

< Design of a musical instrument magnetic anchoring strap system >

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< Design of a musical instrument magnetic anchoring strap system >

< *If God created the world in a single week, I shall make a thesis in two.* >

Resumo

A premissa do presente trabalho assenta sobre o projeto de um sistema magnético de ancoramento para alças de instrumentos musicais e a sua respetiva caracterização.

Para a elaboração deste projeto, estudou-se as diferentes soluções de alças de guitarra atualmente disponíveis no mercado, assim como os diversos materiais magnéticos e suas propriedades. Deste estudo realçam-se as ligas de neodímio como as mais indicadas para a finalidade.

Desenvolveu-se o conceito explorando-se uma solução magnética de quatro polos, complementando-se com uma análise de perto da geometria e construção de uma guitarra clássica. No sentido de explorar o conceito, construíram-se modelos físicos em impressoras 3D, tanto para avaliar soluções, como para ensaios experimentais.

Para aferir características físicas, como a capacidade de carga dos ímanes, realizaram-se ensaios de tração e corte, a diferentes conjuntos de ímanes, e testes acústicos para avaliar a influência do sistema na sonoridade da guitarra. Complementados por provas de audição cegas a um grupo de músicos e instrumentistas.

Seguidamente, analisaram-se resultados, comentando o comportamento mecânico das distintas configurações magnéticas. A configuração magnética cruzada, destacou-se como a mais performante obtendo os melhores resultados nos ensaios de tração e corte.

Após a análise matemática do espectro e decaimento, das diferentes gravações dos testes acústicos, conclui-se que a interferência acústica da presença dos ímanes é considerável e mensurável. Havendo um incremento na taxa de decaimento e variação espectral. A apreciação subjetiva do grupo de teste, demonstrou que as diferenças eram perceptíveis e corroborou os resultados da análise matemática.

Na conclusão, debateu-se sobre o trabalho concretizado, fazendo referencia aos materiais estudados, métodos de prototipagem rápida, testes executados e respetivos resultados, e descreveu-se o protótipo final.

Por fim, é feito um ultimo apontamento sobre trabalhos futuros a realizar.

Abstract

The premise of this work was to design a magnetic anchoring system for musical instrument straps and to describe and characterize the created solution.

For the preparation of this project, a study of the guitar strap solutions currently available in the market was done, and a description of the various magnetic materials and their properties was made. Neodymium alloys were highlighted as the most indicated for the application.

The core design concept was developed, exploring a magnetic solution of four poles. To determine the best locations to install the system an analysis of the geometry and construction of the guitar was done. Following this path, physical models were built in 3D printers, to evaluate solutions and to undertake practical tests.

To assess certain characteristics, experimental trials were carried out on different sets of magnets, namely tensile and shear stress tests. Acoustic tests were done to evaluate the influence of the system on the sonority of the guitar, complemented by blind listening test with a group of experts.

Results were analyzed and commented accordingly, with a report of the mechanical behavior of the different magnetic configurations. The Cross magnetic configuration stood up as the best, outperforming the other configurations, in both tensile and shear stress.

A mathematical analysis on the acoustic consequence of the magnets presence was done, in both spectral and decay domains. Measurable differences were identified, with an increase in the decay rate, and a significant variation in the spectral qualities, with the magnetic system presence. These facts were corroborated by the subjective examination based on the listening group test results.

Finally, there is a conclusion on the work done, referring the magnetic materials studied, rapid prototype technologies, executed tests, final prototype considerations and a last point about future works.

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Abbreviations

€	Euro
3D	Three dimensions
ABS	Acrylonitrile butadiene styrene
dB	Decibel
DC	Direct current
DEEC	Electrical Engineering Department
DEMec	Mechanical Engineering Department
FEA	Finite element analysis
FEMM	Finite element method magnetics
FDM	Fused deposition modelling
H _c	Coercivity
Hz	Hertz
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
kg	Kilogram
LPDS	Products and Services Development Lab
MDFA	Magnet Distributors and Fabricators Association
mm	Millimeter
N	Newton
US	United States
s	second
SLA	Stereolithography
V	Volt

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1. Introduction

The modern classical guitar is one of the most popular instruments in the world, and one of great significance to our country, due to our proximity to his origin (Spain). Portugal is also the birthplace of various remarkable stringed instruments such as the Portuguese guitar and the cavaquinho.

A musician while performing wants to move and interact with his surroundings, being it with an audience or simply at home rehearsing. To fulfill this necessity, straps were designed to attach the instrument to the user, releasing the player from holding the instrument and enabling it to freely play.

Despite the obvious need, still, to today there is no available strap solution that suitably fits the classical guitar and other classical stringed instruments. The existing solutions, all have inherent shortcomings be them insufficient support, permanent modifications on the instrument or impractical use.

Due to the classical guitar popularity, a particular emphasis will be done on this instrument, nonetheless the project here done can extend to other stringed classical instruments.

The present work describes an innovative approach resorting to magnetic fixation, and all the steps to materialize it.

1.1 Background and Motivation

This dissertation was carried out within the scope of the Integrated master in Mechanical Engineering and aims to continue the project started for the “Integrated Product Design” subject.

This theme was chosen for the dissertation due to the previous project significance, as it was well received and solved a genuine problem and demand of the consumers. The author also has a personal motivation and interest in the products development field as well as music and guitar.

As with many creative processes, the best ideas surge from the chaos and disorder in life. Afterwards it is up to the engineer to control that inventive energy and materialize that into working productive solutions.

The concept emerged from a personal need and the drive to find a better solution than the currently available. The steer of the present project follows this path focusing on finding the best solution.

1.2 Objectives

A lack of effective strap solutions to support the classical guitar was identified, to fulfill this void a solution recurring to magnetic force for attachment and a non-permanent adhesive fixation method was envisioned.

The main aim of this project was to continue and improve the work first started in the previous course, with the key goal to develop a working solution that would be fully removable and as close as possible to a final product. To achieve this, the subsequent steps were followed.

A comparison and study of magnetic materials, and multiple magnets configurations. A recreation of the core design to incorporate the four-poles concept, physical modeling with 3d printing. An analyzes of the mechanical capabilities in the magnetic anchoring system. A study and verification of the acoustic interference of the magnetic system accompanied with specialized listening tests.

Despite the outlined plan, the work was not linear with the concretization of new ideas generating new challenges, and the solving and tackling of new problems opening doors to new solutions.

1.3 Structure of the dissertation

This work is organized in seven chapters this one being the first and acting as an insight into the context of this project.

The second chapter ensues the state of the art, where the background is described for a better understanding of the pertinence of this work. A description of the currently available guitar strap solutions is done, as well as an approach to the concepts of magnetism and magnetic materials with a comparison between their different properties.

Chapter number three covers the concept development, completed with a description of the created prototypes and a view of the guitar geometry and construction.

The fourth chapter describes the experimental methods, the tensile and shear stress tests as well as an acoustic interference test accompanied with a blind listening test.

Chapter five presents and compares the results of the experimental tests, with an additional commentary on the final prototype.

Chapter six covers the conclusion on the results, study, and work done throughout this thesis.

The seventh chapter is the last one and presents the future works, outlining what could be done to enrich and develop the present dissertation.

2. State of the art

For a clearer comprehension of the pertinence of this project a link was made with the music instruments field, and a portrayal of the available guitar straps solutions encompassed. In this chapter, a deepening in the study of magnetism and magnetic materials was also carried out, with the purpose of a better understanding of the mechanics behind the magnetic interaction and how to take the best advantage of them.

2.1 Musical instruments

Last year and on the US market alone 1.4 million acoustic guitars were sold, as displayed on the Figure 2.1 [1]. The classical guitar is inserted in this class and the large sale numbers, reveal its popularity.

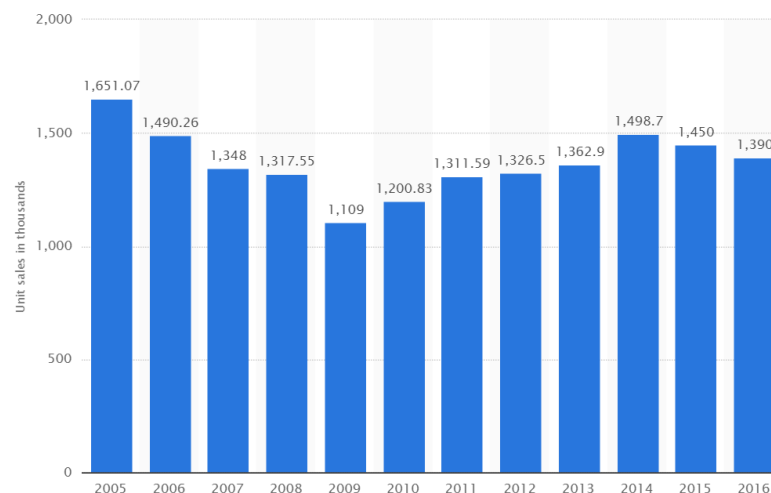


Figure 2.1- Number of acoustic guitar sold in the United States from 2005 to 2016

The traditional method of classic guitar playing requires the musician to play seated with the foot placed on the foot rest, the posture is demonstrated on Figure 2.2 [2, 3].

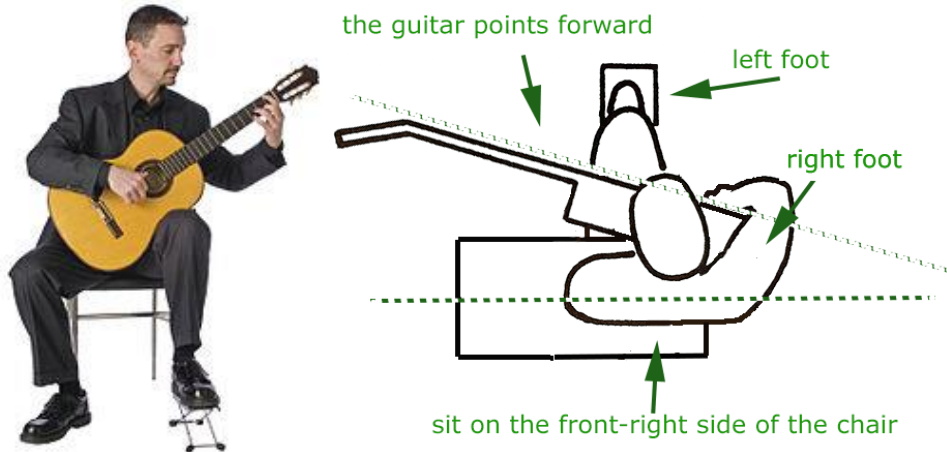


Figure 2.2 – Classical guitar playing posture

This concept of playing seated is so deeply connected with the classical guitar that it is even part of its design with the shape of the guitar curves designed to match the player's leg.

Still, due to entertainment and/or ergonomic reasons a new trend of classic players is defying the pre-established dogma, claiming that the standing posture is better to endure long sessions of rehearsal and that it creates a more evolving and free experience. A path that its modern electric sibling had already trailed.

There are some solutions like the ErgoPlay® support, shown on Figure 2.3 [4] and others alike, that improve the ergonomics of the guitar helping the player support the instrument while seated, but there is no definitive solution to enable fully supported stand up playing. The classical guitar, among many other classical stringed instruments (ukulele, cavaquinho, etc..) doesn't have pins (fixation points) for the traditional straps, this being the major difficulty in the adaption to stand up playing.



Figure 2.3 – ErgoPlay® support for classical guitar

2.1.1 Guitar straps

To fulfill the need of the players to perform standing up, several solutions are available, each with their own advantages and limitations, a description and comment of the available systems will be done below.

Double pin strap

This is by far the most common strap and is widely used in electric guitars.

In order to adapt it to the classical instruments, the most practiced solution is to drill a hole on the body of the instrument to install the pins, and then use it as a normal guitar strap.

Most classical instruments have considerable value, be it monetary, or simply sentimental to the instrumentalist. With that into consideration, making a permanent and unsafe modification such as drilling a hole is obviously taken with concern. Adding to that, the fact that such a hole with the respective nut and bolt in the structure may alter the acoustic properties of the instrument, and it is easy to understand that this solution has his own limitations.

Also, such a modification generally devalues the instrument, and the placement of pins in a classical instrument is seen with contempt since it spoils the classical esthetic of the instrument.

Single pin strap

The single pin strap is very similar to the double pin solution, with the main difference being that it requires one pin for installation, the other end is attached with a string and a knot to the instrument head, as presented on the respective image of Table 2.1. This strap is generally speaking cheaper than the double pin solution, but due to the way the weight of instrument is supported, creates an undesired tension on the neck of the instrument, and for that reason its disregarded by the specialists.

Single hook strap

This design displayed on Table 2.1, is simple and easy to use but only partially supports the weight of the guitar, thus requiring the user to place his arm on the side of the instrument at all times, otherwise it will rotate and fall.

Double hook strap

This design is an evolution of the single hook strap, using an additional strap to counter act part of the weight of the guitar. Despite being more functional than the single hook strap it is also more difficult to use, more expensive and esthetically more intrusive.

Despite the obvious disadvantages, the single and double hook straps are the only designs that are specifically targeted to classical guitars, and can be used with no further modifications.

Table 2.1 - Available guitar strap solutions

Strap type	Isolated	Typical usage position
Double pin strap	 [5]	 [6]
Single pin strap	 [7]	 [8]
Single hook strap	 [9]	 [10]
Double hook strap	 [11]	 [11]

In addition to the products shown on Table 2.1, there are others, less conventional solutions, such as Velcro attachment, and even suction cups, both shown on Figure 2.4 [12] [13].

Suction cups require a clean and dry adhering surface otherwise they will fail and Velcro has inherent wear and tear over time, so the obvious drawbacks and dubious functionality, limit a wider use and adoption of these solutions.

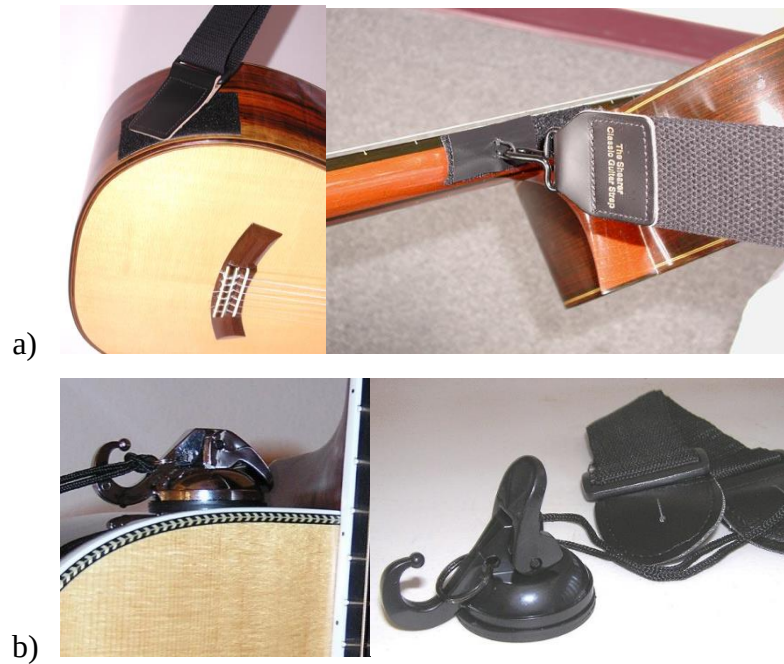


Figure 2.4 – a) Velcro attachment system; b) Suction cup attachment

Research gap

In sum, as today, there is no available solution that completely supports the classical guitar (and other stringed instruments) without the any permanent modifications to the instrument. With many classic instrumentalists being intransigent when it comes to making intrusive and permanent modifications, be it, either by concern of permanent damage or by the subsequent devaluation of the instrument, an unfulfilled needed and a gap is defined.

The solution here presented caters to these needs and seeks an innovative and elegant approach recurring to magnetic attachment to accomplish the same basic necessity of supporting the instrument, striving to make a ready to go product that doesn't irreversibly alter the instrument nor compromises its performance.

2.2 Magnetic Materials

The history of magnetism is coeval with the history of science. Magnetism was allegedly first discovered in a Greek region called Magnesia, from where the name “magnet” derives. There, people noticed that lodestones, naturally magnetized pieces of the mineral magnetite, could attract iron and other metals [14-16], a sample of lodestone is portrayed on Figure 2.5 [17].



Figure 2.5- Lodestone from Arkansas U.S., attracting small nails to its surface.

At an atomic level, magnetism arises from the motion of electrically charged particles. Since electrons, protons, and neutrons are basic to all materials, magnetism is inherent to all substances [18]. The major classes of magnetism and magnetic materials will be addressed on the following pages.

2.2.1 Classification of Magnetic Materials

2.2.1.1 Diamagnets

Diamagnetic materials are materials which are repelled by an external magnetic field. When a magnetic field is applied, an induced magnetic field in the opposite direction is created, causing a repulsive force, this behavior is illustrated on Figure 2.6 [19]. Diamagnetism is a quantum mechanical effect that changes the orbits of the electrons setting up an orbital magnetic moment which opposes the field.

Diamagnetism occurs in all materials and of the three major magnetic phenomena, diamagnetism is by far the weakest being dominated in the presence of others. As so, despite its universal occurrence, diamagnetic behavior is only observed in a purely diamagnetic material [20, 21].

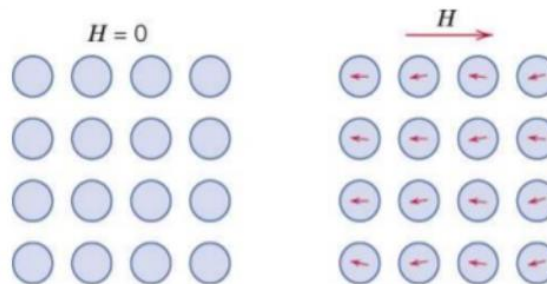


Figure 2.6 - Diamagnetic material under influence of magnetic field, adapted

2.2.1.2 Paramagnets

Paramagnetic materials are attracted by an externally applied magnetic field, and form internal, induced magnetic fields in the direction of the applied magnetic field, as depicted on Figure 2.7 [19].

Paramagnetism occurs in materials which have net magnetic moment per atom due to an unpaired electron spin. Unlike ferromagnets, paramagnets do not retain any magnetization in the absence of an externally applied magnetic field because thermal motion randomizes the spin orientations (assuming temperatures above absolute zero) [20].

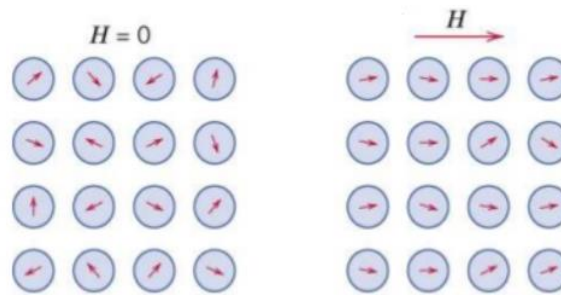


Figure 2.7 - Paramagnetic material under influence of magnetic field, adapted

2.2.1.3 Ferromagnets

Ferromagnetic materials are the most interesting and important magnetic materials, because unlike paramagnetic materials, which only interact with an external field, the ferromagnetic materials interact with each other, even in the absence of external magnetic field as shown on Figure 2.8 [19].

This interaction is also stronger than the other kinds of magnetism, being the only one that typically creates forces strong enough to be felt, and is the basic mechanism behind permanent magnets.

Unlike other materials, ferromagnetic materials can retain its magnetization, only losing it if the temperature is raised to the Curie temperature (specific for each material), at which the ferromagnet loses its ability to retain its magnetization, behaving like a paramagnetic material.

Whereas diamagnetism and paramagnetism are properties of individual atoms, ions or molecules, ferromagnetism is a property of a group of atoms or molecules in solid crystal, accordingly ferromagnetic materials also have the denomination of magnetically ordered materials.

Ferromagnetic materials can be divided into two major classes magnetically soft materials, which can be magnetized but do not tend to stay magnetized, and magnetically hard materials, which do. [20, 22].

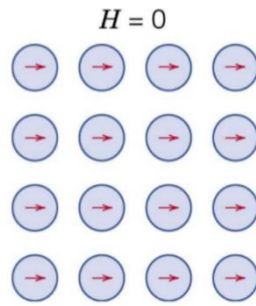


Figure 2.8 - Ferromagnetic material in the absence of external of magnetic field, adapted

2.2.1.4 Ferrimagnets

Ferrimagnets are materials that exhibit a type of permanent magnetism similar to ferromagnetism. This type of magnetism occurs in solids in which the magnetic fields associated with individual atoms, spontaneously align themselves, some parallel, or in the same direction (as in ferromagnetism), and others generally antiparallel, or paired off in opposite directions (as in antiferromagnetism), a schematic is displayed on Figure 2.9 [19].

The magnetic behavior of single crystals of ferrimagnetic materials is attributed to the parallel alignment, the diluting effect of some atoms in the antiparallel arrangement keeps the magnetic strength of these materials to be generally lower than that of ferromagnetic solids. Ferrimagnetism occurs mainly in magnetic oxides known as ferrites and is also the basic process behind the natural magnetism exhibited in lodestones.

Like ferromagnets they hold a spontaneous magnetization below the Curie temperature, and above that temperature, ferrimagnetism is entirely disrupted showing no magnetic order and behaving like a paramagnetic material [23].

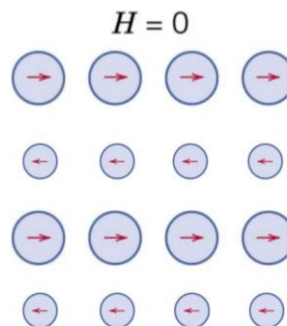


Figure 2.9 - Ferrimagnetic material in the absence of external of magnetic field, adapted

2.2.1.5 Antiferromagnets and others

In antiferromagnetic materials there is, like in ferromagnetism and ferrimagnetism, a manifestation of ordered magnetism in which dipoles of equal strength align themselves in opposite directions. The dipoles cancel each other, and in the absence of external field, results in no external magnetism effects [24], this effect its displayed on the Figure 2.10 [19].

This spontaneous antiparallel coupling of atomic magnets is disrupted by heating, and disappears entirely above a certain temperature, denominated the Néel temperature, characteristic of each antiferromagnetic material [25].

The other types of magnetic interactions such as Helimagnetism, Superparamagnetism, Metamagnetism and others, due to its lack of relevance to this work, will not be described.

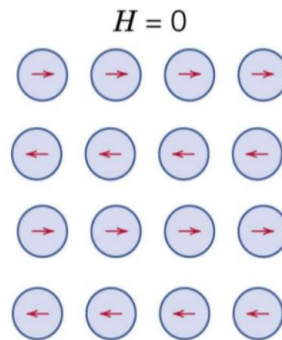


Figure 2.10 - Antiferromagnetic material in the absence of external of magnetic field, adapted

2.2.2 Permanent Magnets

A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field, permanent magnets are made of hard ferromagnetic materials.

