis curve of the material.



Figure 22 – MagHyst® Modular for magnetic measurements [30]

To perform the measurements on the MagHyst modular, external adaptors must be used, and the company offers three kinds of adapters. The differentiation factor for the adapters is the samples geometry used for each one, the samples can be rods, rings or metal sheets.

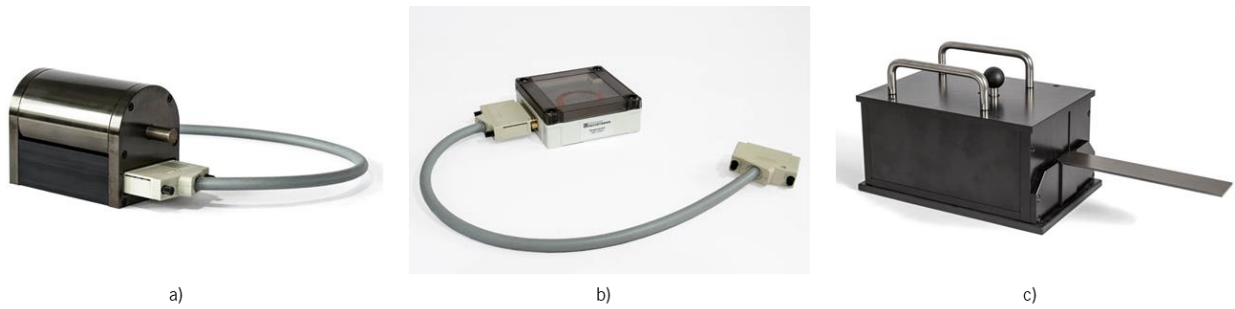


Figure 23 – Maghyst modular adapters; a) rod adapter; b) toroidal adapter; c) sheet adapter [31]

The rod adapter, presented in the Figure 23–a), is the adapter used in the measurement tests for this dissertation, for this adapter the sample should be a metal bar with a diameter of 10 mm and a minimum length of 120 mm. In the case of the toroidal adapter, present in the Figure 23–b), the sample should be a toroidal ring with an outer diameter of 50 mm, an inner diameter of 40 mm and a height of 10 mm. Finally, for the sheet adapter presented in Figure 23–c), the sample should be a sheet metal with the minimum length of 150 mm, the maximum thickness of 3 mm and the width of 30 mm [31].

On the Figure 24 is possible to observe the rod adapter mounted in the MagHyst modular. To perform the magnetic tests this is the assembly that need to be done in the first place.



Figure 24 - MagHyst modular and rod adapter mounted for testing

To perform the magnetic tests there is a procedure that need to be done according with the following steps:

The first step is to prepare samples of the materials that we intend to study, with the adapter required dimensions, as seen in the Figure 25.

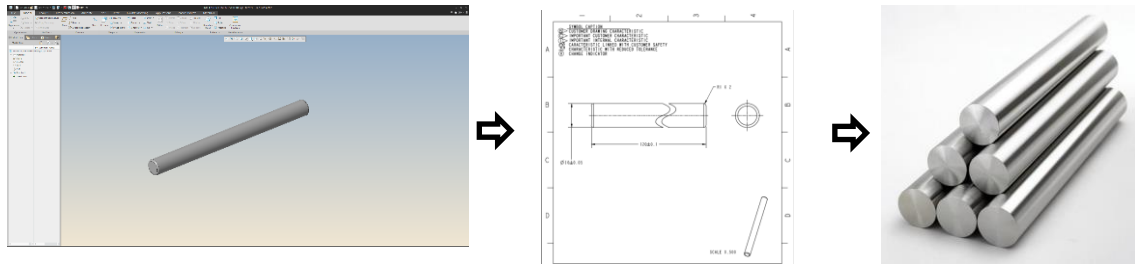


Figure 25 - #1 – Samples Preparation

The second step is to prepare the modular Maghyst, connecting it to the power supply and to the pc that we will use, as seen in the Figure 26



Figure 26 - #2 – MagHyst Modular Preparation

After that, the adapter should be connected to the modular MagHyst concerning his operation manual and his specifications, as seen in the Figure 27.