Since the application in question requires a constant magnetic field, permanent magnets will be the type of material used.

2.2.2.1 Ferrite

A ferrite is a type of ceramic compound composed of iron oxide and other metallic elements. Its discovery dates from 1930 in Japan.

There are two big groups of ferrites: soft or hard ferrites. Since only the hard ferrites can retain its magnetism, these will be the ones described from now on.

Ferrites are usually non-conductive ferromagnetic ceramic compounds derived from iron oxides such as hematite (Fe_2O_3) or magnetite (Fe_3O_4). They have in general high coercivity, which leads to good magnetic stability, but a low maximum energy product (BH_{max}).

The most common ferrites are strontium, barium, and cobalt ferrites. The barium ferrites are being replaced for strontium ferrites due to their better magnetic properties.

The materials and manufacturing processes involved ferrites makes them one of the cheapest permanent magnetic materials in terms of price by BH_{max} , being a good option for applications that do not require a high BH_{max} .

Ferrites due to its ceramic nature are hard and brittle, but also relatively light with the lowest density in the magnetic materials group [26, 27]. A summary of the ferrite magnets strengths and weaknesses is done on Table 2.2.

Table 2.2 - Strengths and weaknesses of ferrite magnets

Strengths	Weaknesses
Moderate operating temperature	Low levels of magnetism mean that magnets have to be large to be effective
High corrosion resistance, good magnetic stability	
Inexpensive	

2.2.2.2 Alnico

Alnico is an acronym referring to a family of iron alloys which are composed primarily of aluminum (Al), nickel (Ni) and cobalt (Co). They also include minor additions of copper and titanium to improve casting and magnetic properties. The development of the alnico alloys started in 1931 in Japan and at the time they were the strongest type of permanent magnet [28].

Alnico magnets can be cast produced or sintered. They are classified using a numerical system (1 to 9) that indicates the chemical composition and magnetic properties [29].

Alnico alloys have a Curie temperature around 800 °C, one of the highest Curie temperature of any magnetic material resulting in a normal maximal operating temperature above 500 °C [30].

Alnico magnets still have a wide industrial application mainly because of its high temperature and corrosion resistance. In Table 2.3 is a description of Alnico's strong points and limitations.

Table 2.3 - Strengths and weaknesses of alnico magnets

Strengths	Weaknesses
High operating temperature	Low resistance to demagnetization (pushing two magnets together in repulsion can permanently damage both of them)
Good corrosion resistance	High production cost
Long-term magnetic stability	

2.2.2.3 Samarium-cobalt

As the name implies samarium-cobalt magnets are magnets made of an alloy of samarium and cobalt. They were developed in the early 1960s with the purpose of creating a high coercivity magnet that could operate at higher temperatures.

Samarium-cobalt magnets are sintered and come in two formulations, series 1:5 and series 2:17. The 1:5 series has one atom of samarium per five of cobalt in its composition and the 2:17 series has two atoms of samarium for every seventeen atoms of cobalt. The 1:5 series are more resistant to corrosion but do not have as good magnetic properties as the 2:17 series.

Samarium-cobalt magnets have good thermal characteristics being resistant to demagnetization at high operating temperatures and able to operate up to 250 °C – 350 °C (depending on the series). They also have very high corrosion resistance and generally do not require protective coatings.

Compared to Neodymium magnets, they have lower magnetic strength, are more brittle, prone to chipping, and more expensive, but can operate at higher temperatures.

The high cost of samarium and cobalt is the biggest limitation to a wider adoption of this type magnets [30]. Table 2.4 succinctly presents samarium-cobalt magnets, advantages and drawbacks.

Table 2.4 - Strengths and weaknesses of samarium-cobalt magnets

Strengths	Weaknesses
Moderately high magnetism	High production costs
High resistance to being demagnetized	
Good power to weight ratio	
Medium temperature resistance	
High resistance to corrosion	

2.2.2.4 Neodymium

Neodymium magnets were developed in 1982 by General Motors, in order to find an alternative to samarium-cobalt magnets whose raw materials cost had risen. Previous attempts to develop a neodymium-iron magnet were made, but only with the breakthrough of the addition of boron to the alloy that magnetic properties drastically improve. The alloy consists of neodymium, iron and boron forming a $\text{Nd}_2\text{Fe}_{14}\text{B}$ crystalline structure. In order to turn into a permanent magnet, the alloy is pulverized and sintered.

The classification of neodymium magnets is graded according to their maximum energy product, BH_{max} (in MGOe), with higher number values indicating stronger magnets and ranging from N35 to N52. The letters following the grade indicate the intrinsic coercivity which relates to the maximum operating temperatures which range from N to EH, the rating system and the respective to temperatures is described on Figure 2.11 [30-32]. An example of neodymium rating can be seen on Figure 2.12.

(none) - up to 80°C / 176°F
M - up to 100°C / 212°F
H - up to 120°C / 248°F
SH - up to 150°C / 302°F
UH - up to 180°C / 356°F
EH - up to 200°C / 392°F
AH - up to 230°C / 446°F

Figure 2.11 - Neodymium Temperature Rating system

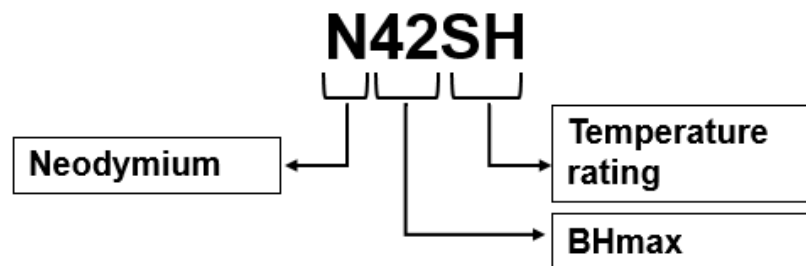


Figure 2.12 - Neodymium rating example, with labels

Neodymium magnets are the most widely used type of rare-earth magnet. They are the strongest of the commercially available magnet types, due to the high BH_{max} value.

Despite their wide use, they have some inherent disadvantages. Neodymium magnets are prone to corrosion result of the high proportion of iron and therefore, a plating or coating is necessary. The neodymium alloy has a lower Curie point (around 350 °C) than the other magnetic alloys, so the maximum operating temperature sits normally below 150 °C. So, for high temperatures applications samarium-cobalt or alnico magnets are still used. A list of the neodymium magnets main assets and shortcomings is presented on Table 2.5.

Table 2.5 – Strengths and weaknesses of Neodymium magnets

Strengths	Weaknesses
High magnetism	Low operating temperatures
Ultra-high resistance to being demagnetized	Poor resistance to corrosion if the plating is damaged
High power to volume or weight ratio	

2.2.3 Comparison of Permanent magnets

The main deciding factors in the choice of a magnet material would be:

- Magnetic strength ($BH_{\max}$), since the magnets must be able to withstand the weight of the guitar and still be compact enough to fit inside it.
- Magnetic stability or coercivity (H_c), it is important to guarantee that the magnets does not get demagnetized upon use, since (as will be seen further ahead) they will be exposed to opposing magnetic fields.
- Density, is relevant to use materials as light as possible to guarantee an ergonomic and practical system.
- Price, the price should be kept as low as possible to guarantee a competitive product.

On Table 2.6 and Figure 2.13 [33] it is possible to see the different properties of the magnetic materials.

Table 2.6 - Properties of different magnetic materials

Type	Composition	H_c (Oersteds)	$BH_{\max}$ (MGOe)	Density (g/cm ³)	Max Operating Temp. (°C)
Neodymium (Grade N42)	Mainly neodymium, iron and boron	115000	42	7.4	80
Alnico (Alnico 5)	Mainly aluminum, nickel, cobalt, iron	640	5.5	7.3	500
Ferrite (Ferrite 8)	Ceramic materials and iron oxide (Fe ₂ O ₃)	2950	3.5	5	180
Samarium cobalt (Samarium 2:17)	Mainly Samarium and Cobalt	9700	28	8.4	350

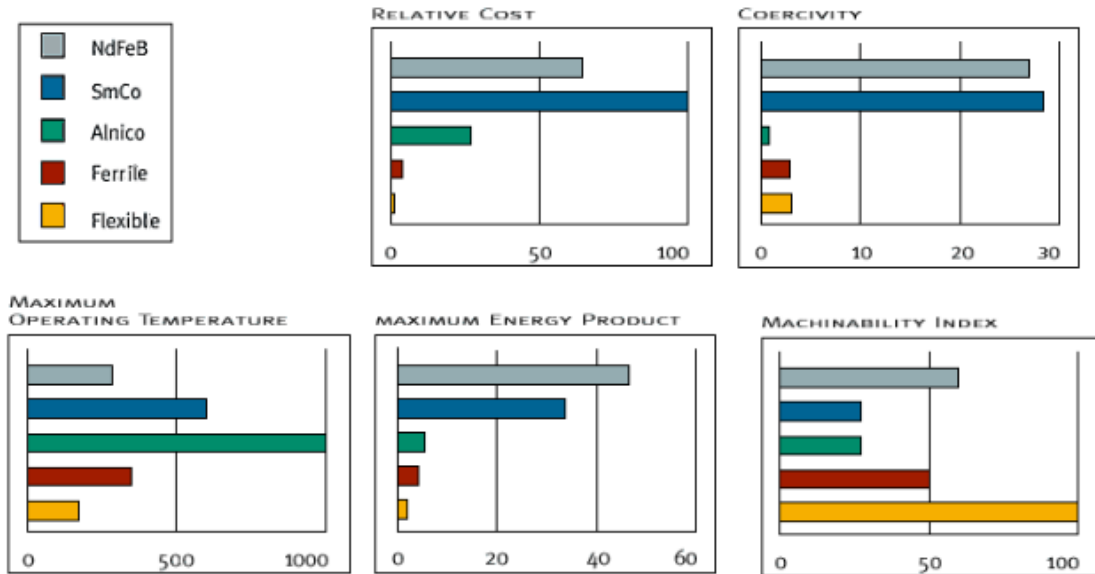


Figure 2.13 - Comparison of permanent magnets properties

The neodymium is the overall best choice of material for the application, having the highest magnetic maximum energy product and coercivity. A comparison between the different types of materials is displayed on Figure 2.13. The main drawbacks of neodymium are its low operating temperature and poor corrosion resistance. For this specific application, the temperature will always sit below 80 °C and the magnets will be inside an enclosure, so its corrosion resistance and operating temperature are not relevant.

In sum, this type of permanent magnet will be the one used in this work since it is the strongest type of magnet currently available and the limitations inherent with this type of material (corrosion, low operating temperature, etc..) are not determinant to this application

3. Concept Development

3.1 Introduction

From the simple fridge magnet of our kitchen, to particle accelerators in sophisticated laboratories, magnet technology is present a little bit everywhere.

With the recent developments in magnetic materials, more and more applications are being found. Neodymium magnets, for instance, enable magnetic strengths that simply were not possible with magnets of the same size and price, a single neodymium magnet of a few grams can lift a thousand times its own weight [34].

These capabilities open new possibilities, and make magnetic non-permanent fixation methods a viable alternative to more traditional methods.

Prior to this project, some work was done within the scope of the course “Integrated Product Design”. The product development process was followed, accompanied by the respective bibliographic, market and patent research. A mission statement was delineated with an identification of the consumer needs based on surveys and interviews, and the metrics and units of the consumers wants established. An executive summary of the the work done can be consulted in appendix A.

The concept was created and developed during the course of the subject and a prototype was done at the end.

3.1.1 *First Prototype*

The prototype created at the end of the course was quite basic, as it comprised of a modified guitar strap with two embodied S-20-10-N magnets, one at each end, as displayed on Figure 3.1 a), and two other S-20-10-N padded magnets (Figure 3.1 b)) that would be placed oppositely on the inside of the guitar [35].



Figure 3.1 – a) Modified guitar strap; b) Padded magnets.

Although the prototype was functional, the magnetic system was not able to cope with stronger movements like jumping or heavy turning, the final prototype can be seen suspending a guitar in Figure 3.2.

The obvious solution would be to increase the strength of the magnets, but the use of stronger magnets would cause other problems to arise. Namely, the removal and handling of the latter. Since we were now dealing with forces of much higher magnitude, removal and handling of these magnets became difficult and cumbersome.

The making of this prototype was also important for the realization that due to the guitar curvature the use of a large single flat magnet would not be the best approach.



Figure 3.2 - Classical guitar suspended by magnetic strap

3.2 Four-poles Concept

In order to deal with these challenges, changes to the original solution had to be imagined.

The envisioned approach takes base in the use of multiple magnets and on the magnetic attraction-repulsion principles, the bipolarity of the magnet.

Since there is no experimental evidence that magnetic monopoles exist, every magnet has two poles, normally designated “north” and “south”.

As its possible to see on Figure 3.3 [36], the bar magnet has two designated poles, the south one that acts as a field sink for the magnetic field lines that originate from the north [37].

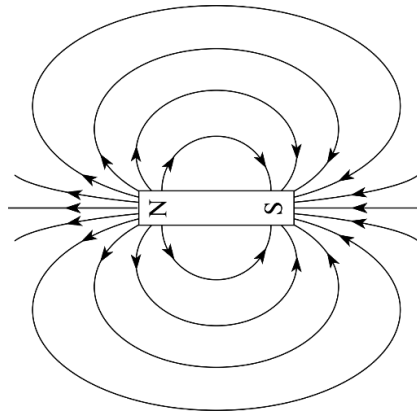


Figure 3.3 – Bar magnet and field lines schematic

Each pole is attracted by its opposite and repelled by its homologous, with that basic principle into consideration, the author planned a system that would change its magnetic behavior upon rotation, being repelled or attracted depending on the relative rotation.

For this type of behavior multiple magnets must be used and although there is no limitation to a magnet possible shape, the most common and easy to obtain shapes are: disks, blocks and spheres. For the application in question the use of block magnets was chosen since it allows for a more closed packing.

The use of four magnets was preferred instead of two, since the array can be done with cubic or squared block magnets (most popular type) for efficient use of area, the use of four magnets also enables more magnetic configurations and allows for a smaller turning angle (90° vs 180° in the “dual pole”) topic that will be better explained the paragraphs ahead. An array of more than four magnets was not considered, since it would lead to an impractical and complex solution.

For the sake of simplicity and since no nomenclature is defined for the specific array of four magnets with four poles in the same plane, from now on, the “four-poles magnets” designation will be adopted, Figure 3.4 a) illustrates a schematic of such configuration.

In Figure 3.4 b), there is a model of two four-poles magnets array together (top to top). Each big square represents the magnet pole that sits below and each small square inside represents the pole right above it. As it is possible to check, each pole has its opposite one right above it.



Figure 3.4 – a) Four-poles schematic; b) Schematic of two Four-poles on top of each other

If any side is rotated 90°, in Figure 3.5 the bottom one is rotated, then each magnet is faced with its homologous pole directly above it, thus being repelled. This kind of approach allows the use of very strong magnets for non-permanent methods of fixation, since it does not require the user to overcome the total force of attraction of the magnets to move or remove them. If removal is necessary, only the relative rotation of one side to the other is required, as the juxtaposition of each magnet pole with its homologous creates a repellent force that allows the user to remove the magnets with ease.



Figure 3.5 - Four-poles magnets rotation.

3.2.1 Four-poles versions

There are two basic design versions of the four-poles magnets setup that change to repulsive state upon 90° rotation: the cross model, on Figure 3.6 a), and the square model, already displayed on Figure 3.4 a), but also portrayed in Figure 3.6 b).



Figure 3.6 – a) Four-poles magnet cross model; b) Four-poles magnet square model

The compactness of the square configuration allows for the use of stronger and bigger magnets in the same size and form factor, so this will be the one used from now on.

3.2.2 Four-poles configurations

There are four possible configurations for the magnets regarding the square model setup. Each configuration was labeled from A to D as presented in Figure 3.7, and from now on will be referred as such.

Configuration A, since it has unidirectional orientation, is not compatible with the rotating ability and will only serve as a point of reference for the other configurations. Configuration D will be excluded due to its inherent asymmetrical behavior when rotated, which leads to an undesired unpredictability upon use. Configurations B and C will be further studied and described on the following pages.

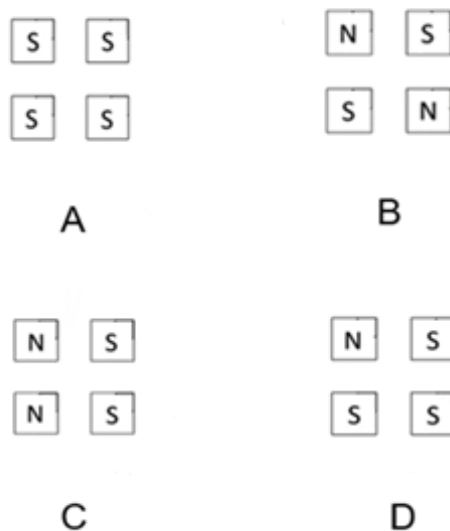


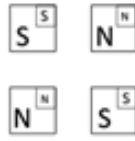
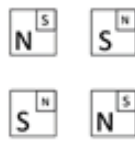
Figure 3.7 - Different four-poles magnetic configurations (A, B, C and D)

3.2.3 Configuration B

Configuration B, or the “cross configuration”, can be assembled without the need of individual housings for each magnet, as depicted in image Figure 3.8 b).

The magnets are attracted to each other in this configuration, thus eliminating the requirement for external support, allowing for more compact builds in comparison to other configurations.

In the repulsive state, (when the poles are rotated in relation to each other) configuration B has maximum repulsion, since each pole is in contact with its homologous, as depicted on Figure 3.8 a).



a)

b)

Figure 3.8 – a) Configuration B schematic in both attracting and repulsive state (left and right); b) Configuration B array of magnets

3.2.4 Configuration C

Configuration C needs specific housings for each individual magnet. This array is not stable and without a physical barrier the magnets repel each other and move away.

In the Repulsive state of Configuration C, only half of the poles are repelled, with the other half being attracted, as displayed in the Figure 3.9. This way, the theoretical magnetic net force generated is zero, this may be a desired feature in cases in which a strong opposing force is unwanted.

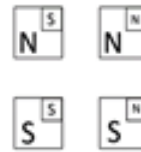
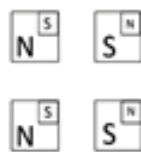


Figure 3.9 - Configuration C schematic in both attracting and repulsive state (left and right).

3.3 Inside the Guitar

For a better understanding of the geometry of the classical guitar, an old guitar was dismantled and studied. A schematic is shown on Figure 3.10 [38], with common nomenclature for guitar components.

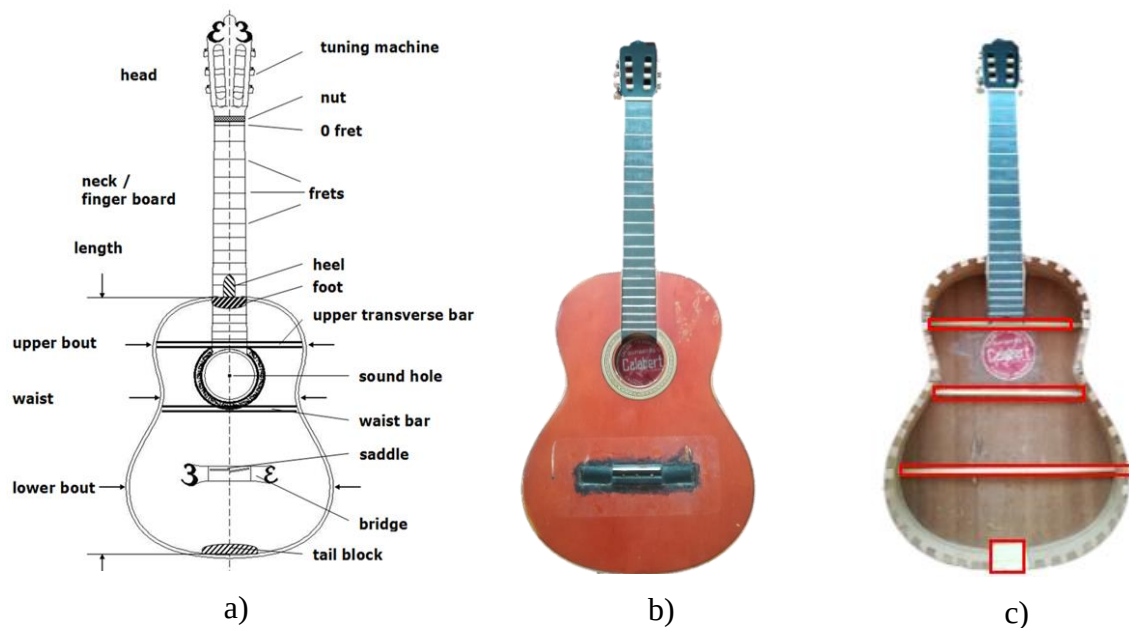


Figure 3.10 - a) Classical guitar components schematic; b) Standard classical guitar; c) Classical guitar with top removed

The soundboard (or top) of the guitar was removed, this procedure allowed a direct view of the guitar internal geometry, and a better understanding of the potential locations to appropriately place and install the anchoring system, a before and after comparison can be seen on Figure 3.10 b) and c).

The sections highlighted in Figure 3.10 c), are areas that should be avoided for the anchoring system installation due to the increased thickness, on the back, the of transverse bars, and on the bottom, the tail block.

The places that yield the best results are the ones shown on Figure 3.11, the apexes of both lateral curves, this way both magnets are solicited in the tensile direction and are in places with minimal thickness (only 2mm of wood, as it will be seen ahead), thus performing at its optimum.

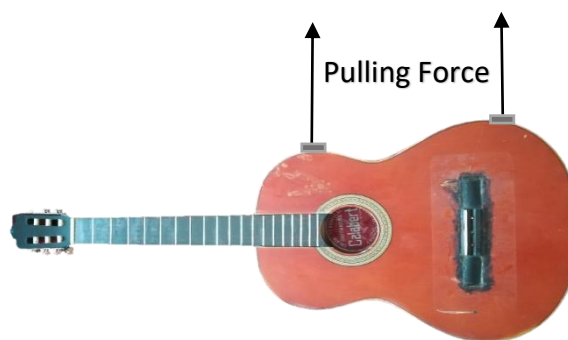


Figure 3.11 – Classical Guitar with magnets and ideal pulling force schematic

However, due to ergonomic reasons, this solution cannot be adopted, since it does not leave enough space for the musician's arm to freely play.

The best compromise found was the solution shown in Figure 3.12 with one magnetic end keeping the tensile solicitation and staying on the apex of the top curve (as shown on Figure 3.13 a)) and the other one placed on the bottom submitted to shear.

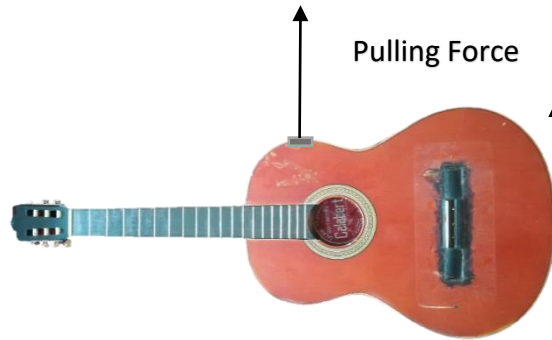


Figure 3.12 – Classical guitar with magnets and practical pulling force schematic

To improve shear stress performance, the bottom magnets should be placed in direct contact with the tail block, this way, when solicited the magnets can lean and support on it, as shown in Figure 3.13 b).



a)

b)

Figure 3.13 – a) Magnets on top curve of the guitar (inside and out); b) Magnets on bottom curve of the guitar (inside and out)

The guitar curve geometry is also of significance to this project and worth study.

In order to optimize the design of the anchoring system, the contact surface should trail the curvature of the guitar. A flat contact surface adjoining the guitar curved shape does not provide the best results since it will lead to additional strain on the shell, and the magnets performance is diminished

The use of multiple smaller magnets instead of a single bigger one allows for a better contour of the shape of the guitar, as demonstrated on Figure 3.14. This way, the strain in the shell is minimized, since the compression of a flat anchoring system exerts the force on a smaller contact area, and the performance of the magnets is improved since the attraction force is related to the distance, and with this approach the magnets are at a smaller relative distance.



Figure 3.14 - Four-poles magnets contouring the guitar

To have an approximation of the guitar geometry top and bottom curvatures, an outline was made with pen and paper, and later scanned, and imported to Solidworks™ as shown in Figure 3.15.

In the software, the correct dimensions were introduced and the curve was approximated with the *spline* function and later used in the final prototype design.

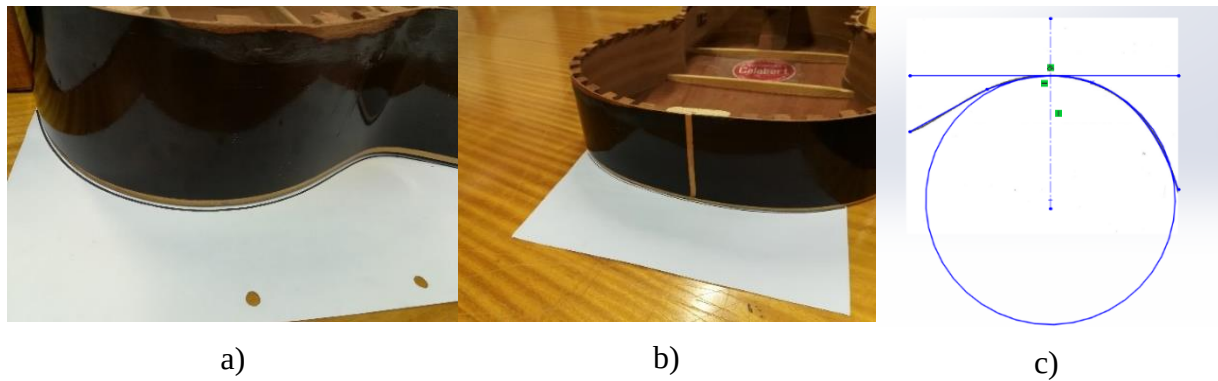


Figure 3.15 – a) Pen tracing of top guitar curve; b) Pen tracing of bottom guitar curve; c) Solidworks™ import of scan tracing

Measurements

In order to acquire valuable information about the classical guitar specifications some measurements were done.

The thickness of the side walls was measured with a caliper rule, Figure 3.16 a), and the weight of the guitar determined (value without strings) on a laboratory scale, as shown on Figure 3.16 b).



Figure 3.16 – a) Wall thickness measurement; b) Guitar weighting

Although no reliable source for the typical classical guitar weight was found, upon research the values obtained for different models varied between 1-2 kg, so the studied guitar weight of 1.4 kg fits on mentioned range of values. The lateral walls, measured 2 mm in thickness.

3.4 Anchoring System Prototype

This was the last iteration of the design, featuring bigger stronger Q-10-10-04-N magnets and a redesigned enclosure. The main design philosophy on this prototype was to make a product as simple and effective as possible. Complementing this, some predefined design guidelines were followed.

- **Ergonomics** - The product should be as easy and safe to handle as possible.
- **Safety** - A single set of magnets should be able to withstand the weight of the guitar, to safeguard the case of one strap ends failure.
- **Reversibility** -The strap should be symmetric using same type of magnets at each end, allowing the user to always use either ends when attaching it to the guitar, avoiding possible misuse.
- **Cost** -The product design should avoid unnecessary complexities and inefficiencies, since those will inflate the production cost.

3.4.1 Prototype Magnet

A total of sixteen neodymium magnets were used in the whole prototype, with each enclosure including four magnets and each strap end having two enclosures (exterior and interior). The magnets used were the ones displayed on Figure 3.17 and their properties can be consulted in appendix B.



Figure 3.17 – Q-10-10-04-N magnet, 1€ coin for scale.

3.4.2 Four-poles Magnet Enclosures

Top Exterior Enclosure: Design features

As the name implies this will be the enclosure sitting on the exterior and on the top curve of the guitar, and serve as anchor point for the strap to attach. Like the other models in this work, the model was rendered on Solidworks™ 2016 software, the renders done are depicted on Figure 3.18.

This enclosure has a single housing for the four magnets, with a protruding rim all around to prevent magnets movement. The housing has an extra clearance to facilitate assembly and give room for the magnets to adapt when attracted. The exterior surface is curved to better adjust the contact to the specific guitar shape. On the back, there is also a holed protuberance for a string or thread to pass through and connect to a strap. The sharp edges on this piece are all filleted for a more comfortable and safe handling.

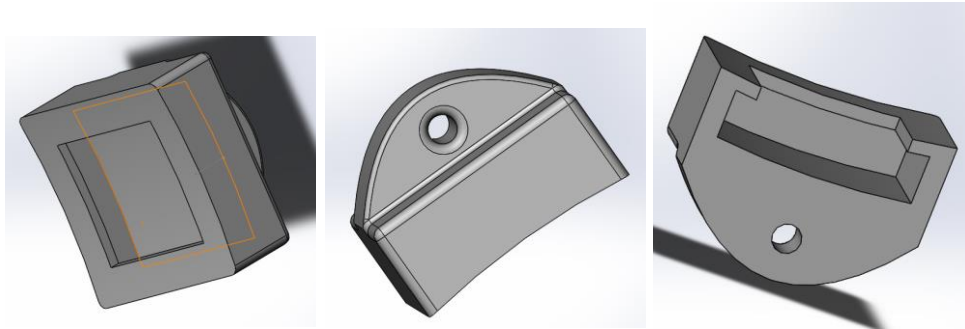


Figure 3.18 - Solidworks™ renders of the top exterior enclosure, with section view on the right.

Bottom Exterior Enclosure: Design features

The design is the same as the one in the top enclosure, differing in the contact curve, that now emulates the one present in the bottom portion of the guitar, and in the holed protuberance, that is now on the lateral part of the piece to minimize momentum since this piece will be solicited in the shear direction, as presented in the Figure 3.19,.

Despite the design guideline of reversibility, a compromise was made on this regard with an optimization of the bottom enclosure design for the shear stress performance. The misuse consideration is partly safeguard since this enclosure has a distinct shape that only suitably attaches to the bottom part. To further evidence the difference, enclosures should have color coding or labeling.

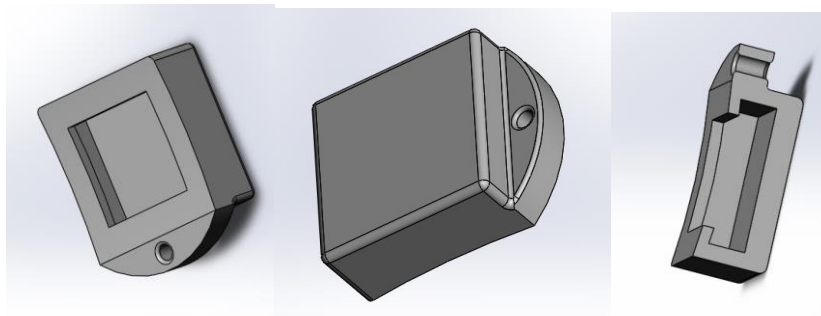


Figure 3.19 - Solidworks™ renders of the bottom exterior enclosure with section view on the right.

Interior Enclosures: Design features

Identical to the designs of the previous enclosures, only altering the contact curve that is now convex and mirrors the interior guitar curve profile. There is also no saliences or holes since there is no need for external attachment, the design can be seen in render in Figure 3.20.

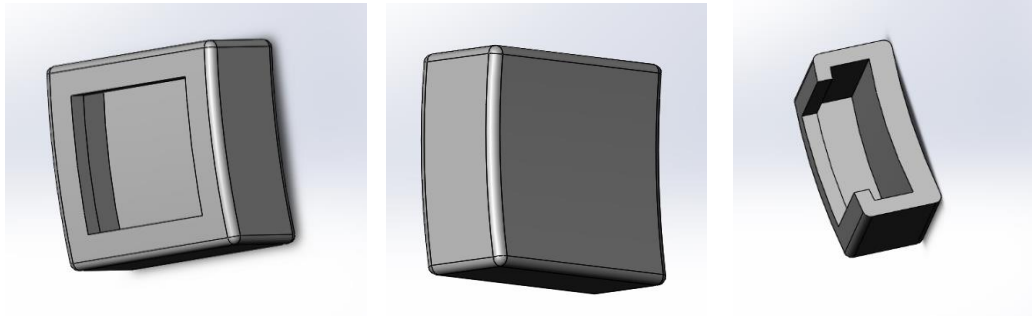


Figure 3.20 - Solidworks™ renders of the interior enclosure with section view on the right.

3.4.3 Final Assembly

In order to assemble the prototype, the magnets were individually placed inside the housing, with the magnetic force holding them together and the rim prevented them from exiting the enclosure as a whole.

The magnetic enclosures secure each other into place via the magnetic attraction, but when the strap the external magnetic enclosures are no longer there to provide the magnetic force and fall. To solve this, the interior enclosures were fixed in position with double-sided adhesive tape, so that even when the exterior enclosure is removed, they remain in place. The final assembly of the top exterior enclosure can be seen in Figure 3.21 a) and in use position Figure 3.21 b).



Figure 3.21 – a) Exterior top enclosure, 1€ coin for scale; b) Exterior top enclosure in use position

4. Experimental methods

In this chapter two major types of tests are described, the bench tests, those being the tensile/shear stress tests regarding the mechanical properties of the different magnetic configurations, and the acoustic tests that evaluate the sonic interference of the magnetic anchoring system on the guitar, completed with a blind listening test.

4.1 Bench tests

Due to the complex nature of the interactions between the magnetic fields and the difficulty to obtain a mathematical model, an empirical method was the chosen approach to obtain the most real-like results in regard to the tensile and shear performance.

The Bench Tests followed an adapted version of the MDFA (Magnet Distributors and Fabricators Association) Pull Test Standard [39] and were carried out on the Instron Electropuls™ E1000 machine. The tests would compare four different magnetic configurations in both shear and tensile stress.

Small scaled models were made with the goal of testing and comparing the different magnetic configurations.

4.1.1 Models

The models here described are a small scaled prototype envisioned and designed for the bench tests. They essentially consist of four magnets and their respective enclosures with the proper fittings for the testing machines. A finer description of the models and the stages involved in their making is done ahead.

4.1.2 Test Magnets

The test magnets chosen for the small scaled models were the W-05-N picture in Figure 4.1, full description in appendix B. The choice of these magnets relates to their small size, measuring only 5mm on each side, and the cubic geometry makes them easier to array. The magnets were purchased from supermagnete, German supplier.



Figure 4.1 – W-05-N magnet, 1€ coin for scale

4.1.3 Test Magnet Enclosures

To expedite the trials, and to avoid the fabrication of an enclosure per magnetic configuration, a goal was set to design a single pair of enclosures capable of changing magnetic configuration and allow tests in both tensile and shear stress. If accomplished only one prototype had to be made, and the setup didn't have to be changed accordingly to the configuration, only the magnets inside the housings, key factor due to the significant amount of trials to be done.

Change in the magnetic configuration

To allow the change in magnetic configuration a screw fixation system was idealized. The cavity in which the magnet was inserted would have two lateral screw holes in which screws would be fitted and press the magnet against the walls of the housing, securing it in place. The case also had one additional hole in the bottom to facilitate the removal of the magnets in case they get stuck.

A basic 3D model was made in Solidworks™ 2016 as seen on Figure 4.2. This test model was made to fit only one magnet because it had the single purpose of testing the concept.

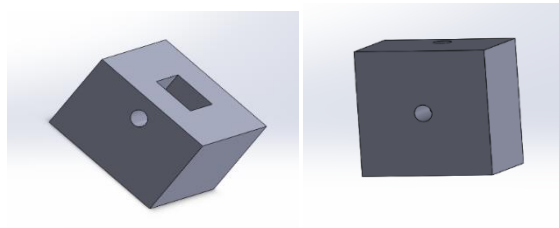


Figure 4.2 - Solidworks™ render of the screw system test model.

Printing the model

The model was first printed on a CubePro 3D printer, shown in Figure 4.3, in the LPDS (Products and Services Development Lab) of DEMec (Mechanical Department) using Fused Deposition Modelling (FDM). Due to the limitations of this technology at this scale, defects appeared, expressly in the screw hole, that wasn't circular, and on the back side that had a very rough and uneven surface. The irregularities were highlighted on Figure 4.4.



Figure 4.3 - CubePro 3D and respective printing material (on the right)

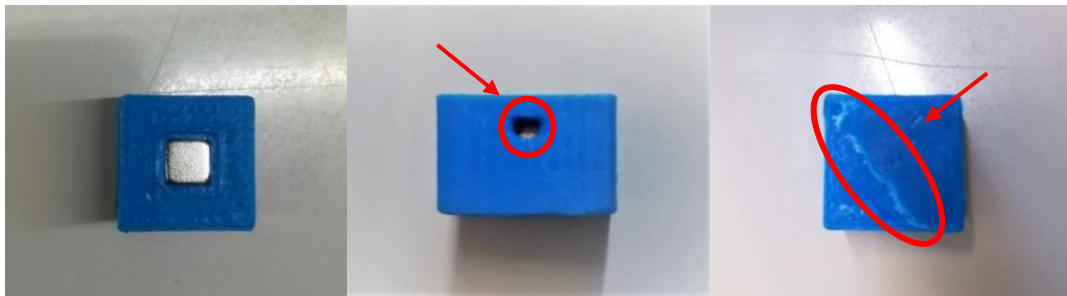


Figure 4.4 – FDM printed Screw system test model

Since this process couldn't produce enough detail at this scale, a more precise method was required. The necessary part was made by a 3D Systems Viper Si2 machine, displayed in Figure 4.5 located in the INEGI facilities. This machine prints using the Stereolithography process, and this way assures the necessary dimensional precision for the small scaled magnet enclosure. The printing material was ABS (SL 7810), full description on Appendix C.



Figure 4.5 - Viper Si2 SLA machine with respective curing oven on the right

As is possible to see on Figure 4.6 the enclosure has now much better precision with sharp clean edges, a more precise circular hole in the lateral and a now visible, hole in the bottom.

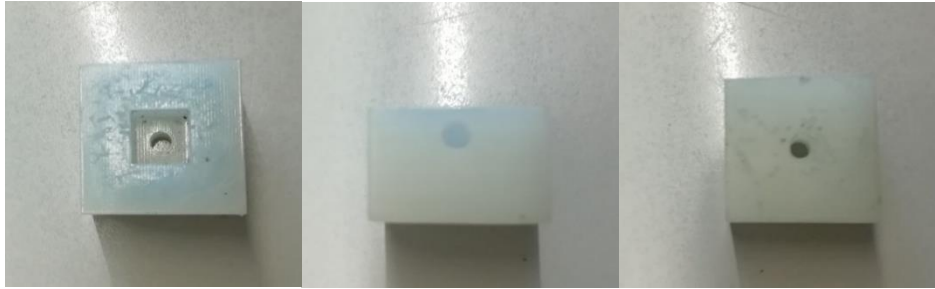


Figure 4.6 - SLA printed screw system test model

Screw hole

To maximize the contact area of the screw with the magnet, the biggest screw size possible was chosen. The biggest normalized screw, that could fit the center of the magnet enclosure and not physically interfere with the head of the screw that would sit above it, was the M2.5 size.

For the M2.5 screw to fit, the part was printed with a lateral hole with 2 mm diameter, that was later manually threaded for the screw, as displayed on the Figure 4.7.



Figure 4.7 - Manual opening of a M2.5 screw thread

After finished and assembled the model was then tested, and successfully secured the magnet in place when subjected to the attracting force of another magnet. The model completely assembled can be seen on Figure 4.8.



Figure 4.8 - Screw test model with screws and magnet.

Tensile and shear stress tests

Due to the low magnitude of forces involved (below 50 N), the Instron Electropuls™ E1000 machine and its small load cell, was a suitable option for the tensile and shear stress tests.

To use the Instron Electropuls™ E1000, specific enclosures for the magnets had to be designed. Two enclosures were designed, each with four housings to test the pull force of the different four-poles magnetic configurations, they would stay top-to-top with the bottom one secured and fixed to the machine, and the one above attached to a steel wire and dragged vertically.

Tensile and shear stress tests require proper and specific fixation of the testing objet to the machine. To achieve that, the bottom enclosure, designed in Solidworks, was planned to be secured with two M10 bolts to the machine, so it has one through hole on each side as shown in Figure 4.9 a).

The top enclosure was designed with a holed protuberance on the top and on the lateral each serving for tensile and shear tests respectively, as depicted on Figure 4.9b), to allow the passage of the pulling cable that would attach in the other end to the machine, the final tensile setup can be seen on Figure 4.10 a).

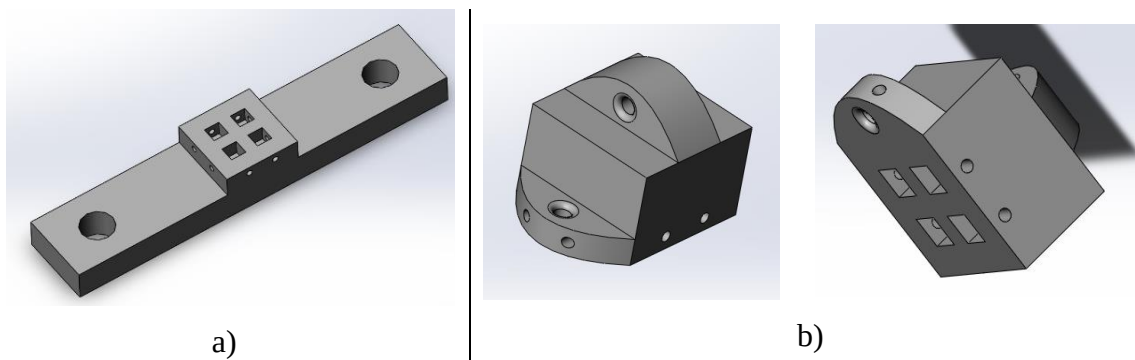


Figure 4.9 – a) Solidworks™ render of the tensile and shear test model bottom part; b) Solidworks™ renders of the tensile and shear test model top part

To perform the shear stress test, the bottom part would not lay flat, but instead be on the side and secured with gramps, the top part would also be rotated and pulled by the lateral flap, as demonstrated on Figure 4.10 b).

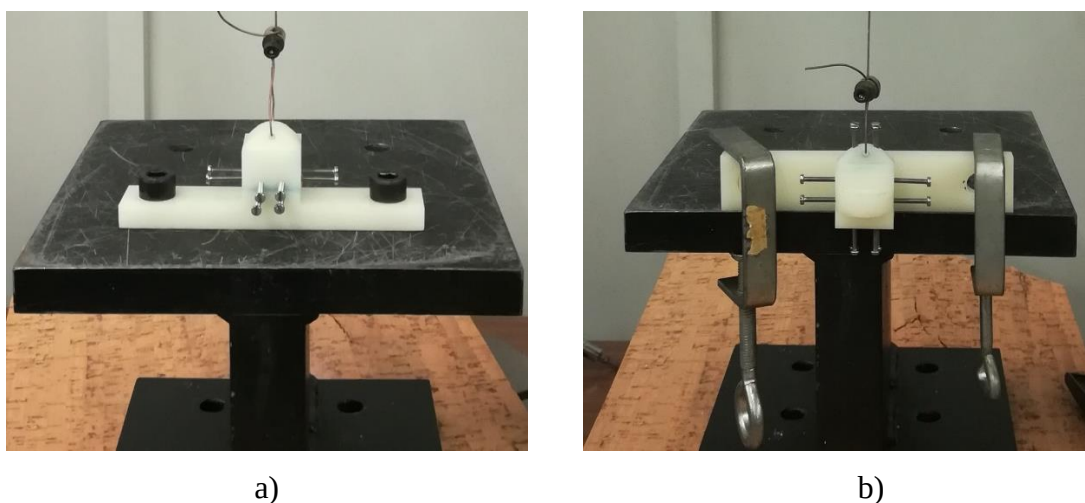


Figure 4.10 – a) magnet enclosures tensile setup; b) magnet enclosures shear setup

Final enclosures

The final enclosures were made with the stereolithography process and can be seen, already with screws and magnets assembled, on Figure 4.11 .

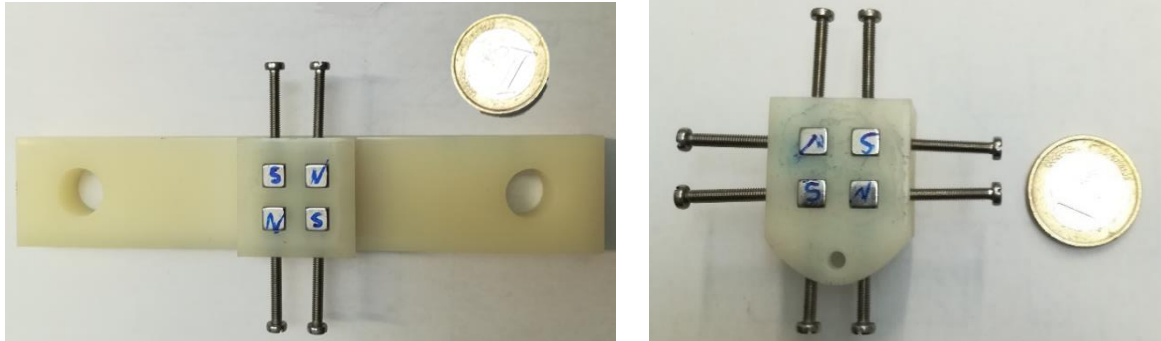


Figure 4.11 - Final models for the shear and stress tests, 1€ coin for scale.