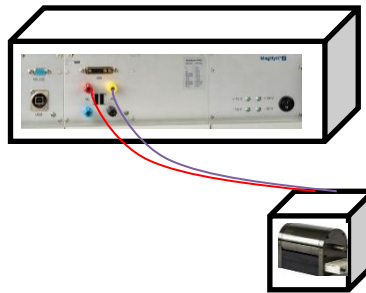


Figure 27 - #3 – Adapter Connection

After all of that is connected, the software should be started all the points previously seen must be defined, like the adapter specifications, the sample dimensions, the current interval, etc. As represented in the Figure 28.



Figure 28 - #4 – Software Preparation

For the test realization, one sample must be placed in the adapter and then the software must be started as represented in the Figure 29. After the test is concluded, the software will give us the referent curve, and the values that lead to that curve.

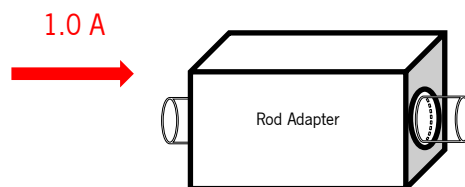


Figure 29 - #5 – Test Realization

The last point for this procedure, is the data analysis, that is when the user can inspect and work on the data presented by the MagHyst and take conclusions of it, and the curve given by the software is as represented in the Figure 30.

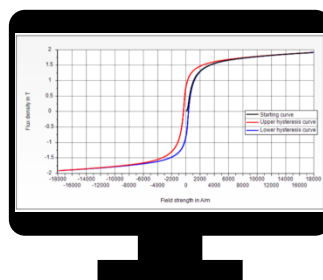


Figure 30 - #6 – Data Analysis

5.2. Adaptation of the coil designs for Simulation

Concerning the benchmarking of the different selected designs one copper coil design needed to be froze. After the study of the different designs and considering the adaptations that need to be made to change the copper coil, it was chosen not only a copper coil, but an overmoulded coil also including the carcass and the connector pins.

5.2.1. Coil Specifications

The standard coil that is used for the comparison of the different designs has 1120 turns.

5.3. Magnetic Simulation

The benchmarking of the different solenoid valves will be mostly based on the numerical simulation, for that the Ansys Maxwell will be the software that will be used.

Ansys Maxwell is an electromagnetic field solver for electric machines, transformers, wireless charging, permanent magnet latches, actuators, and other mechanical devices. It solves static, frequency-domain and time-varying magnetic and electric fields [32]

For the magnetic simulations, reference materials must be chosen. For that, will be used B-H curves of the materials, instead of the permeability values once the permeability varies with the variation of the magnetic field density. Normally the company use, some curves that were made available for this purpose, in his own library. For this paper, it was decided to also use materials that were previously measured. For the benchmarking of the different designs, it was decided to use the material 1 data, that was available in the material library of the company, for the plates and the shell. For the mobile and fixed cores to be used the data measured with MagHyst, for the material 2.

For each design, some predefined points have been defined. These points are referent to a combination of one current intensity and one value of gap between the mobile core and the fixed core. The Table 3, presented below, is the general set of points for each design.

Table 3 – Simulation predefined points of study

Current (A)	0,25		0,5		0,75		1			
Displacement (mm)	0	0.1	0.25	0.5	0.75	1	2	3	4	5

5.4. Experimental Validation Tests

In order to validate the magnetic simulations, some experimental tests have to be done. In this case, the experimental tests are only realized for the reference design that is the design number 5. In this case, only one design should be tested once there is the necessity of physic prototypes to be used. Having one design validated, is possible to conclude that all the simulations that will be runned for the other designs should be valid too. And if there is a difference between the simulation and the tests, is also possible to calculate a coefficient for that difference.

5.4.1. Magnetic Force

To validate the magnetic force simulated, the same force has been measured in a physical test. For that, 3 solenoid valves were prepared, being the hydraulic part cut once that is the magnetic part that is important to the measurements. These 3 solenoid valves, that can be considered the test samples, are presented in the Figure 31.



Figure 31 – Test samples for the magnetic force measurement

For the magnetic force measurement there is the necessity to use different equipment's as presented in the Figure 32. In order to have the force measurement there is the necessity to adapt the operation of the tensile test machine setting it up to simulate the movement of the mobile core and measuring the exerted force for the displacement variation. For the electric activation of the solenoid valves, is used a power supply controlled by a multimeter.

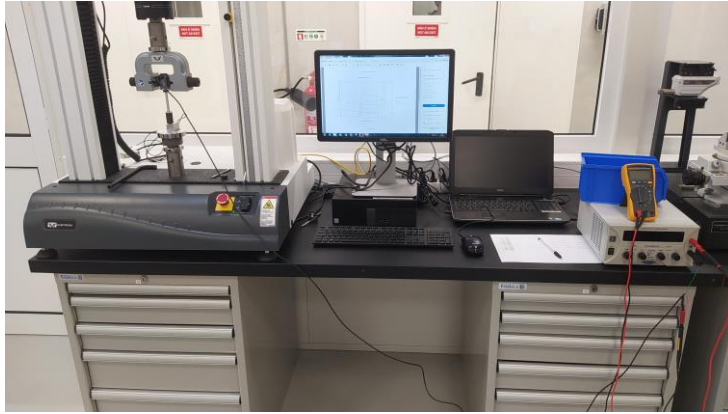


Figure 32 - Magnetic force test full mounting

In the tensile test machine, there was the necessity to change the load sensor for a most precise one. The sensor commonly used for the tensile tests has a capacity of 100 kN and does not show the best accuracy to measure loads of around 2N like the ones developed in the solenoid valves. For that, it was replaced by a smaller sensor with the capacity of 100 N, represented in the Figure 33, which has a better accuracy for the kind of measurements needed.



Figure 33 – Load Sensor of 100 N

The power supply used for the test presents a resolution of 0.1 A which makes impossible the use of the input current values used for the simulations, 0.25 A and 0.75 A. With the multimeter, which as a resolution of 0.001 A is possible to input the electric current values needed, so this was the solution found to reproduce the tests with the correct electric currents. The assembled equipment's is presented in the Figure 34.



Figure 34 - Power supply assembled with a multimeter

The procedure that has been used for the realized test started with the setting of all the equipment's. After that, the solenoid valve had to be fixed in the clamps of the tensile test machine and a round bar in the load sensor located at the bottom. This round bar has been previously manufactured to enter inside the solenoid valve body and push only the needle. The solenoid valve had also been connected to the power supply for the electric activation. This mounting is presented in the Figure 35.



Figure 35 – Mounting of the solenoid valve for the measurement of magnetic force

Before the start of the test the initial displacement point needs to be established, for that the solenoid valve is activated with a small value of current. This current value must be just the minimum to move the mobile core and consequently the needle against the round bar. Increasing the displacement of the solenoid valve towards the bottom, the force is increased, so there is the necessity to decrease this displacement to the point where the force is null, being this our starting point.

With this setup done is now possible to run the tests.

5.4.2. Magnetic Test Procedure for Solenoid Evaluation

The MagHyst modular is a powerful tool to identify the magnetic characteristics of materials but also to study the behaviour of the solenoid valves. For that, in this paper is presented the procedure realized to evaluate the solenoid valves magnetically and the interpretation of the resultant curves.

The procedure to the magnetic test is as simple as connect the solenoid valve to the machine and select the electric current for the test and the most adequate induced voltage.

The induced voltage is a concept that although it has not been included in the theoretical foundations should be understood. If there is a variation on the magnetic flux that flows through a magnetic circuit, there is an induced voltage in the coil, as Faraday's mentioned in his law of induction. And this is important because in an electromagnetic circuit, the variation of the magnetic flux can be caused by the variation of the electric current (I) in the wire, by the variation of the magnetic circuit reluctance ($\mathfrak{R}$), or by the movement of a permanent magnet near a coil.

The general expression of the magnetic induced voltage is:

$$U_i = - \frac{d\phi}{dt} \quad (23)$$

Where ϕ is the magnetic flux. But the MagHyst results are presented by the magnetic flux linkage, λ , that can be related to the magnetic flux by the following expression:

$$\lambda = N \cdot \phi \quad (24)$$

Being the N, the number of turns of the coil.

In conclusion, MagHyst is constantly measuring the induced voltage of the circuit and adjusts the variation of the voltage on the power supply to control the variation of the electrical current and maintain a constant induced voltage in the coil.



Figure 36 - Magnetic measurements for solenoid valves with MagHyst

6. RESULTS DISCUSSION

In this chapter are presented the results of all the realized studies as the simulations, the magnetic force test and. the magnetic flux test. A comparative analysis of the designs is also presented in the end and is with this comparative study that the designs are evaluated in order to understand which ones have better performances.