4.1.4 Control Test

To have a better idea of the forces involved, prior to the execution of the bench tests, a control test was made.

This control would just test the pull strength on the tensile direction of the different magnets configurations and give a rough estimate of its maximum value.

The method used consisted of simply attaching a container to one of the magnet enclosures with a steel wire and firmly securing the other one on a clamp. The container would then be slowly filled up with sand until the magnets were unable to withstand the weight, thus meaning that the maximum load was achieved. The setup is showed on the Figure 4.12.



Figure 4.12 – Control test setup

The sand jug was weighted before and after each trial, with the difference, the amount poured, recorded after each trial.

4.1.5 Pull Test Standard

This test method addresses the measurement of the normal force required to detach a magnet from a work load surface.

In the following trials, some adaptations to the methodology of the Standard were made since the standard describes a manual pull test of a magnet on a steel sheet [39].

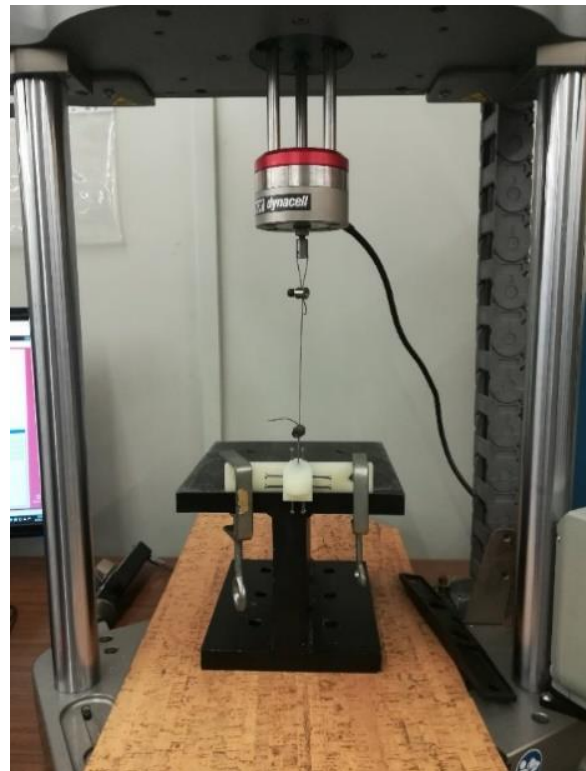
Due to a lack of qualitative data regarding the speed of the trial in the MDFA standard, since the described trials are done manually, premonitory tests were made with different pulling speeds to take this factor into consideration.

4.1.6 Speed tests

The tests here described were done with the B (crossed) magnetic configuration and with 0mm gap between the magnets. The tests were identical to a tensile or shear stress test but with the testing variable being the pulling speed. The tests were done for both tensile, Figure 4.13 a) and shear, Figure 4.13 b) setup. Every trial was repeated two times for consistency reasons.



a)



b)

Figure 4.13 – a) Tensile stress setup; b) Shear stress setup

4.1.7 Tensile Stress test

With this test, the main objective was to determine the distance force curve in the tensile direction and compare the different magnetic configurations.

To accomplish that each configuration was tested with four different spacings them being, 0 mm (air gap), 0.55 mm, 1.17 mm and 1.74 mm, the spacings, other than the air gap, were achieved by stacking six, twelve and eighteen sheets of paper respectively.

Each trial was repeated three times to minimize error and variance.

The tested configurations were the A, B and C already described in 3.2.2 plus a B' configuration, the different magnetic configurations can be seen on Figure 4.14.

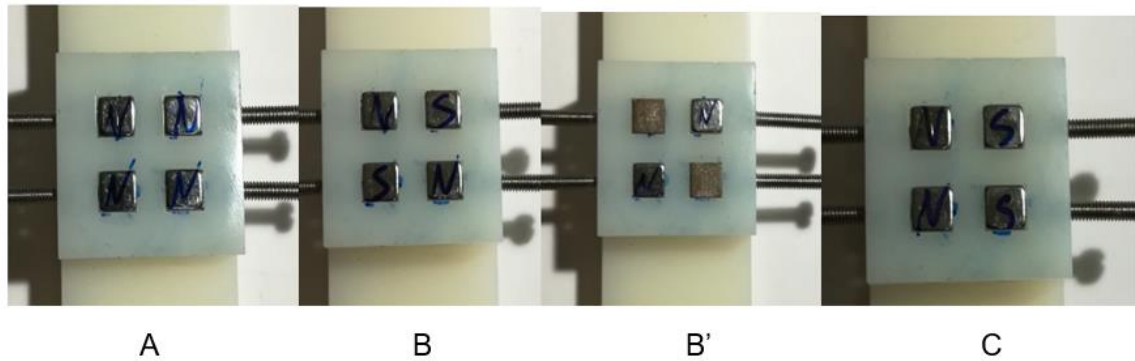


Figure 4.14 – Final Assembly of Different magnetic configurations

The configuration B' is an altered version of the configuration B containing two iron cores (only on the bottom part) in place of the magnets. This iron cores were purposely machined 5 mm cubes, the same dimensions as the magnets. The altered configuration was made to see the influence of the iron replacement would have on the load. The B configuration was the chosen configuration to be altered due to the higher load capacity shown in the control tests results. A more detailed schematic of the configuration B' is portrayed on the Figure 4.15.

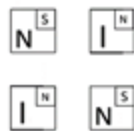


Figure 4.15 – Configuration B' Illustration, “I” representing Iron

4.1.8 Shear Stress test

The tensile tests would give a view of the load capability of the magnet in the normal direction, but to fully characterize the mechanical behavior of the magnets and to address the fact that the magnets in this specific application will not be subjected exclusively to tensile stress, the response of the magnets to shear load had to be tested.

The shear stress tests were made analogously to the tensile one, testing the same magnetic configurations and spacings with the common objective of obtaining the respective distance force curves. All the variables stayed the same only changing the position of the magnets enclosures that now were set up for testing in the shear direction.

The shear stress test values vary with the materials used for spacing since they are in direct contact with the magnets. This type of solicitation is sensible to friction and as referred in 4.17, the material used for spacing was paper, so the values here presented were in regard to paper.

4.2 Acoustic Test

The acoustic of the classical guitar (or any classical stringed instrument) and its inherent sound is the defining feature of the instrument and the one that appeals the most to the musician. As so, is of extreme importance that any accessory that is implemented onto the classic guitar is tested regarding eventual changes in the acoustic characteristics of the instrument.

To appraise the influence of the presence of the magnetic strap an acoustic test was planned. The test would be conducted on the DEEC (Electrical Engineering Department) electromagnetic anechoic chamber.

This division despite not being purposely built for acoustic tests, has radiation-absorbing material covering the entire room, shown on Figure 4.23, mitigating external noise since the foam acts as insulator, but most importantly and preponderantly, the spike structure of the insulator foam chops the soundwaves minimizing reverberant sounds that would otherwise be generated alongside the emitting source [40].

Without the presence of reverberation, the sensors are exclusively exposed to direct sounds, making the recordings more accurate and clear, allowing for subtle differences to be easier to detect.

The basic idea behind this test is to sample sounds in different situations, with and without the magnetic strap and to compare possible alterations.

For that, different sensors were employed, to capture the guitar sound in multiple ways. Those are listed below.

4.2.1 Test Guitar

The guitar tested was a $\frac{3}{4}$ student model, the Yamaha CS-100A, shown on Figure 4.16.



Figure 4.16 - Yamaha CS-100A, with zoomed label on the side

The guitar was tuned with standard tuning, E'BGDAE the order going from the tuning of the highest pitch E' to the lowest pitched E. The according pitches and frequencies are described in the table Table 4.1.

Table 4.1 - Guitar strings with respective frequencies and pitch notation in standard tuning.

String	Frequency Hz	Scientific pitch notation
1 (E)	329.63	E4
2 (B)	246.94	B3
3 (G)	196.00	G3
4 (D)	146.83	D3
5 (A)	110.00	A2
6 (E)	82.41	E2

4.2.2 Sensors

The sound pickup sensors utilized were of two kinds, microphones and piezo-electric pickups. Laboratory condenser microphones, from Bruel & Kjaer were used, these devices were selected due to the accuracy, precision and compactness and can be seen on Figure 4.17.

Two microphones were used in this setup, one to capture the sound inside the sound hole of the guitar, and another one dedicated to capturing the sound emanated from the guitar.



Figure 4.17 – Bruel & Kjaer microphones type 4190, type 4165 right and left respectively

Piezo-electric sensors, a piezo electric material is one that accumulates electric charge in response to mechanical stress. A Piezo-Electric transducer was used with the purpose of catching the sound and vibrations emanated through the guitar body. The used sensor was a Shadow SH-2000 pick-up as is possible to see on Figure 4.18.



Figure 4.18 – Shadow SH-2000 on the left, and installed on a guitar on the right

The point in this application would be to try to detect variations on the vibration properties of the guitar body since now part of it its being compressed between two magnets.

4.2.3 Actuators

To actuate the guitar strings an automatic solution was designed to eliminate human variability and the associated error.

The idea would be to have the ability to trigger the guitar sound at distance minimizing also the error associated with the presence of the player inside the anechoic chamber.

To do so an electro magnet adapted from the ringing bell of an old styled telephone, was used, shown on Figure 4.19.



Figure 4.19 - Telephone Bell electromagnet

In order to expand the range of the actuator as well as having a more similar stroke to of a guitar player, a specific pick was made to mimic the guitar pick, example shown on Figure 4.21 a), and designed to be attached to the electromagnet.

Three versions were made, following the fabrication method shown on Figure 4.20, with three different materials each with different rigidities, with the purpose of assessing the most suitable one for the application.



Figure 4.20 - Fabrication of the pick in the milling machine

As seen on Figure 4.21 b) from left to right, carbon fiber, polycarbonate and nylon picks. After premonitory tests, due to the electromagnet relative low power, the one that achieved the best results was the softer one, the nylon.

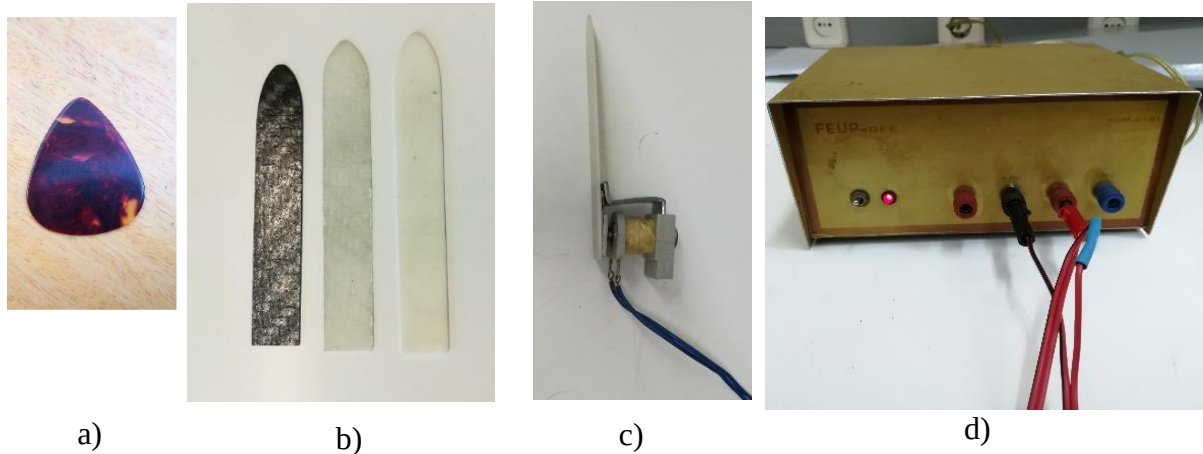


Figure 4.21 – a) Standard guitar pick; b) Three different versions of custom picks; c) Electromagnet with pick attached; d) DC power supply used for the electromagnet

The actuator was connected to a 15 V DC power supply, shown on Figure 4.21 d), and when turned on, the current would excite the electromagnet coil creating a magnetic field that would attract the steel reed originating the actuator movement.

4.2.4 Setup

The actuator (electromagnet) was connected to a simple switch coupled with the power source to be remotely activated by the test conductor.

All of the sound input (microphones and piezo-electric pickup) were sent to a Edirol UA-101 soundcard, pictured on the Figure 4.22, where the analogic signal would be converted to a digital one. The sound card was then connected to a Personal Computer where the Reaper software would acquire and record the data.



Figure 4.22 - Edirol UA-101 Soundcard

The setup was assembled with all the necessary components inside the chamber and as portrayed on Figure 4.23, only the computer and the actuator activator were placed outside for interference reasons, (computer noises, fan, keyboard clicks, and operator's noise, breathing, moving etc.) this way the automated tests could be done remotely from outside the chamber. The actuator integrated in the final assembly, can be seen Figure 4.24.

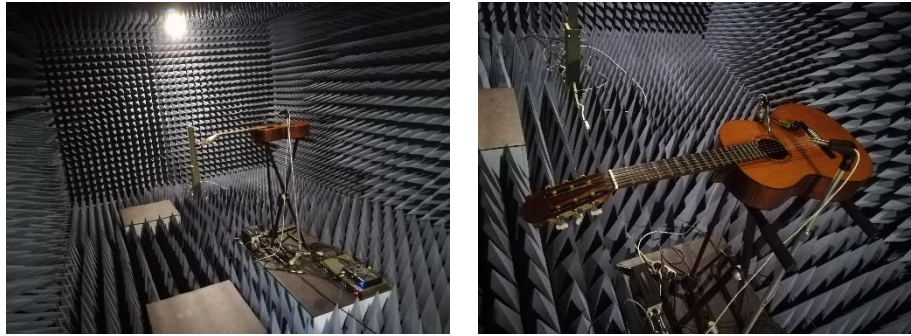


Figure 4.23 - Final Setup in anechoic chamber

The guitar was laid down supported by a stand, All the tests were done with and without the magnetic strap, to compare both results. The magnetic system used, was the first prototype, shown Figure 4.24 on the left, since it was the only one available at the time.

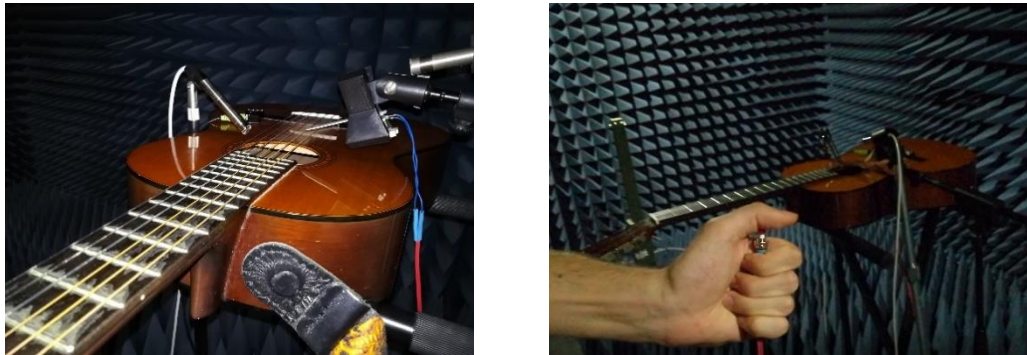


Figure 4.24 - Actuator in the final setup

The played notes were all open strings since it would assure better consistency since it would dismiss the variability in the fret pressing. To have a more comprehensive test, the full range of strings were tested and recorded, one at a time, to analyze the full acoustic range of the guitar.

The selected strings are labeled and highlighted on Figure 4.25. To reproduce a more typical use scenario, the strings beside being automatically (electromagnet) plucked were also manually played by a musician.



Figure 4.25 – Selected strings and according label

4.2.5 Recordings

The computer acquired the data via Reaper™ software, since it was capable of multitrack recording (more than stereo), and recorded individual twenty seconds tracks for each sensor, in wav file format. Automated tests were repeated five times, but due to practical reasons, such as the restraining conditions for the test operator (inability to move or comprise sound producing behaviors) and the extensiveness of the trials, only three replications were made for the manually operated tests.

The point of the repetitions process was to ensure consistency and to calculate averages, for error minimization.

The recordings made were all individually listened, to check parasitic noises and other anomalies.

Due to the high amplification of the interior microphone, the recordings carried an electric noise and hum. To solve this condition, the Adobe Audition software was used. The pre-playing sound of each track, which contained only noise was selected as *Noise print*, as shown in Figure 4.26 b) and applied as noise cancelation, with the *Noise reduction* function. Note that the noise on the spectral frequency display (the purple grain over the spectrum) disappears after the *Noise reduction* is applied, a direct comparison can be made observing Figure 4.26 a) and Figure 4.26 c). Due to its effectiveness, this procedure was then done to all recordings.

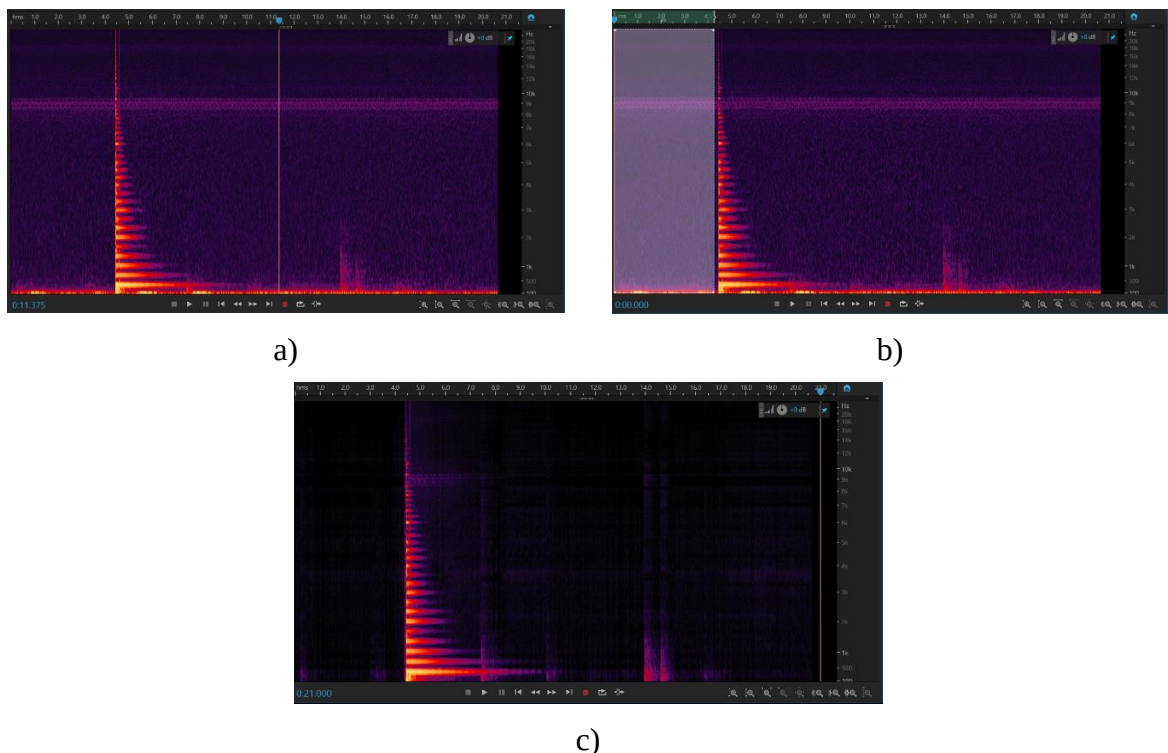


Figure 4.26 - a) Guitar recording in spectral frequency view, Adobe Audition; b) Selection of ambient noise for *Noise print*; c) Recording after noise reduction applied

For further analyses the recordings were opened in Praat software.

4.2.5.1 Decay

For the decay test results, the *IntensityTier* was extracted from the audio clip. An *IntensityTier* is an object that represents a time-stamped intensity contour, containing a series of time intensity, points in dB [41].

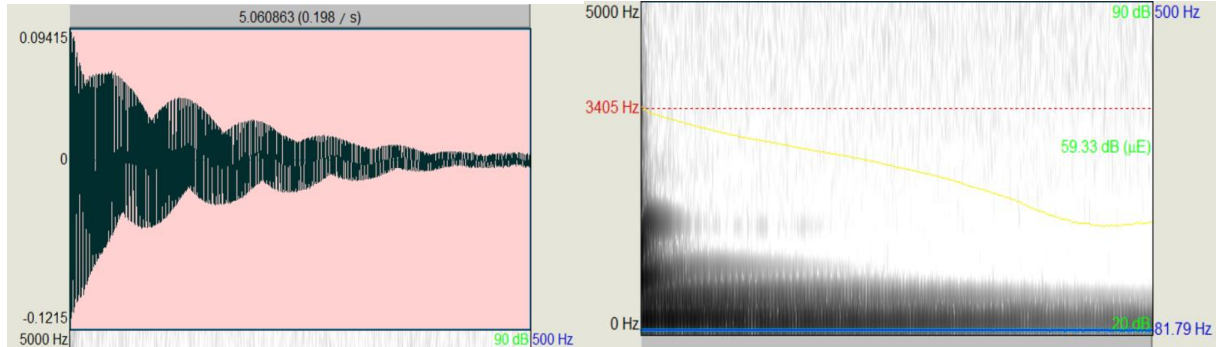


Figure 4.27 - Praat software time selection on the left and IntensityTier on the right

The *IntensityTier* was selected starting from the moment of attack (peak value) until five seconds after, the file was then launched to MATLAB software where the trend lines and averages were done and plotted.

4.2.5.2 Spectrum

For the spectrum analyses, the process was similar. A selection was made from the moment after the attack (as shown on Figure 4.28) until five seconds after and the track was trimmed for the said selection.

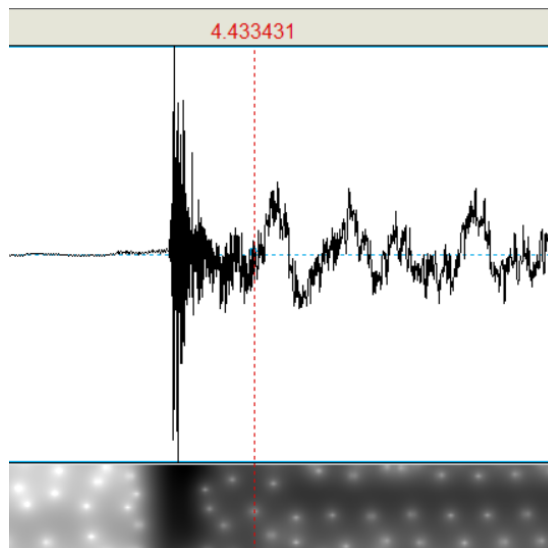


Figure 4.28 – Praat software selection for spectrum analyses

4.3 Listening test

For a better interpretation of the acoustic tests results, and a more practical view of the significance of the respective values, a subjective exam was envisioned.

The listening test would give a frame of reference for the real differences in sound detected by the human ear, to complement the previous acoustic analysis.

The test was done in survey layout in google forms. This format allows for an easy distribution of the inquiry, since it is online, and the digital nature of the content allows the inclusion of media files such as audio recordings, the full survey can be consulted in appendix D.

4.3.1 Survey Questions

The survey comprised essentially of a series of yes or no questions with an open field to describe eventual differences, designed to be accompanied with the listening of the respective audio tracks, an excerpt is shown in Figure 4.29.

2. **Após audição do Ficheiro 1, Notou alguma diferença entre as diferentes notas? ***
Marcar apenas uma oval.

☐ Sim

☐ Não

3. **Caso tenha respondido que sim na resposta anterior, tente descrever as diferenças que ouviu (opcional)**

Figure 4.29 – Listening test, online survey, excerpt 1

At the end of the four hearings, the listener is asked to identify in which audio file they felt that there were the biggest variances.

10. **Após audição de todos os Ficheiros (pode repetir se achar necessário) em qual crê ouvir mais ou maior diferenças? ***
Marcar apenas uma oval.

☐ Ficheiro 1

☐ Ficheiro 2

☐ Ficheiro 3

☐ Ficheiro 4

☐ Não consegui ouvir diferenças nenhuma

Figure 4.30 - Listening test, online survey, excerpt 2

If the option regarding the magnetic system interference is selected (file 3), a hidden question emerges (Figure 4.31), requesting the inquired to grade from one to five the differences in this recording, one representing hardly noticeable and five, very evident.

Avaliação Qualitativa

11. Numa escala de um a cinco como classificaria as diferenças escutadas no Ficheiro 3 *

Marcar apenas uma oval.

	1	2	3	4	5	
Pouco perceptível	☐	☐	☐	☐	☐	Muito evidente

Figure 4.31 - Listening test, online survey, excerpt 3

4.3.2 Audio files

A total of four audio files was presented in the survey and were created from the recordings of the exterior microphones, made with the automate system playing the A string 110 Hz, with and without magnetic system. The A string was chosen as the test subject, since in the decay and spectral analysis was the most affected by the magnetic system presence, and this way the test would embody the worst-case situation. All of the files were made in audition software.

The first file comprised the recordings of the five trials, without the magnetic system installed, played back to back. This file and the corresponding question would serve as reference to see if the variances in the different trials were significant enough to be detected.

The second file would serve as a control test to detect false positives, and was simply a repetition of a single trial audio track five times.

The third file included the direct comparison of the magnetic interference. The file played alternately the recording with and without the magnetic system. Playing three trials with the magnetic system and two trials without to match the previous audio tracks lenght.

The fourth and final track was made analogous to the first one but with the recordings taken from the trials with the magnetic system installed.

5. Results and discussions

5.1 Control Test

The results regarding the control test are listed on Table 5.1.

Table 5.1 – Tensile control tests results

Configuration	Trial 1 (g)	Trial 2 (g)	Trial 3 (g)	Trial 4 (g)	Average mass (g)	Average force (N)
A	2971	3133	3156	3084	3086	30.02
B	3678	3866	3691	3709	3736	36.65
C	3486	3509	3603	3555	3538	34.71

As illustrated in Table 5.1 the average maximum attraction force ranges from 30 to 40N, values that will serve as reference for future tests. From these preliminary tests, the configuration B showed the best results.

5.2 Speed tests

5.2.1 Tensile speed test

As observed on Figure 5.1, a total of six different pulling speeds were tested ranging from 0.1mm/s to 5mm/s, the maximum load value varies from 30 to 40 N, and the breakaway displacement oscillates between 6 and 8 mm.

The results show a tendency of an increase of the maximum load with the pulling speed. The chart on Figure 5.2, was constructed with the peak values of the curves in Figure 5.1. This phenomenon becomes more visible in Figure 5.2 as it shows an increase from around 30 N for 0.1 mm/s pulling speed to 40 N for 5 mm/s speed. Despite the efforts, the reason behind this phenomenon is not yet understood.

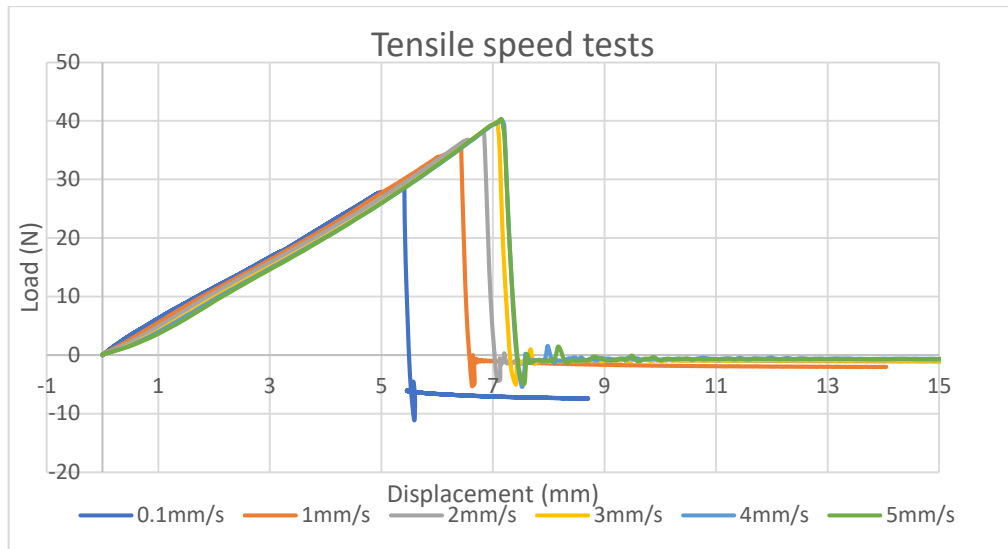


Figure 5.1 - Tensile speed tests chart

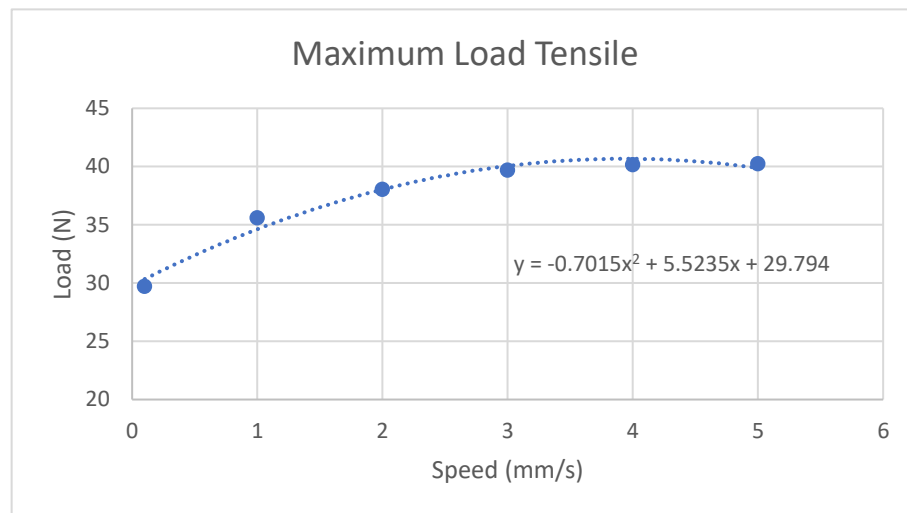


Figure 5.2 - Tensile Maximum Load vs. Speed, chart

5.2.2 Shear speed tests

Shear stress speed tests were done homologous to the tensile ones but with only five pulling speeds tested, ranging from the same values. The maximum load is smaller, peaking at around 20 N, and the breakaway displacement sits around 9 mm. The results are represented on Figure 5.3.

The results now had a more predictable behavior with no meaningful influence of the pulling speed on the maximum load, like the horizontal slope of the trendline in Figure 5.4 illustrates.

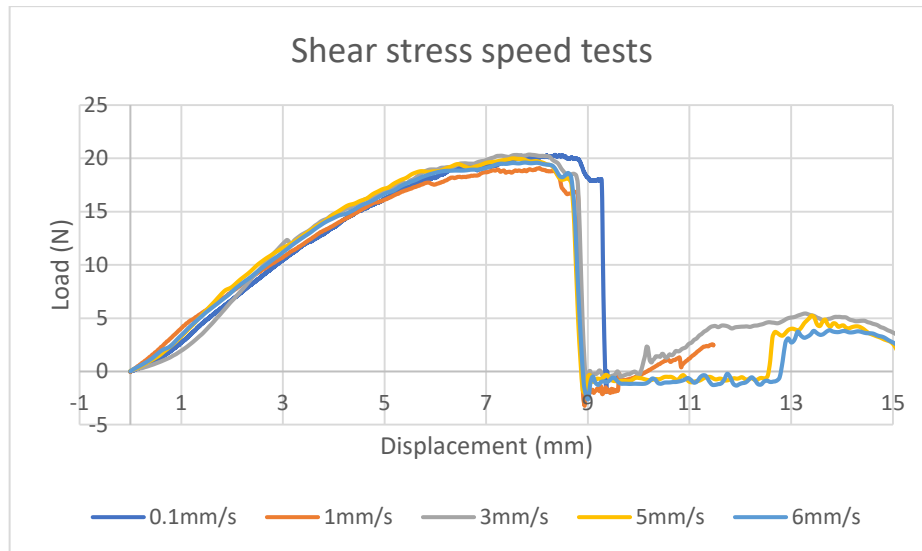


Figure 5.3 - Shear stress speed tests chart

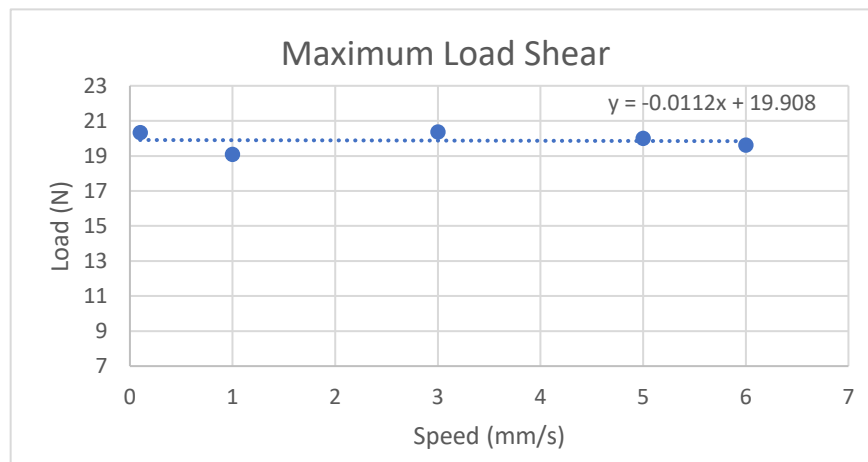


Figure 5.4 - Shear maximum load vs speed chart.

Selected speed

The first pulling speed selected for the tensile tests was 2 mm/s, since it would give the average value for the load, but due to slight fluctuations on the machine readings, a compromise was made at 1 mm/s.

For the sake of simplicity and since the pulling speed didn't influence the maximum load in the shear configuration, the same speed (1 mm/s) was used in both tensile and shear stress tests.

5.3 Tensile and shear stress test

Four different configurations with four different spacings in both tensile and shear orientation were tested, each trial was repeated three times, totaling up 96 trials. In addition to that the speed tests, which tested five and six speeds, in shear and tensile orientation respectively, and were repeated two times, adding up to a grand total of 118 trials done.

The tests results are shown in both average and true form. The tests were done with the computer acquiring data at 100 Hz refresh rate, and every trial started at the same ordinate. Because of this no interpolation was needed to obtain the average.

Each curve labeled 0, 6p, 12p, 18p represents the number of paper sheets placed for the correct spacing. The charts on the right have the full twelve curves corresponding to the trials realized for each configuration and the charts on the left have the curves corresponding to the average generated of the three repetitions.

5.3.1 Tensile stress test results

Figures 5.5, 5.6, 5.7 and 5.8 present the results from the tensile stress tests for configurations A, B, B' and C respectively.

Configuration A

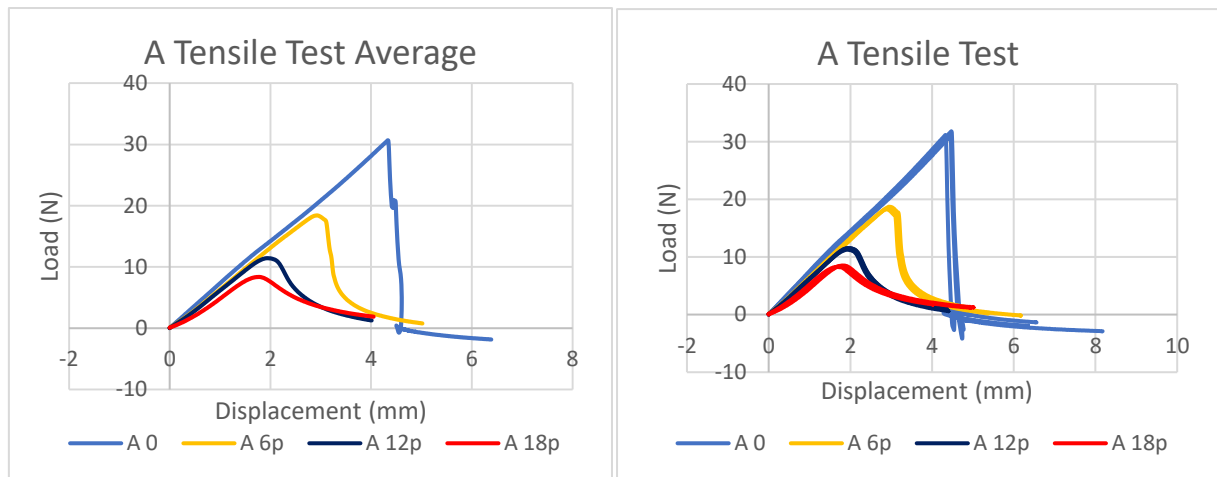


Figure 5.5 – Configuration A tensile test results

Surprisingly, configuration A despite its unidirectional arrangement, which indicated a good tensile performance, behaved worse than the other configurations, achieving low max values for 0 mm (airgap), and only surpassing the configuration B' for higher distances. As displayed on the Figure 5.9.

Configuration B

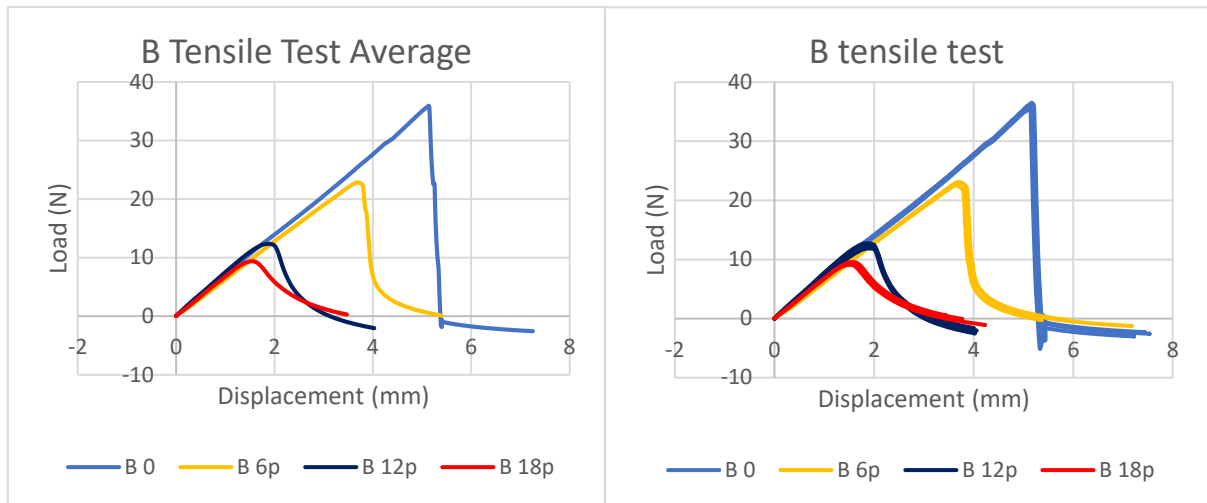


Figure 5.6 - Configuration B tensile test results

Configuration B was the best performer at short distance, achieving the highest peak value (36 N), and was only marginally surpassed by the configuration C for higher distance values, as is possible to confirm on Figure 5.9.

Configuration B'

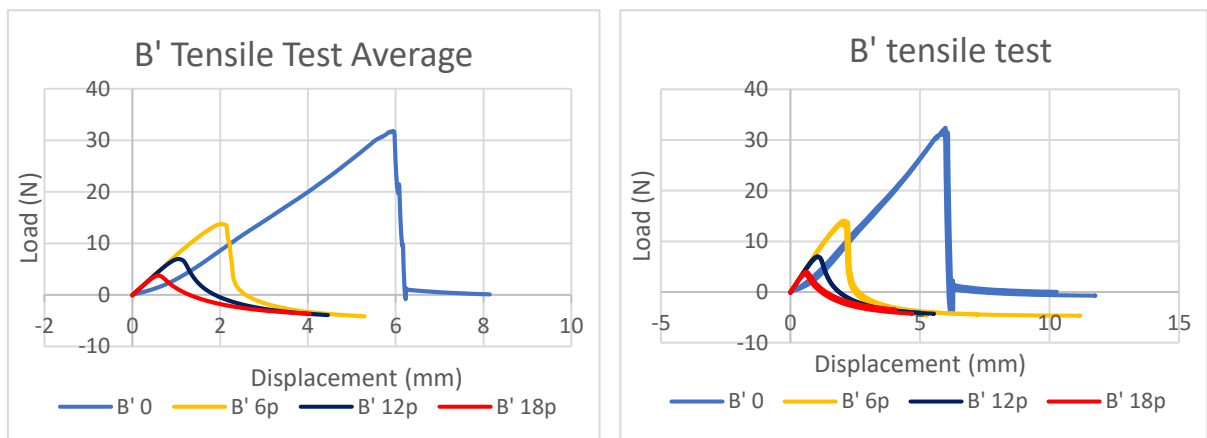


Figure 5.7 - Configuration B' tensile test results

The B' tensile test despite the presence of iron cores had very similar curves to the other configurations, only showing a more accentuated decrease of max load with the increase in spacing. This is noticeable on the 6p, 12p and 18p curves having a different slope than the 0mm one. The configuration B' is unexpectedly the configuration with the biggest breakaway displacement being the only configuration surpassing 6 mm.

Configuration C

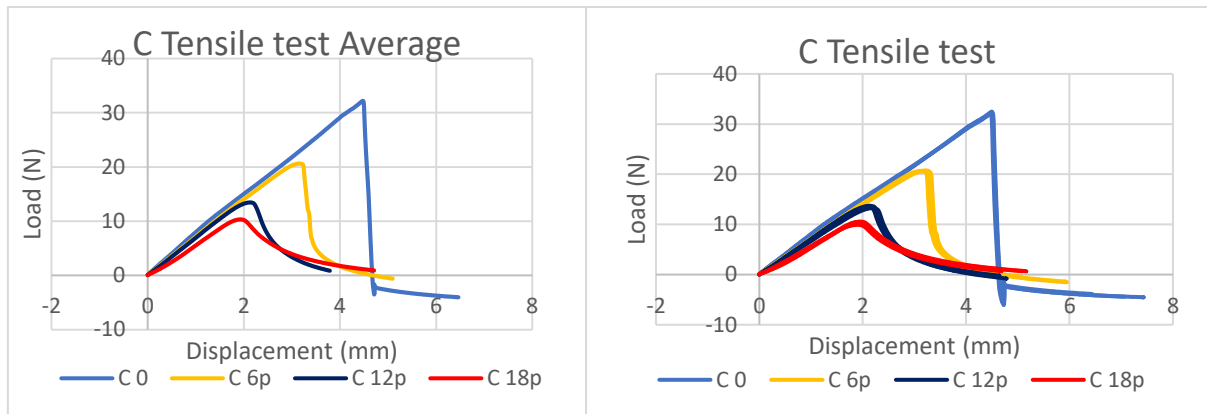


Figure 5.8 – Configuration C tensile test results

Configuration C performed somewhat in between the other configurations, with no particular behavior worth mentioning.

Comparison

For a clearer comparison between the different max load values, Figure 5.9 can be analyzed.

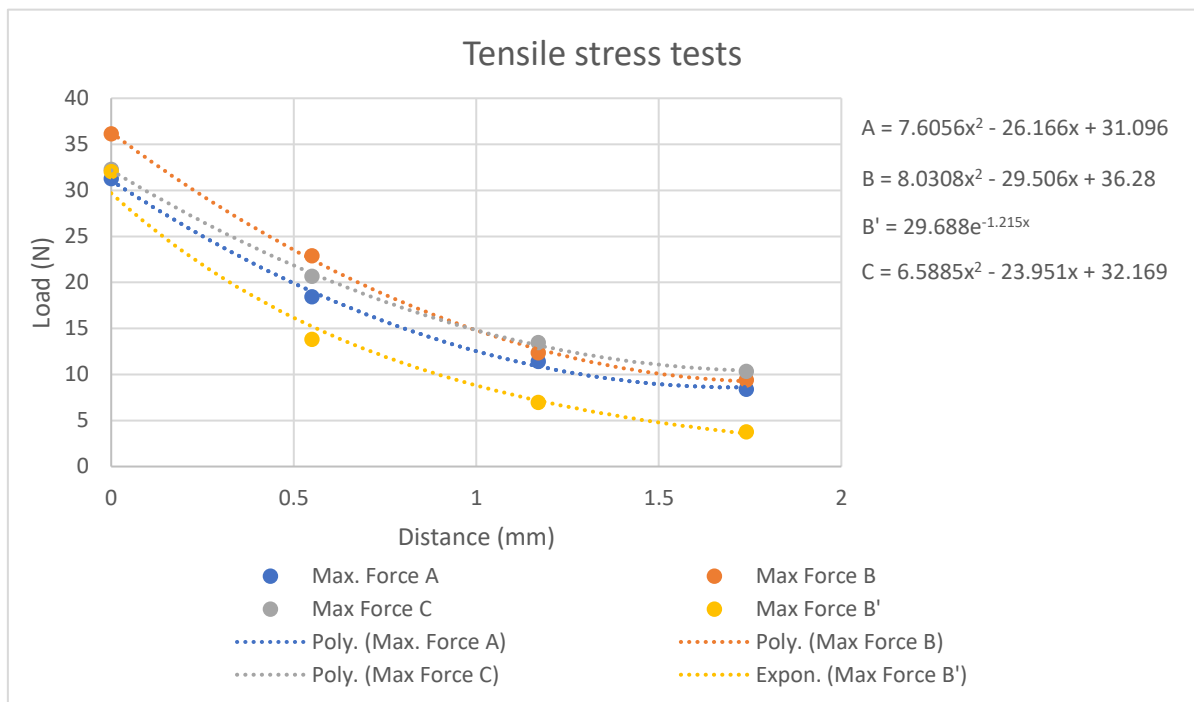


Figure 5.9 – Tensile maximum load vs distance

The chart in Figure 5.9 was constructed off the peak values of the several configurations average curves. The equations on the right represent the curves from the respective A, B, B', C configurations.