6.1. Magnetic Test Results of Materials

The chosen material for the magnetic tests was the material 2, which is a material used to produce components such as the mobile cores and fixed cores used in the SV's. The choice of this material is due to the fact that it is used in the majority of the SV's produced by the company and the study of it is an increase of know-how for the product development.

After that and with the test realized the B-H curve is presented in the Figure 37, and with this data is now possible to have more real conclusions with the simulations.

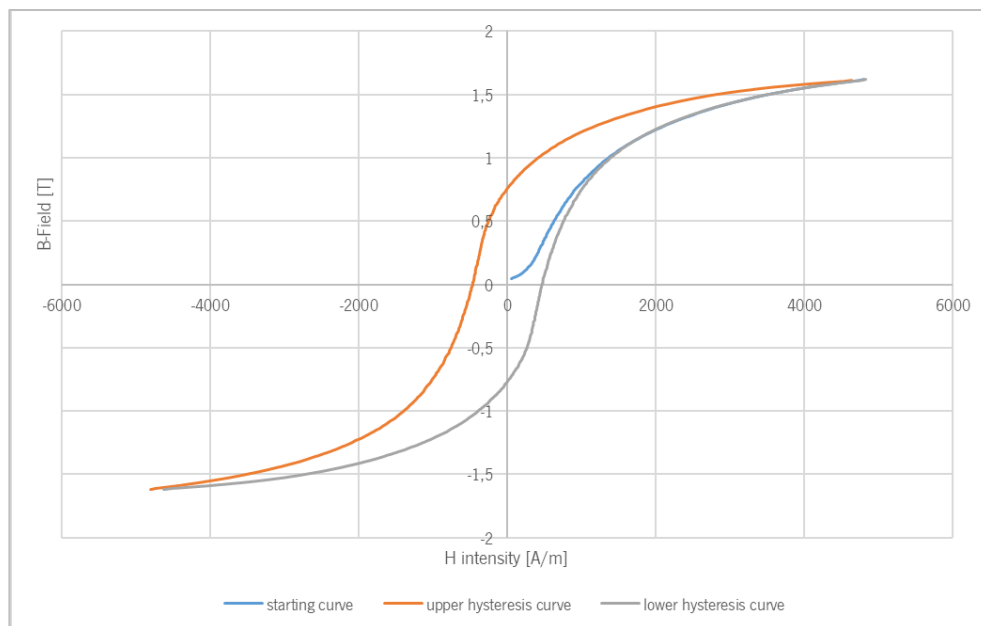


Figure 37 - B-H curve of the material 2 obtained with the practical test realized on MagHyst

With the starting curve is possible to have the variation of the magnetic permeability along the current intensity increase. The maximum B-field attained for this material is around 1.6 T.

6.2. Magnetic Flux Measurement Results

In order to validate the simulation for the magnetic flux results, 3 solenoid valves have been evaluated with the MagHyst as represented in the Figure 38. For that, there was the necessity to realize the tests with the solenoid valve in the vertical position securing that the mobile core would be in his final position all the time, and with this is possible to compare the simulation results for the same position, that in this case is when the gap between the cores is 0.7 mm, the thickness of the washer present inside the fixed core. It is in this position where the magnetic flux is higher, because the magnetic circuit is in his better configuration (less gap between the cores).



Figure 38 – Magnetic flux testing of the solenoid valves in the MagHyst

With the analyse of the results, where the magnetic flux is increased with the increase of the electric current, is possible to observe that the average curve of the measurements is lower than the simulation curve. It is also possible to notice that the solenoid valve 1 has higher values of magnetic flux than the solenoid valves 2 and 3, so having these two solenoid valves similar curves, the average curve will tend to be more like them.

Comparing the simulation curve with the average curve is possible to conclude that the simulation gives higher values than the reality, what was already expected and seen in the magnetic force analysis.

For these curves is possible to conclude that with an electric current of 1.0 A the difference between the magnetic flux real value and the simulation is 6.9%.

6.3. Simulation Results

In this chapter are presented the simulation results and the consequent analysis. For that, a separate analysis has been made, taking in consideration the different operation modes of the solenoid valves.

6.3.1. Proportional Application

The proportional solenoid valves aim to provide controllability of a system or mechanism on a wide range of gap distance using the average current as an input.