Due to the inverse-square law behavior of magnetism, in which its intensity is inversely proportional to the square of the distance, a second-degree polynomial equation was used as a regression equation to describe Coulomb's law [42].

The configuration B' was an exception because due to the more rapid decline in strength had better results with an approximation with an exponential function.

Conclusion

Despite the pulling force of a single magnet amounts to 10.8 N, no configuration achieved the theoretical maximum of 43 N (4×10.8) N. This can be attributed in some part to the eventual infinitesimal misalignment of the enclosures that could diminish the overall values, but more significantly to the fact that the magnetic fields, due to the magnets proximity, interfere adversely with each other's.

As expected, the maximum load and breakaway displacement decrease as the spacing.

The shape of the curve gradually changes from a linear slope with a sharp decline after the breakaway point to a flatter, bell-shaped curve for higher paper sheet counts.

The B configuration performed the best at close distance, but was marginally surpassed by the C configuration for higher distances. The B' configuration was similar to the other configurations at close distance but declined rapidly for higher values of separation. In light of these results, the use of iron cores in replacement of magnets as a cost saving solution, might not be the best solution with increasing distance (the guitar walls have 2mm in thickness) the configuration performs substantially worse. The C and A configuration performed intermediately between B and B'.

The max load decreases with an inversed power of two with distance, so its of extreme importance to minimize its value.

5.3.2 Shear stress test results

Figures 5.10, 5.11, 5.12 and 5.13 present the results from the shear stress tests for configurations A, B, B' and C respectively.

Configuration A

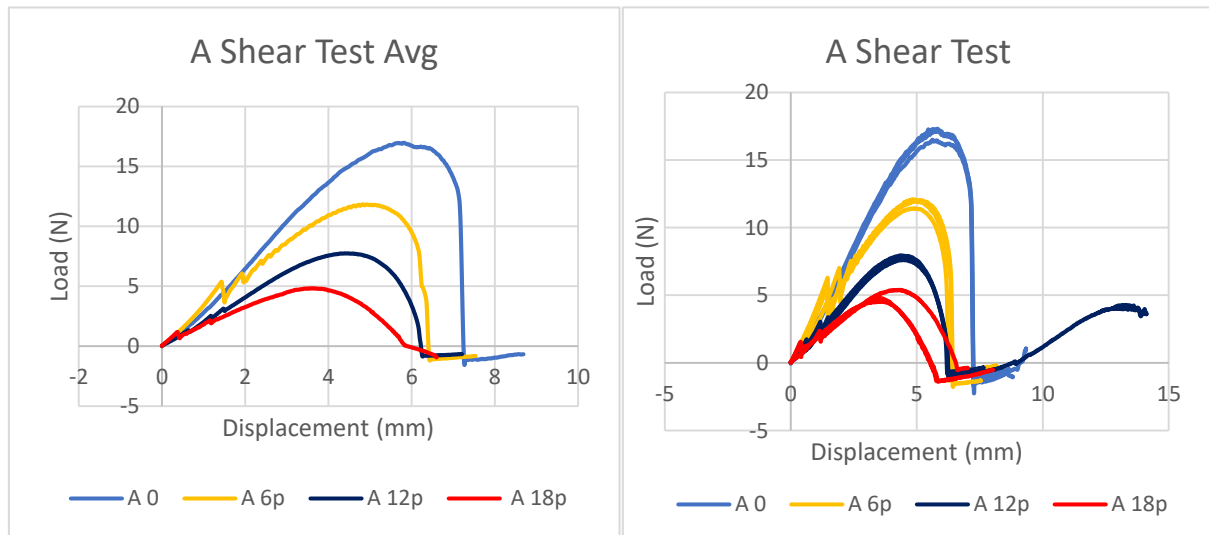


Figure 5.10 - Configuration A shear test results

Configuration A shows some anomalies and increased variance on the first part of the curves, that can be attributed to the magnets movement trying to adapt to the more stable position. This effect, although common to all configurations, is more pronounced here due to the unidirectional comportment of this configuration that doesn't restrain the magnets rotation.

Configuration B

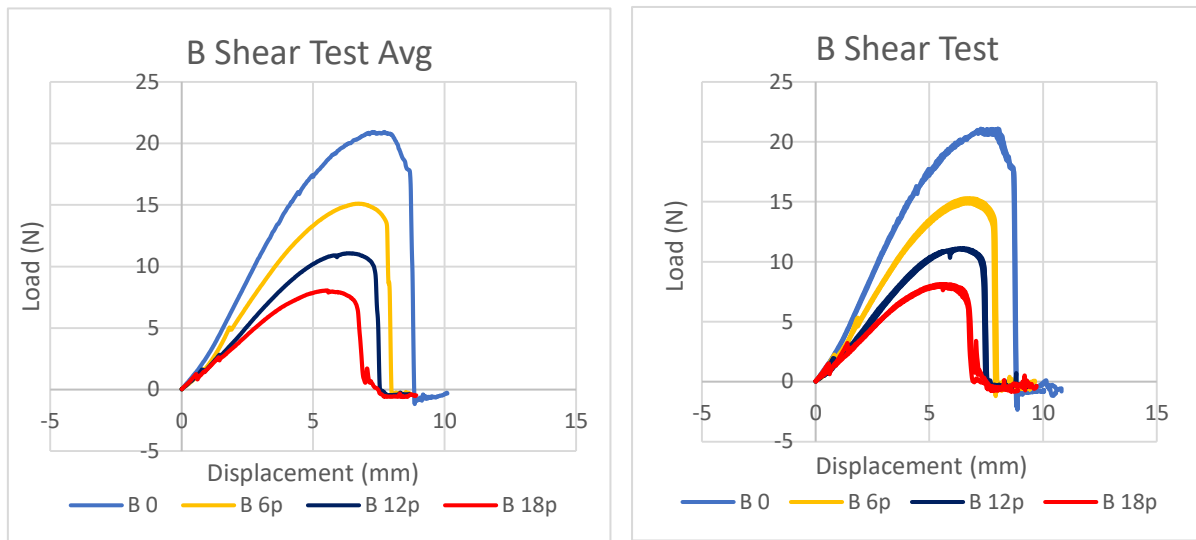


Figure 5.11 - Configuration B shear test results

The configuration B was again the most performant one, as can be more evidently seen on Figure 5.14, with the highest max load across all distance range, and with biggest breakaway displacement.

Configuration B'

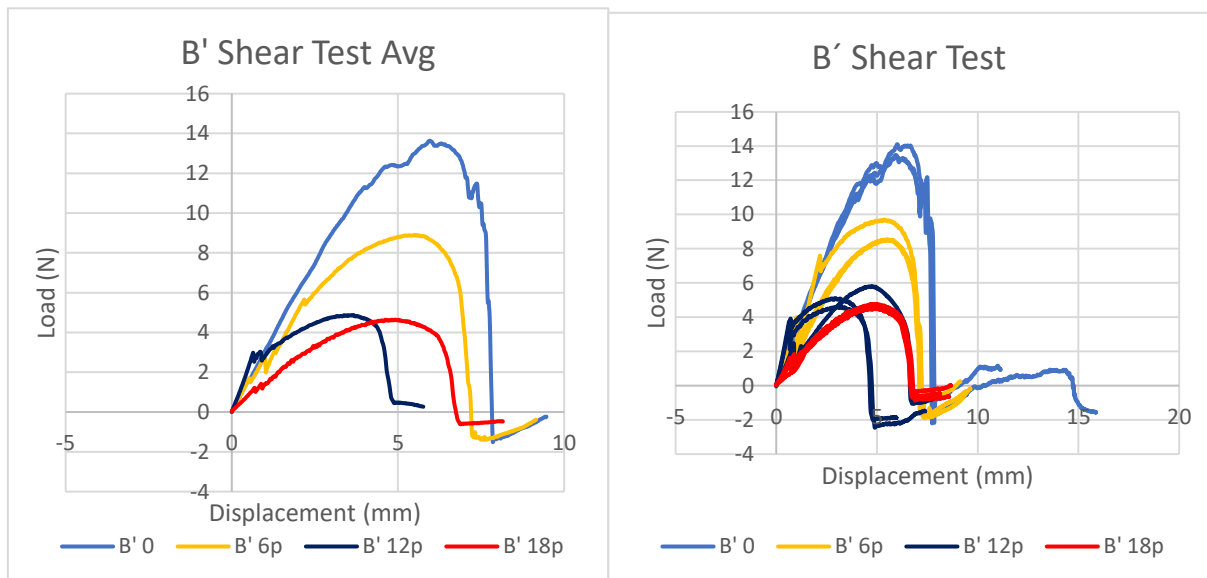


Figure 5.12 - Configuration B' shear test results

Unsurprisingly the configuration B' performed worse than configuration B, registering more variation partly due to the weaker load values.

Configuration C

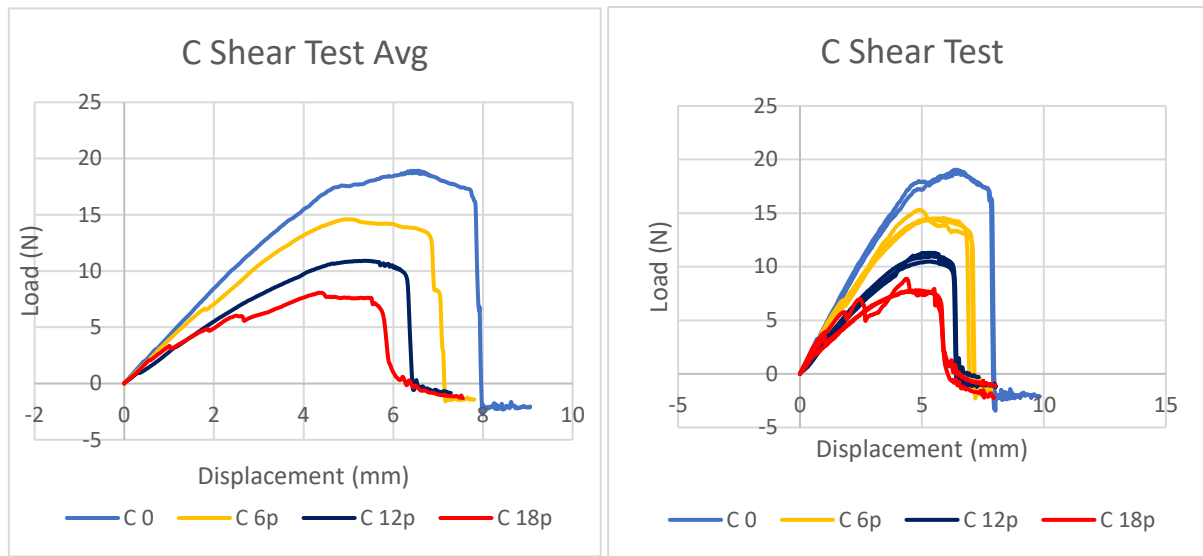


Figure 5.13 – Configuration C shear test results.

As with the tensile test, the configuration C had an intermedium performance, performing behind the configuration B.

Comparison

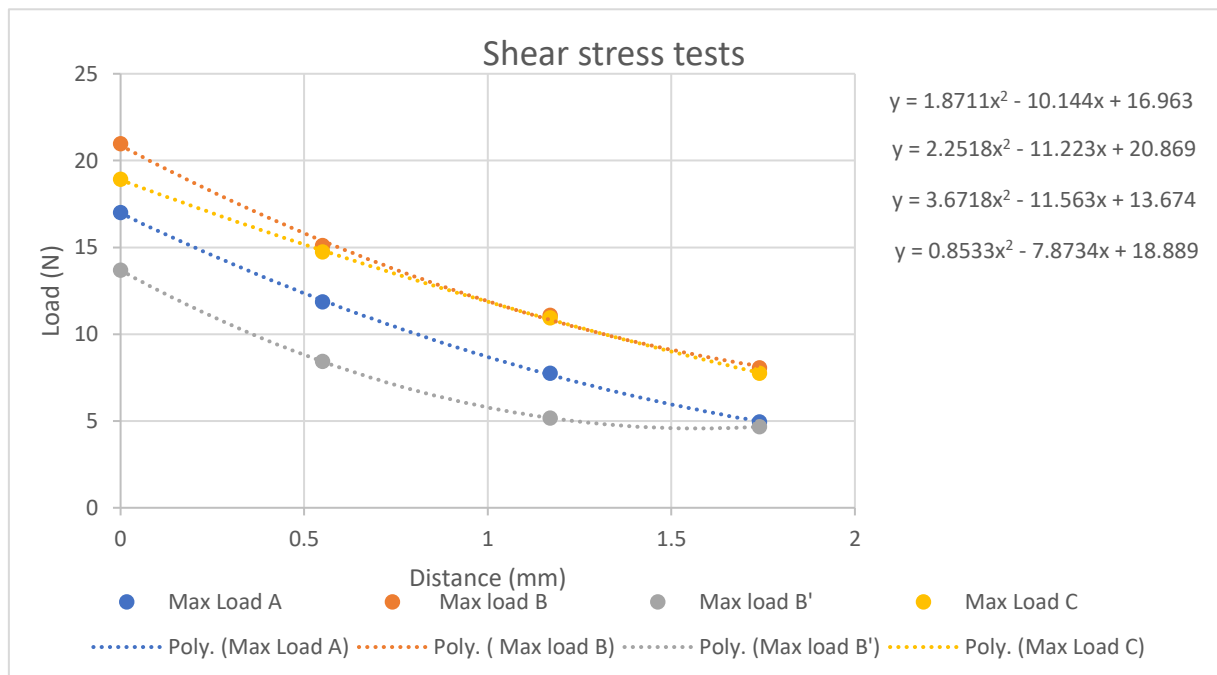


Figure 5.14 – Shear maximum load vs. distance

The same approach was made as the one for Figure 5.9 for constructing the chart showed in Figure 5.14, recurring to the peak average values of the shear stress tests. The equations were obtained using the same polinomial regresion.

As expected, the shear stress tests have lower load values when compared to the tensile tests. This type of test is sensible to the contact material, the values here presented were in regard to paper and might have been improved if a more adhering material was used.

In the shear direction, all of magnetic configurations performed substantially worse when compared to the tensile orientation, achieving much lower loads (peaking at around 20N), and ad decreasing with increasing distance, in comparison the test curves also exhibited a flatter profile.

In some trials, there were notable oscillations on the curve, due to the magnets rotation and aligning.

The best configuration on the shear tests was again the B one.

Conclusion

In terms of load capabilities, the best configuration was the configuration B, outperforming the others in both tensile and shear orientations. Adding to this the configuration has the advantage of allowing for more compact builds.

5.4 Acoustic test

The results here displayed reference the decay and spectral (timbrical) analysis of the magnetic system influence for singular notes.

5.4.1 Decay

The decay in sound, is the pace at which the note or sound drops in intensity after the maximum value on the attack, all the way to silence [43]. This is an important sonic characteristic of the instrument and relates directly with the sustain of the same, with less decay meaning more sustain.

As referred before, four strings were experimented, played both manually and remotely, three and five repetitions for each case were made and each string tested with and without the magnetic system. Everything was recorded by three different sound inputs, adding up to a total of 192 recordings done. Due to the large amount of data, only the most relevant charts and graphs will be shown below. The graphs shown, are in decibel by seconds, and exhibit the plotting made in MATLAB, from the *intensity tier* extracted in Praat software.

5.4.1.1 Unfiltered vs Filtered

In order to enhance the definition and accuracy of the data, a filtration of the ambient noise was done. As is possible to see the decay curve is much more defined in Figure 5.15 a) than in the unfiltered one Figure 5.15 b), particularly past the three seconds mark where due to the lower intensity (dB) signal, the noise has a significance influence and notably alters it.

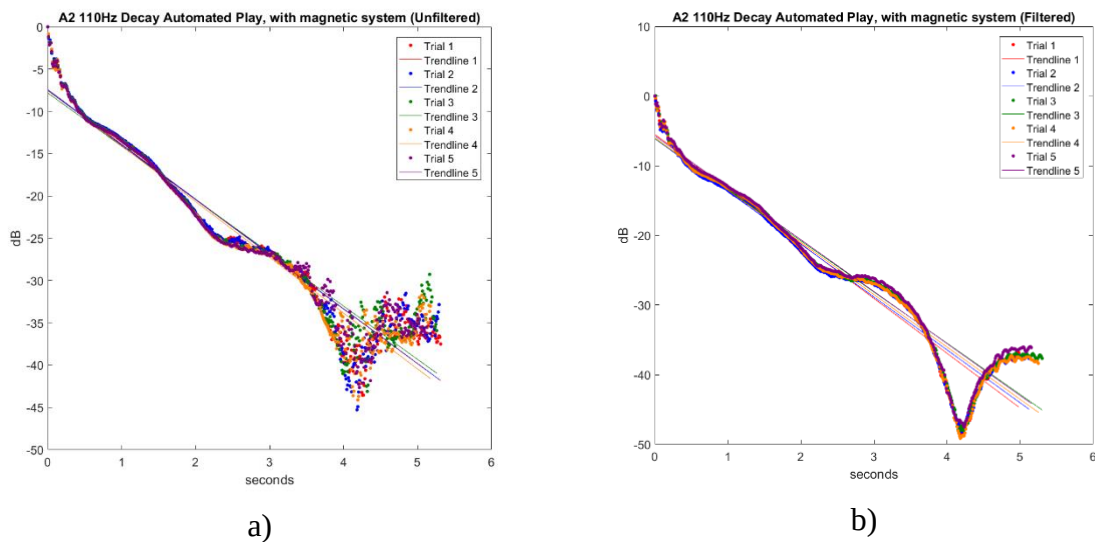


Figure 5.15 – a) A 110 Hz Decay, Automated play with magnetic system Interior microphone, Unfiltered; b) A 110 Hz Decay, Automated play with magnetic system Interior microphone, Filtered

The automated system has a smaller intensity when compared with the manually played notes as it didn't have the same plucking power as manual play. So, due to its lower intensity is more susceptible to noise interference. The smaller influence of the noise filtration in the manual played recordings Figure 5.16 corroborates that fact.

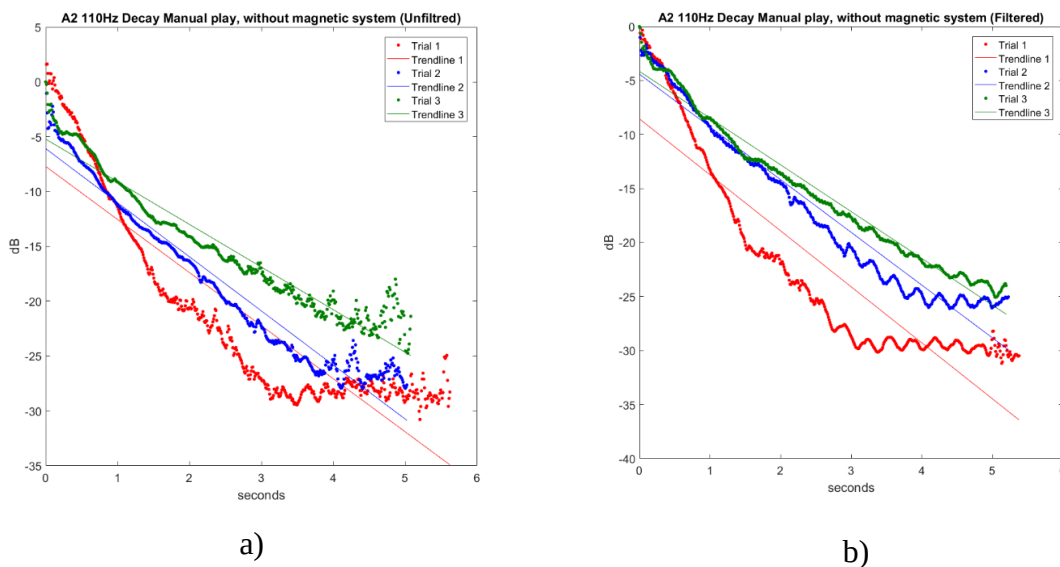


Figure 5.16 – a) A 110 Hz Decay, manual play, without magnetic system, Interior microphone, Unfiltered; b) A 110 Hz Decay, manual play without magnetic system Interior microphone, Filtered

Since it yields clearer results, from now on, only filtered curves will be displayed and analyzed.

5.4.1.2 Manually operated vs automated

As is possible to see on Figure 5.16 and Figure 5.17 a), the manually operated tests show some variability and inconsistency, with the decay rate and curve shape changing from trial to trial.

These discrepancies in the results can be attributed to the difficulty in the reproducibility of such a complex process as guitar playing, and to the inherent human error.

The automated tests in the other hand, showed regular results, with almost full overlapping of several curves and very parallel decay tendency lines, as shown on Figure 5.17 b).