In order to create a ranking for the classification of the studied designs for a proportional application, the different analyses of the different criteria were compiled in a final table. This table presents the classifications obtained by each design when it was placed in the ranking of each criterion. For a more accurate study, a relevance factor was assigned to each criterion, which in this case differentiates the criterion in terms of their importance for the mode of application. That said, the value obtained by each design in the ranking of each criterion is multiplied by this relevance factor, and the final ranking is the sum of the criteria ranking positions multiplied by the relevance factors. Therefore, this final ranking is the classification that presents the different designs from the best to the worst considering that the final application is the proportional SV.

For the relevance factor, it was decided that the criterion A would have a relevance factor of 4, so as the criterion B is less important but with some relevance, it was assigned 2 as the factor and the other two which have an decreased importance have the lower factor of 1.

Table 4 - Ranking analysis of the different designs considering the proportional application

Proportional Application (from 1 to 5mm)						
Designs	Criterion A Ranking	Criterion B Ranking	Criterion C Ranking	Criterion D Ranking	TOTAL	Classification
Design 01	5	6	4	8	44	6 th
Design 02	1	5	9	6	29	10 th
Design 03	2	9	8	9	43	7 th
Design 04	7	4	2	5	43	8 th
Design 05	6	8	3	7	50	1 st
Design 06	8	3	7	4	49	2 nd
Design 07	3	7	10	3	39	9 th
Design 08	9	2	6	2	48	3 rd
Design 09	10	1	5	1	48	4 th
Design 10	4	10	1	10	47	5 th
Relevance Factor	4	2	1	1	8	

With the final ranking, is concluded that the design 5 is the better suited for a proportional application. The following designs in this classification are the designs 6, 8 and 9 that are the 2nd, 3rd and 4th classified which are similar performance wise.

Analysing the design 9, that is the best ranked in terms of the criterion A, the most relevant, is possible to see that it is low ranked in the others. If the purpose is to have a good design all this component must be taken in consideration, not only one of them.

The worst design is the design 2, and the explanation for that is his good applicability when considering the on/off application that will be presented next.

An important point is that this analysis is based on numerical studies and when developing a new design this should be complemented with the graphic analysis, because sometimes is possible to have graphic curves that cannot be seen in the numerical analysis.

6.3.2. On/Off Application

Considering the analysis for an on/off application, a similar had to be made. For this case the gap studied is between 0 mm and 1 mm, with the different points of study being 0 mm, 0.1 mm, 0.25 mm, 0.5 mm, 0.75 mm, 1.0 mm. The study of the gaps between 1mm and 5mm can be discarded due to the considerations for an on/off operation. The purpose of this operation mode, as has been already said, is to always push or pull completely an electromagnetic mechanism with the maximum force that the system can attain.

With the purpose of developing an analysis for the on/off application in the same terms of the analyse developed for the proportional application, four other criterions have been chosen.

With the following table, is compiled the ranking of the designs when considered the on/off application. This ranking is based on the analysis of the criterions. The classification obtained by each design is the sum of the classification obtained for each criterion multiplied by a relevance factor related to the importance of the indicator to the desired application. The higher relevance factor has been assigned to the criterion B concerning the on/off operation characteristics, and it was given a factor of 3 to it. The criterion C and D have been both assigned with a relevance factor of 2 since they are both equally important for the operation.

Table 5 – Ranking analysis of the different designs considering the on/off application

ON/OFF Application (from 0 to 1mm)						
Designs	Criterion A Ranking	Criterion B Ranking	Criterion C Ranking	Criterion D Ranking	TOTAL	Classification
Design 01	8	7	3	8	51	4 th
Design 02	10	10	8	10	76	1 st
Design 03	9	9	2	9	58	2 nd
Design 04	1	2	5	1	19	10 th
Design 05	3	4	4	2	27	9 th
Design 06	2	1	9	4	31	8 th
Design 07	5	3	10	3	40	7 th
Design 08	6	6	7	7	52	3 rd
Design 09	4	5	6	5	41	6 th
Design 10	7	8	1	6	45	5 th
Relevance Factor	1	3	2	2	8	

With this analysis is possible to conclude that the design 2 seems to be the best design, when the required application is On/Off SV's, followed by the design 3. The designs 1 and 8 are the ones that come next, being the 3rd and 4th classified in the ranking. The design 4 seems to be the worst design for an on/off application, being the 10th classified of the ranking.