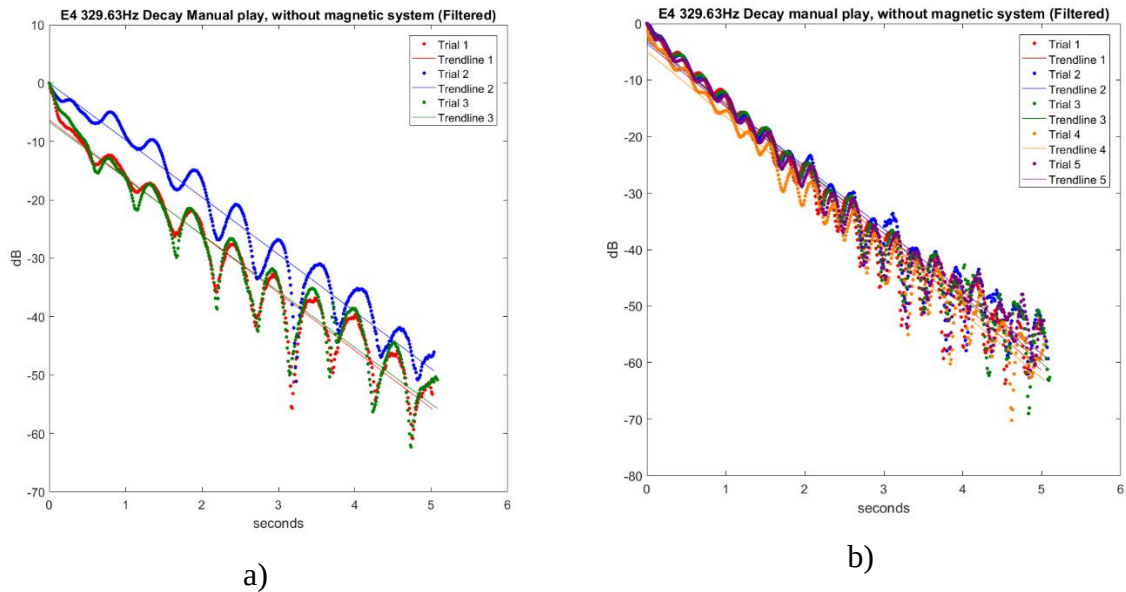


Figure 5.17 – a) E 329.63 Hz Decay, manual play, without magnetic system, Interior microphone, (Filtered); b) E 329.63 Hz Decay, automated play, without magnetic system, Interior microphone, (Filtered)

5.4.1.3 Different Sound pick-ups

Since all the recordings were made through three separate recording devices, a comparison and analyses of the different inputs will be made.

The results shown on Figure 5.18 a) and b) are quite similar since they were made using the same equipment only changing the positioning in the guitar and the amplification. The inside microphone due to its higher amplification caught more subtle details. The piezo pick-up due to its vibration operated system has a higher decay rate and distinct curve shape compared to the microphones.

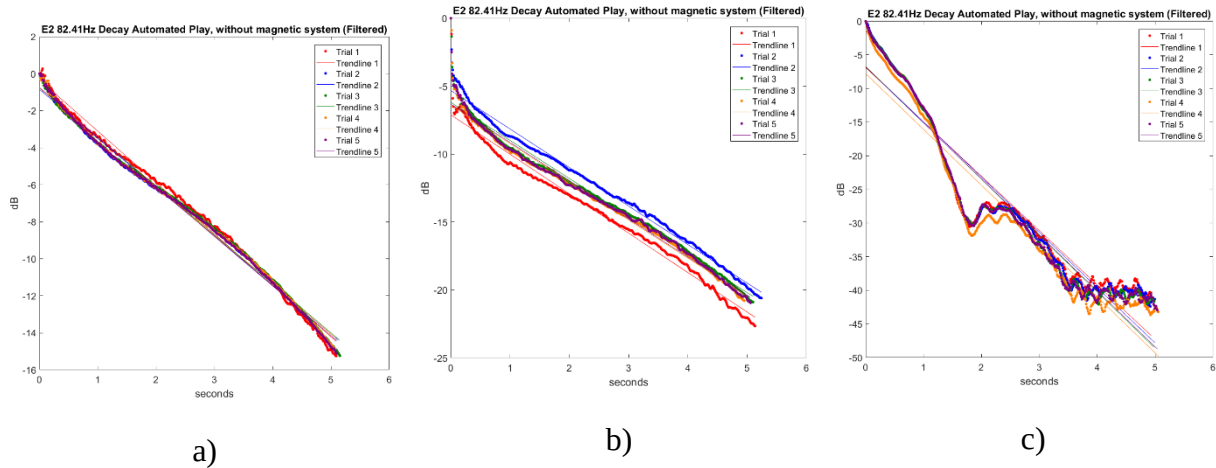


Figure 5.18 – a) Exterior microphone, E2 82.41 Hz decay, automated play, without magnetic system; b) Interior microphone, E2 82.41 Hz decay, automated play, without magnetic system; c) Piezo pick-up, E2 82.41 Hz decay, automated play, without magnetic system

To cover the full frequency spectrum a similar comparison to the Figure 5.18 was done, but now regarding the high-pitched E string, as can be seen on Figure 5.19.

In the high frequency string, the scenario stays the same with the interior and exterior microphones showing similar results and the piezo pick up with a distinctive decay curve.

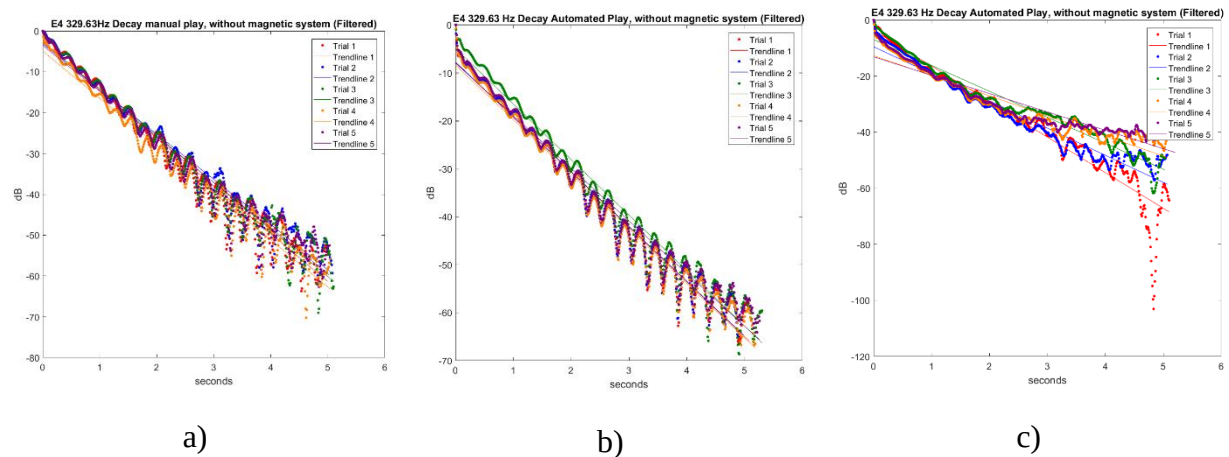


Figure 5.19 – a) Exterior microphone, E4 329.63 Hz decay, automated play, without magnetic system; b) Interior microphone, E4 329.63 Hz decay, automated play, without magnetic system; c) Piezo pick-up, E4 329.63 Hz decay, automated play, without magnetic system

5.4.1.4 Trials average

To minimize the error and condense the different trials in a single curve a simple average was made. Since the data processed in Praat software had the same sample frequency and started on the same point, the peak of intensity, the average curve was possible to calculate without interpolation. Two examples of the trials curves with respective average curve is shown on Figure 5.20. Due to the high concentration of the lines and curves, the average curve and respective trendline was translocated 7 dB above the other curves for a better visualization and interpretation.

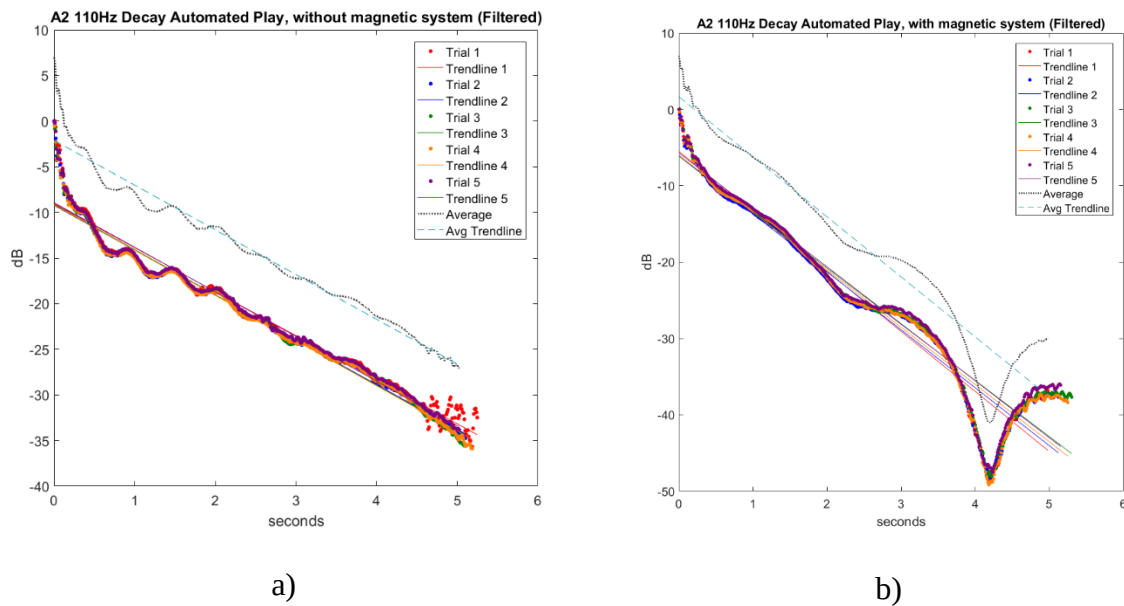


Figure 5.20 – a) A2 110 Hz Decay, automated play, without magnetic system and average, Interior microphone;
b) A2 110 Hz Decay, automated play, with magnetic system and average, Interior microphone

5.4.1.5 Magnetic system influence

This is the most important analysis since the main point of the acoustic test was to evaluate the influence of the magnetic system. To do so direct comparisons between homologous recordings with and without the magnetic anchoring system will be displayed. For a more simple and direct view only the average curves will be displayed and compared.

Figure 5.21 shows a direct comparison of the average decay lines of the four different strings with and without the magnetic system installed, the displayed curves were obtained in regard of the external microphone since this provides a more analogous sound to the one a listener would experience.

As can be observed on Figure 5.21 the different slopes show a clear tendency, with the magnetic system increasing the overall note decay in all the strings.

This result can be justified with the fact that any solid body introduced in the instrument airbox will reduce the volume of air, consequently, the reverberation air is diminished thus decreasing the sustain of the instrument. Worth noting is the fact that for higher frequencies the magnets influence is minor due to the already high decay rate as Figure 5.21 d) proves.

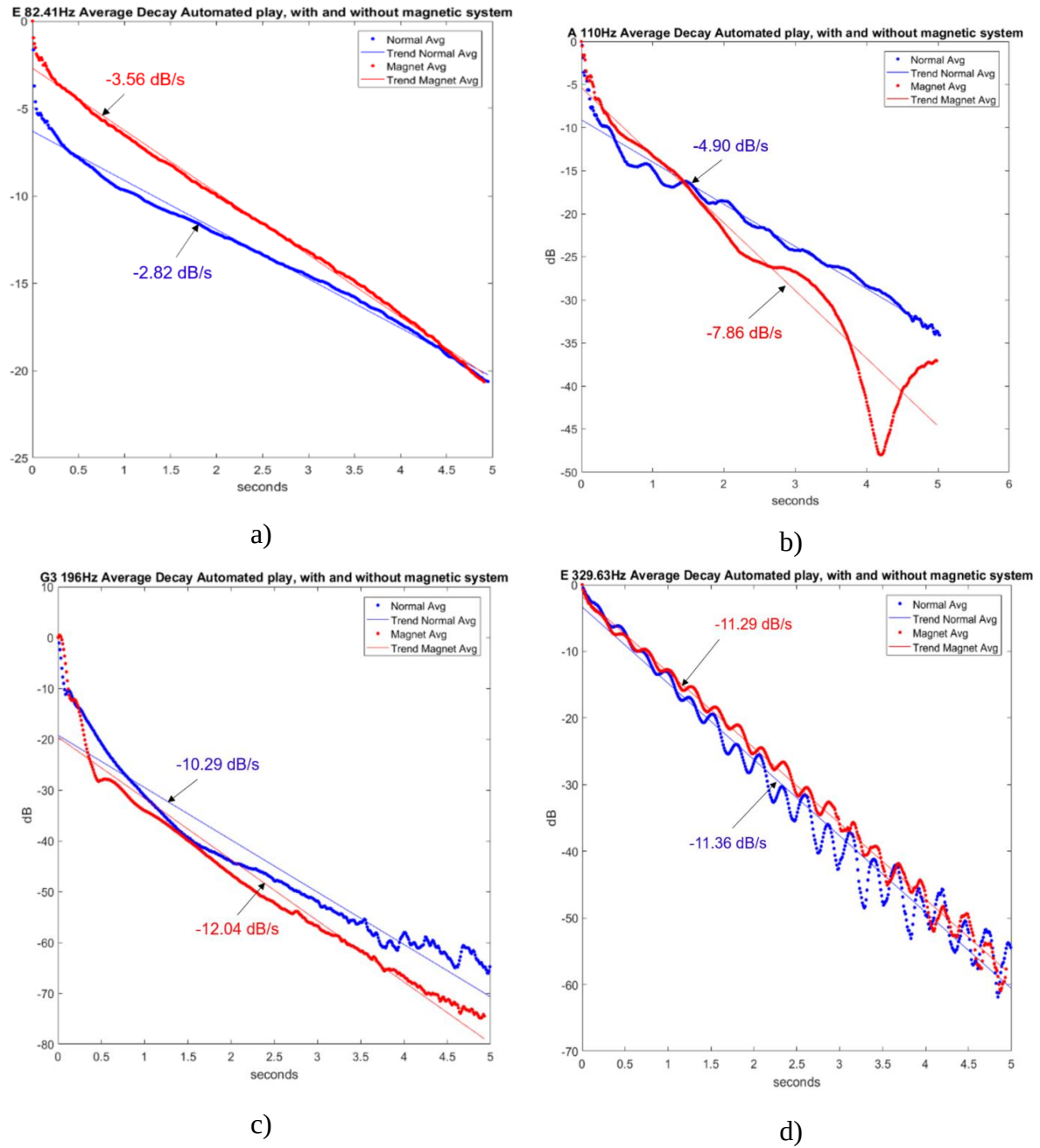


Figure 5.21 – a) E2 82.41 Hz average decay, automated play, with and without magnetic system; b) A 110 Hz average decay, automated play, with and without magnetic system; c) G3 196 Hz average decay, automated play, with and without magnetic system; d) E4 329.63 Hz average decay, automated play, with and without magnetic system

Perhaps most unexpected is the phenomena registered in Figure 5.21 b), with the presence of the magnets modulating the wave form. This can be speculated and attributed to the presence of a localized mass (the magnet), that is substantially denser than wood and alters the vibration pattern of the guitar shell resulting on the demonstrated behavior.

5.4.2 Spectrum

The timbre or tone quality of an instrument is its most distinctive characteristic and it's the major property that allow to distinguish between different types of instruments. Determining the timbrical impact of the magnetic system in the guitar is then of the utmost relevance.

To check the consistency of the trials and to have reference values for the spectrum differences the different automated trials were compared. The spectrum analyses are done in pairs comparing the differences between two signals. The studied string was the A 110Hz string since it was the one which demonstrated more differences in the decay analysis.

In Figure 5.22 is illustrated a spectrum analysis between automated trials 1 and 2 (without magnetic system) of the A 110 Hz string, in the first row both trial 1 and 2 wave form are displayed in amplitude over time, with both samples having 5 seconds duration. On the second row of figures, both spectrums are displayed with the waves in amplitude (now in dB) by frequency format. In the third row, periodical spectrum waves are demonstrated with a mathematical generated comb with stripes of fifteen harmonics. On the bottom of the figure, on the left, there is a harmonic spectrum superposition of the periodical parts of both waves, already normalized. Normalization equalizes the signals to the same intensities guaranteeing that only the spectrum aspect is being compared. On the last row, on the right there is presented the quadratic differences in both spectrums, the values are squared because this way only the modulus is presented not considering the sign. All of the subsequent results and figures were obtained in MATLAB software.

5.4.2.1 Spectrum Analysis without magnetic system

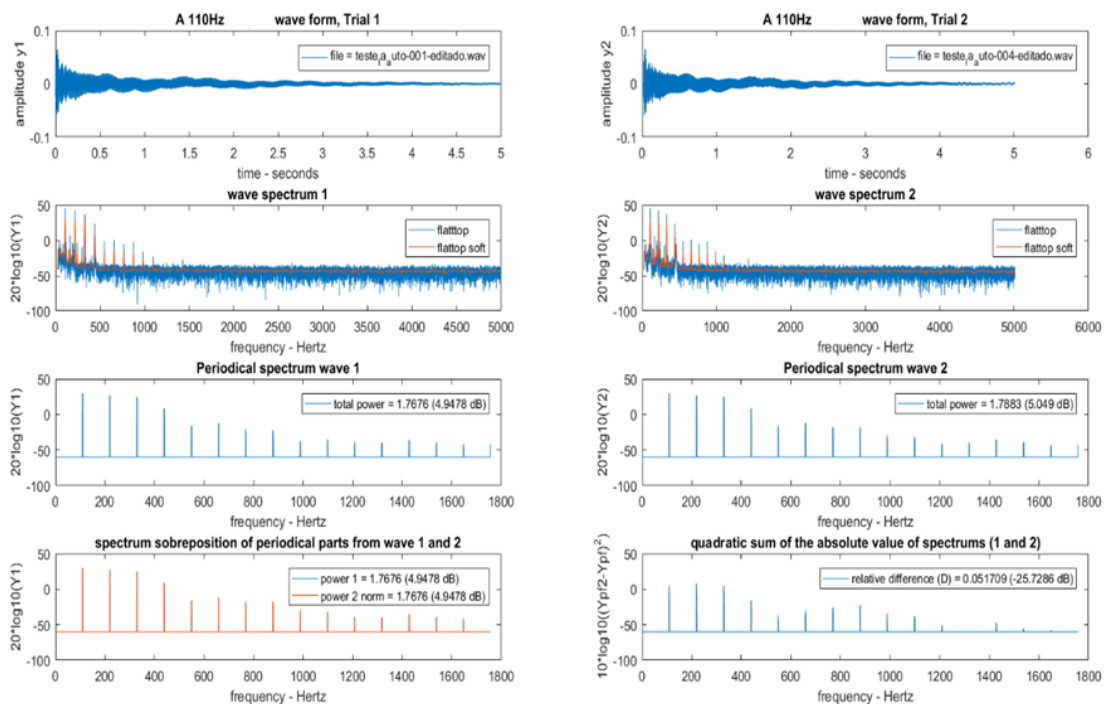


Figure 5.22 – Uniformity of spectrum analysis, A 110Hz Trials 1 and 2, exterior microphone

The complete spectrum analysis is only displayed on Figure 5.22 and for trial 1 and 2. The values concerning the spectrum difference both in relative (D) and absolute (D dB) form, for all the trials, can be seen on Table 5.2.

Table 5.2 – Uniformity of relative differences in spectrum analyses for A 110 Hz trials, between trials without magnetic system

Trial 1 vs	Trial 1	Trial 4	Trial 7	Trial 010	Trial 013	Avg
D	0	0.0517	0.0791	0.0515	0.0329	0.0538
D (dB)	$-\infty$	-25.73	-22.03	-25.77	-29.66	-25.80

5.4.2.2 Spectrum Analysis with magnetic system

The same analysis is presented in Figure 5.23, now assessing trials 1 and 2 with the magnetic system installed. The full list of relative difference values can be seen in Table 5.3.

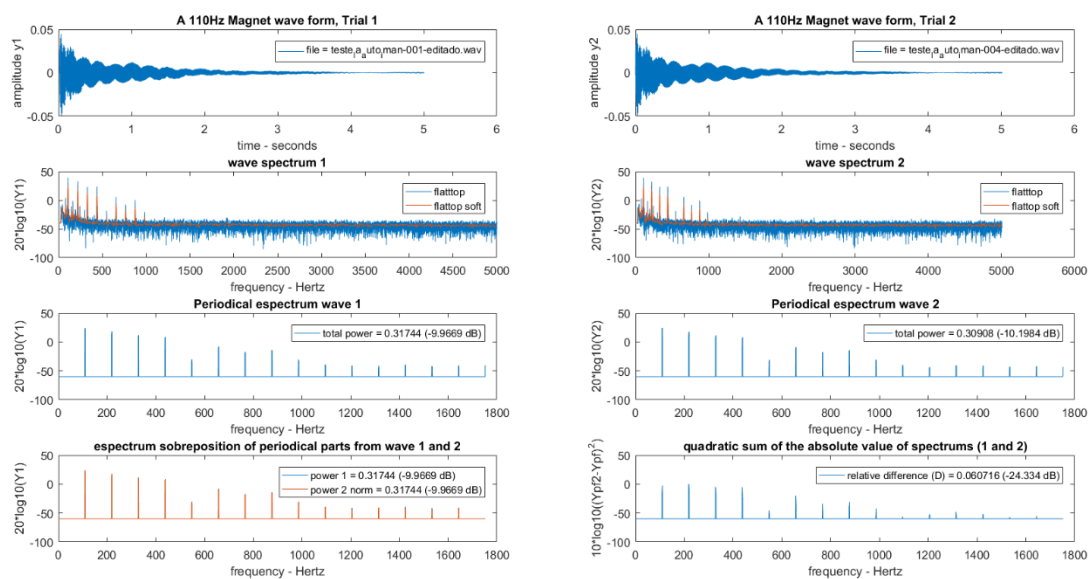


Figure 5.23 – Uniformity of spectrum analyses, A 110Hz Trials 1 and 2 with magnetic system, Exterior Microphone

Table 5.3 – Uniformity of relative difference in spectrum analyses for A 110 Hz trials, between trials with magnetic system

Trial 1 vs	Trial 1	Trial 4	Trial 7	Trial 010	Trial 013	Avg
D	0	0.0607	0.00889	0.0163	0.0153	0.0253
D (dB)	$-\infty$	-24.33	-41.03	-35.74	-36.30	-34.5

5.4.2.3 Spectrum Analysis with and without magnetic system

A spectrum analysis comparing the trials with and without the magnetic system is done in Figure 5.24. The trial 1 was done without the magnetic system, and the trial 1M refers to the use of the magnetic system.