7. CONCLUSIONS

For this paper was created in the first place an electromagnetism library where the theoretical foundations needed to better understand the product were intensively studied and explained.

After that, was created a solenoid valve library with products that have been developed by the company since 2001. In this library was compiled all the data relative to each reference, as the winding properties, the materials used for each component, and the functional properties of each solenoid valve. With the study of this library began an analysis to encounter patterns between the different models and as result this library originated the division all the products in 10 different groups with similar constructive characteristics between them. These groups have been chronologic ordered to understand the evolution of the developments made in the company.

With the different designs stablished, were now possible to benchmark them, to understand the how the performance is affected by the changes found on them. For that, the different designs were adapted to perform simulations with them. For the simulations, the software that have been used was the Maxwell, which is properly for electromagnetic mechanisms.

Hereupon, the results analysis has begun, and for that have been encountered the need to make two separate analyses in order to come up with better solutions. For the numerical analysis, were used criterion values. With these were possible to analyse the designs and the conclusions that were obtained were that the design 5 is the more suitable design for a proportional application, followed by the designs 6, 8 and 9, ordered from the best ranked to the worst. The design 2 for this application was considered as the worst design.

In the second analysis were considered the on/off application of the different designs. For the numerical analysis of the on/off application, 4 other criterions have been chosen. With these the designs had also been ranked from the best suited to the worst, regarding the desired operation. The design 2, which has been the worst ranked when analysed for a proportional application, turned out to be the best ranked by far for the on/off application. Next to it was the design 3 which is also a good suit for the on/off solenoid valves. The worst ranked design was the design 4.

For the validation of the simulation results were realised practical test, to analyse the magnetic force and the magnetic flux. When the resultant curves were compared with the simulation curves the differences encountered were not significant and therefore is possible to conclude that the simulations realised can be used for the purposes of comparison and validation of the studied designs.

In conclusion, the methods adopted for the presented work turned out to be well suited and bringing good conclusions for future developments in the company. There is just the need to state that a method should not be used alone, to analyse solenoid valves like these, the graphic surfaces, and the numerical analysis should be taken in consideration together and only with these the conclusions should be considered reliable.

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APPENDICES

Appendix I. Magnetic Force Equations Deduction

The energy of the air gap inside the solenoid is given by the equation:

$$U = (\text{volume}) * (\text{magnetic energy density})$$

Replacing for the equations:

$$U = (A * h) * \left(\frac{B^2}{2\mu_0} \right)$$

Using this equation for the magnetic force calculation:

$$F = \frac{\Delta U}{\Delta dx} \Leftrightarrow$$

Replacing the ΔU for U_1 and U_2

$$\Leftrightarrow F = \frac{U_1 - U_2}{\Delta dx} \Leftrightarrow$$

Replacing U_1 and U_2

$$\Leftrightarrow F = \frac{\left[A * dx_1 * \frac{B^2}{2\mu_0} \right] - \left[Ab * dx_2 * \frac{B^2}{2\mu_0} \right]}{\Delta dx} \Leftrightarrow$$

Considering that the $dx_2 = 0$, all the U_2 will be cut:

$$\Leftrightarrow F = \frac{\left[A * dx_1 * \frac{B^2}{2\mu_0} \right]}{\Delta dx} \Leftrightarrow$$

Since the dx_1 is the same as the Δdx due to the $dx_2 = 0$:

$$\Leftrightarrow F = \frac{B^2 A}{2\mu_0} \Leftrightarrow$$

Transforming now the B to Φ_B , and since $B = \frac{\Phi_B}{A}$:

$$\Leftrightarrow F = \frac{\left(\frac{\Phi_B}{A} \right)^2 A}{2\mu_0} \Leftrightarrow$$

Squaring the denominator and numerator:

$$\Leftrightarrow F = \frac{\frac{\Phi_B^2}{A^2} A}{2\mu_0} \Leftrightarrow$$

Cutting the square of A:

$$\Leftrightarrow F = \frac{\frac{\Phi_B^2}{A}}{2\mu_0} \Leftrightarrow$$

Finally, the equation of the magnetic force is obtained with the magnetic flux:

$$\Rightarrow F = \frac{\Phi_B^2}{2\mu_0 A}$$