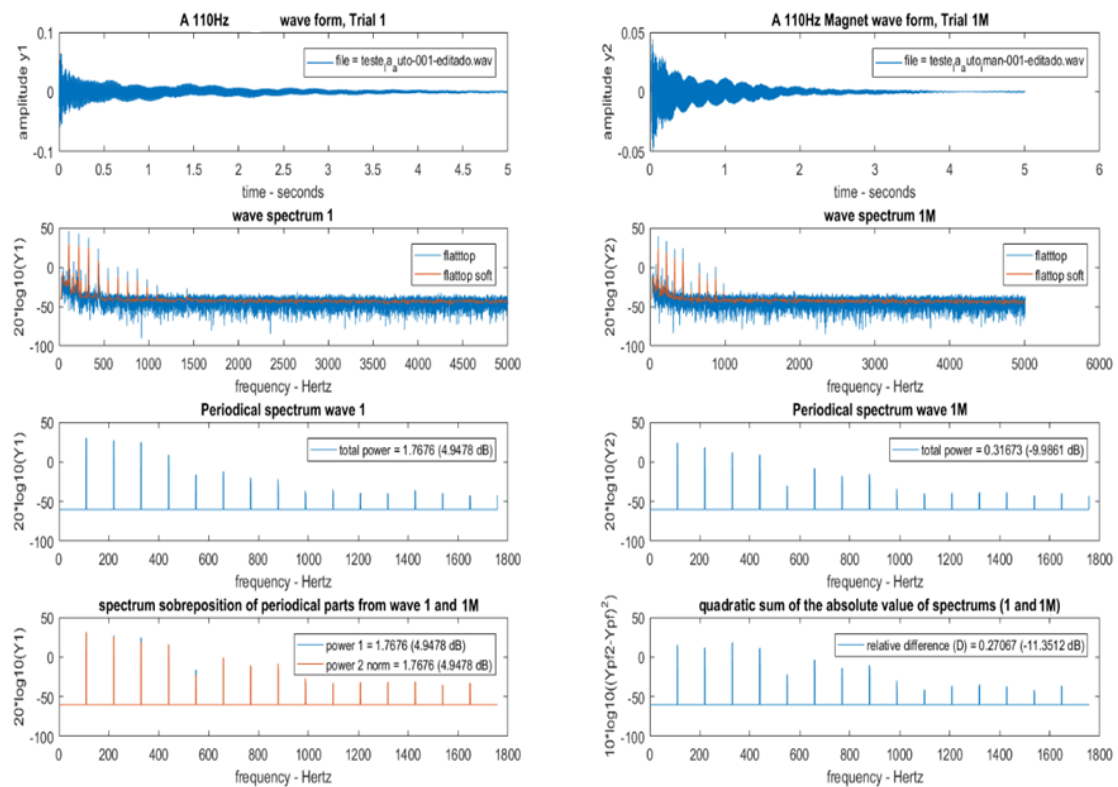


Figure 5.24 - spectrum analyses, A 110Hz Trial 1 with and without magnetic system, exterior microphone

The relative differences of the several trials can be consulted on Table 5.4, the comparisons were made pairing the homologous trials with and without the magnetic system.

Table 5.4 – Uniformity of Relative difference in spectrum analyses for A 110 Hz between trials, with and without magnetic system

Trial vs	Trial 1	Trial 4	Trial 7	Trial 010	Trial 013	Avg
D	0.271	0.270	0.243	0.250	0.259	0.259
D (dB)	-11.35	-11.38	-12.30	-12.02	-11.74	-11.76

The average value for the relative difference in the magnet vs no magnet comparison is 25.9%, a value noticeable higher than the 5.4% and 2.5%, that can be found on the averages of Table 5.2 and Table 5.3. These results indicate that there should be an influence on the spectrum, related to the presence of the magnetic system.

5.5 Listening test

The results here presented were made from a test group of seven participants, all of them guitarists or qualified instrumentalists. The decision of having a smaller more qualified group sample was preferred to a broader one, since a more trained ear can more easily detect subtle differences and nuances, providing more accurate and precise results.

5.5.1.1 Perceived Differences

As is possible to see in Figure 5.25, all of the participants pass the false positive test with none of the inquiries denoting any perceivable differences on file 2. In file 1 and 4 though, variations were identified by the majority of the participants, this indicates that despite the automated mechanism, the small fluctuations of the trials were enough to be perceived by the listeners. The matching descriptions in the open answer questions (Table 5.5) corroborate that fact. The file 3, the one with the direct comparison of the magnetic anchoring system, was the most remarked as containing variations, with only one out of the seven inquiries not sensing audible alterations in the notes played.

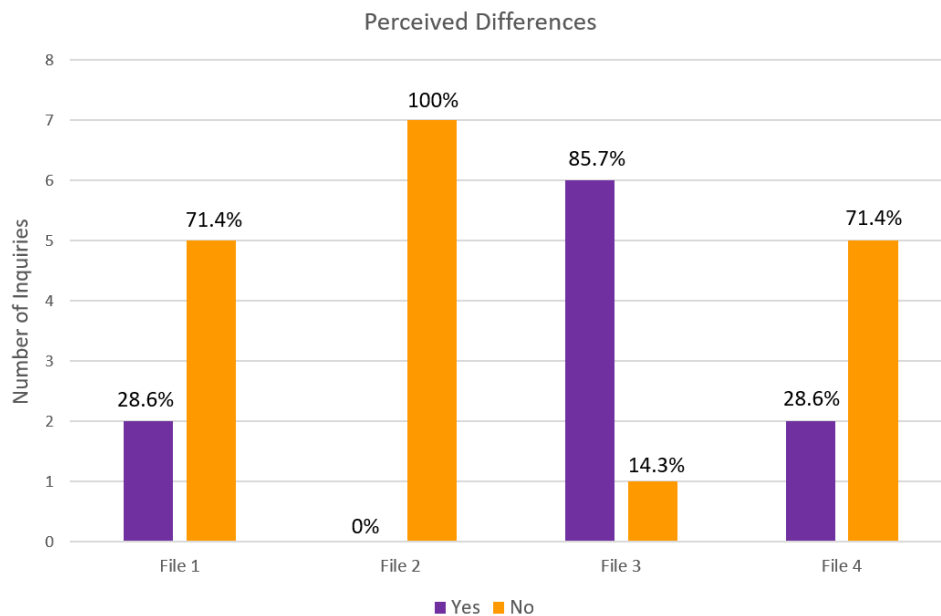


Figure 5.25 – Results from the yes or no questions of the survey

Table 5.5 Answers from open questions regarding file 1 to 4*

Question	File 1	File 2	File 3	File 4
Answers	-	-	Third time, the sound is a bit muffled	Some sounds are more amplified than others
	Different attack	-	More bass in some	Different volumes
	Attack different between first and second note	-	Some last longer and have a stronger attack	-

*answers translated from Portuguese

Perhaps the most interesting observation is that, besides the single negative answer, all participants remarked the file 3 as the one with the most sonic deviations, supporting the idea that the changes in acoustic performance by the magnetic system are perceivable and more significant than the minute variations of the trials.

This supports the results obtained in the spectrum and decay analysis, with the small variations in the different trials being denoted by some participants, and the more significant changes in decay and spectrum produced by the magnetic system presence, perceived by the majority.

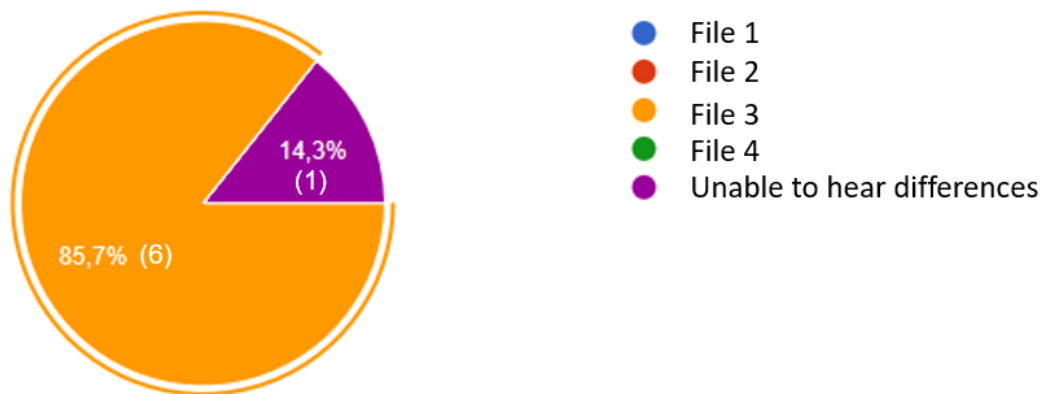


Figure 5.26 – Results from the multiple-choice question to the file with the most changes.

In Figure 5.27, there are the results of a 1 to five scale rating. With 1 being barely perceivable and 5 evident.

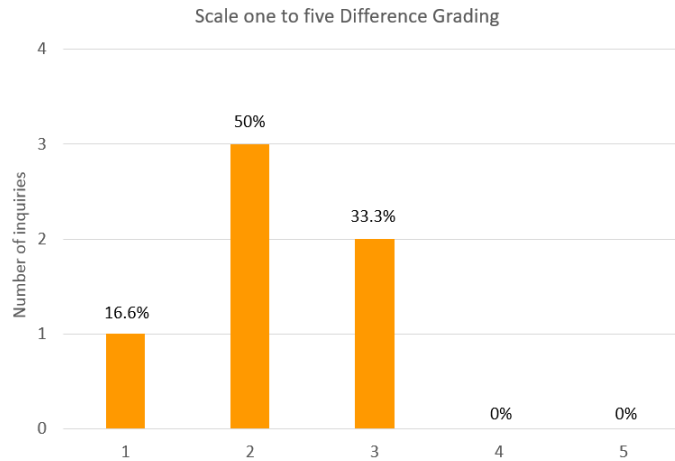


Figure 5.27 – Qualitative grade answers to the survey.

When asked to rank the perceivability, of the listened differences in file 3, the majority of the inquiries ranked the test with 2. Indicating that the variations could be classified as subtle.

5.6 Final Prototype

In the final prototype, some important design choices were made. The options taken, despite targeting the biggest benefits possible, were often not, made with compromises. A summary of the perceived results after the completion of the prototype is done below.

Advantages

The curved surface design of the enclosure allows for a better contour of the guitar, reducing the strain on the shell and simplifying the removal of the magnets, since due to its one-sided curved shaped the relative distance of the magnets increases upon rotation.

It has a simple assembly with no need for screws or glue.

The interior magnets are hidden inside the instrument, meaning that there are no visible evidences that the guitar has the system installed. Prominent issue due to the interest many classical musicians have to keep the classical appearance of the instrument.

Disadvantages

The protruding rim that secures the magnets into place, increases the distance between them and the exterior magnets diminishing their performance.

This design requires 16 magnets, which is complex and costly due to the relative high prices of neodymium magnets.

No repair or maintenance can be done on the product since once the magnets are inside the enclosure they cannot be removed

Materials

A good choice of base material for the enclosure would be either a soft plastic or a hard rubber. The low rigidity of the material would allow the enclosure to flex and allow for an easier

assembly of the magnets. The choice of a flexible material would also increase the adaptability to different guitars and instruments shapes and contours. The use of a softer and rubbery material would increase the contact grip (especially relevant for the shear solicited enclosure) and reduce the wear and eventual scratches on the polished finish of the instrument.

6. Conclusions

In this dissertation, the design of a magnetic anchoring strap system for stringed instruments was attained a description of some of the steps to achieve it and subsequent conclusions, is done below.

A report in magnetism and the different magnetic materials was made, with neodymium alloys arising as the better option for the application in question.

A development of the four-poles concept was done with an analysis of the possible magnetic configurations.

For a better integration of the system, a study of the inner geometry and construction of the guitar was made. The apex of the top curve and the bottom portion of the guitar (next to the tail block), were determined as the best place for installation, ensuing the best compromise in magnet performance and ergonomics.

Prototypes were made, through rapid prototyping, to endow a better perception of the objects in three dimensions as well as enabling experimentation and physical interaction.

During this work, the importance of rapid prototyping quickly became evident and was a determining factor in the viability of the work in the stipulated time. A better understanding of the different processes under this branch, namely FDM and SLA, was acquired. SLA proved to be the best option to guarantee dimensional precision and finer details at the worked scale.

Mechanical and acoustic tests were done in order to characterize the system.

The tensile and shear stress tests allowed a characterization of the two basic solicitations that the magnets can undergo under use and permitted the comparison of the magnetic configurations. On the tensile speed tests, an unexpected relation emerged between the tensile max load and the speed of the trial, with no explanation found for this phenomenon. Configuration B (crossed) achieved the best results outperforming the other configurations in tensile and shear stress tests.

The acoustic test was determinant to appraise the influence of the magnetic system on the guitar acoustic performance. Decay and spectrum analyses were done, with both indicating a measurable difference in behavior appointed to the magnets presence.

A listening test complemented the mathematical approach with more subjective but practical deliberations. The results corroborated the previous findings, with the majority of listeners denoting variations from the magnetic system influence.

To have more defining conclusions, and to compare with the other strap solutions in the market acoustic influence benchmarks and further testing should be done.

On a more general note about the product, it showed potential of being a valid solution, filling a void in the market through a novel approach, with the magnetic attachment serving also as a differentiating factor.

The present solution boasts some important advantages over the already available.

The product comprises a non-intrusive, non-permanent solution, allowing the user to remove product at will, so does not devalue the instrument.

The product can completely hold the instrument with no need for additional support from the user.

When not in use, shows no visible evidence that the guitar has the system installed, maintaining the classical appearance of the guitar.

There are nonetheless things that can be done to improve, expand and solidify the concept. All the aspects described on following chapter, Future works, are valid ways to enrich the project.

7. Future works

Alternative concept

Despite the inherent advantages of the four-poles design, the use of 16 magnets in the final solution makes it costly and intricate. A viable alternative would be to use of two rectangular block magnets that would take the place of two squared blocked magnets as depicted on the Figure 7.1. This way the attracting force would remain similar and only 8 magnets would be necessary, lowering cost and complexity.

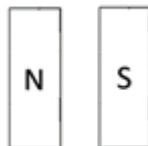


Figure 7.1 - Dipole magnet schematic

This concept entails one main operating difference, that would be that, in order to remove the system, it now requires 180° of relative rotation, situation demonstrated on Figure 7.2. Due to the lower pole count, half than before, the turning angle necessary to change the magnets from attracting to repulsive state is now doubled.

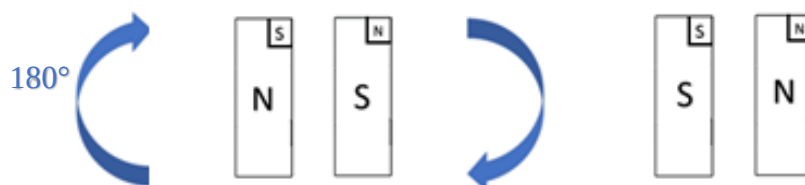


Figure 7.2 – Dipoles magnets rotation

The enclosures already designed for the four-pole concept can also be adapted for this application. If the planned assembly utilizes Q-20-10-05-N magnets from supermagnete (full description in appendix A), shown on Figure 7.3 [44], only a slight increase in the clearance of the housing is necessary, to cope with the increased thickness of the magnet from 4 to 5 mm.



Figure 7.3 - Q-20-10-05-N magnet, 1€ coin for scale

This solution should be studied and compared with the four-poles concept.

Use case scenario load analysis

In the work here presented, for the sake of simplicity and since the load distribution on the strap ends was unknown the same magnets were used in both the top enclosure, and bottom enclosure, that condition implies that the load is distributed equally in both ends which might not be the case.

If for instance there is an asymmetric load distribution, as the one depicted on Figure 7.4, the use of stronger or weaker magnets depending on the application might be advantageous for a more competitive or effective product.

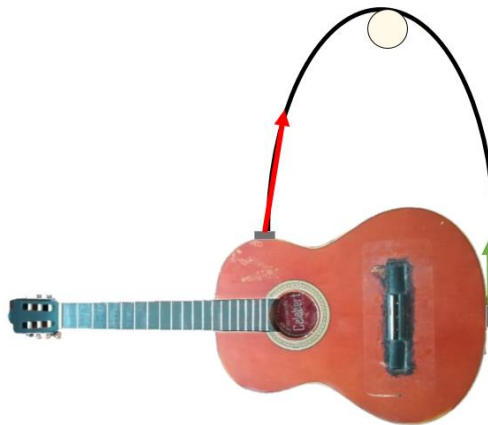


Figure 7.4 – Hypothetical asymmetrical load distribution on both strap ends of a suspended guitar.

The calculation of the magnetic force necessary, based on only the weight of the instrument is a simplification that doesn't take into account, the dynamic nature of the musician playing. To not overlook this fact, an experimental determination of the exact force the instrument applies on a strap during play, would allow for a precise determination of the required force the magnets should have to withstand the weight of the instrument when performing. A suggested setup with load cells in both strap ends is schematized on Figure 7.5.



Figure 7.5 – Suspended guitar with load cells schematic

Benchmarking in acoustic test

A benchmark in acoustic influence, comparing the magnetic anchoring system with the other alternatives in the market would be of important. This way the magnetic configuration could be positioned in terms of acoustic interference with the other available products, giving a judging context to whether the acoustic interference of the magnetic anchoring system is relevant or not.

Vibrational analysis

The traditional classical guitar top vibrates in many ways, but some fundamental frequencies below 500-600 Hz are of prime importance. These are the (0.0), (1.0), (0.1), (1.1) and (2.0) modes as shown in Figure 7.6 [38].

The making of a vibrational analysis of the classical guitar side panels, would be important to determine the intrinsic vibrational nodes. These nodes would be the ideal locations where the magnet system should be installed to minimize the interference in the vibrational pattern.

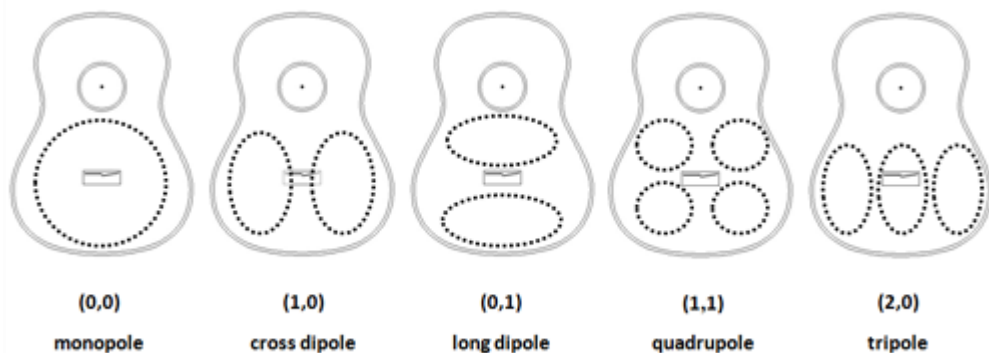


Figure 7.6 - Primary modes of oscillation on the guitar top.

Materials, manufacturing process, and price estimate

As referred before the ideal material in authors view for the enclosure would be a flexible plastic or rubber. The determination of the exact materials either for the magnetic enclosure but also for the strap would take this project one step closer to the final product and would enable a more realistic price estimate

The same goes for the manufacturing process, the determination of the optimal process would allow for a better view of the final product since it would have considered the intrinsic design constraints associated with said process and likewise allows for a more precise price estimate and more developed project.

As in any product, price is a determining factor for its success, and as so the determination of the manufacturing cost is of utmost pertinence.

In the price estimate, there are two major components weighing in, the cost of the materials or components, and the cost of manufacture or assemble.

in order to accurately estimate the cost of the product the project had to achieve a more defined and mature form with the materials and manufacturing processes previously defined and selected.

Finite Elements Analysis

Finite element magnetic modelling, is an industry standard to analyze technical magnetic problems and develop more effective solutions. Using FEA (Finite Element Analysis) techniques is possible to calculate flux densities, torques, forces etc.. and fine-tune a solution for optimal performance, examples are illustrated on Figure 7.7 [45].

To further study and optimize the magnets configuration, a finite element methods approach would be of great interest since it would allow for a more finer and wider analysis of the magnets physical characteristics.

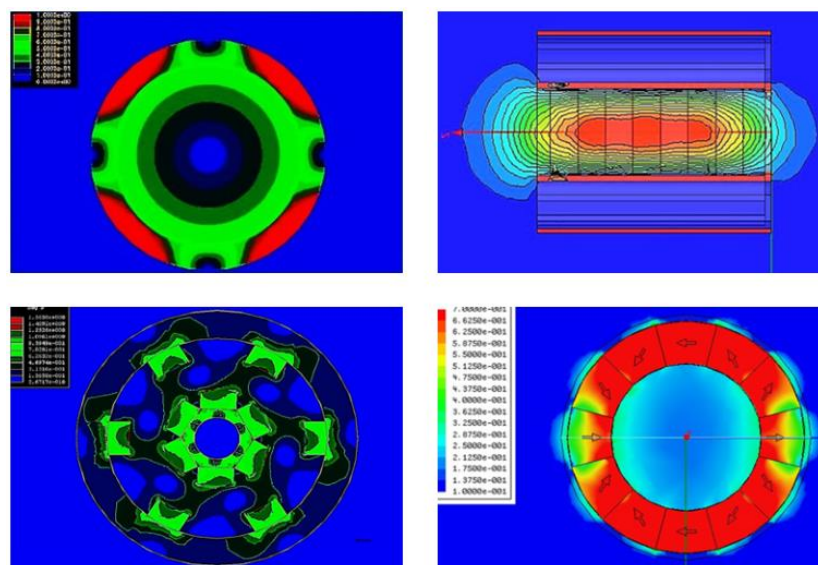


Figure 7.7 - Examples of finite element analyses modeling magnetic applications

FEMM (finite element method magnetics) it's a software tool used by several magnet manufacturers (including supermagnete) that is specifically designed to work with permanent

and electromagnets. Despite being a tool specifically designed for the magnetism area, it can only calculate the force between rotation-symmetric objects like discs, rods, rings and spheres [46], so its not capable of calculating the attracting force between cubic or block magnets used in our models.

Polymagnet Technology

Innovative technologies are emerging in the magnet industry, one of the most revolutionary ones would be the Polymagnet of Correlated magnetics, this technology can imprint customizable north and south patterns on the surface of the magnets, as illustrated on the Figure 7.8 [47]. The two magnets have different polarities imprinted on the same surface with the blue and red dots represent south and north respectively.

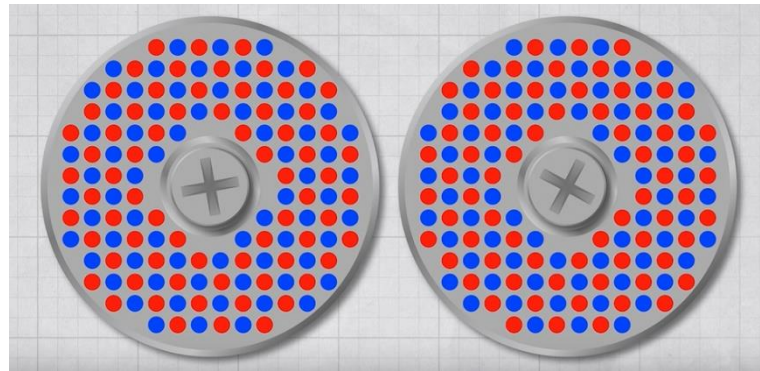


Figure 7.8 - Diagram illustrating Polymagnet printed magnetic poles

Using this complex magnetic fields, examples displayed on Figure 7.9 [47], this technology allows for new functionalities for magnets, and new magnetic behaviors that extend far beyond the simple attract and repel. The technology is new and applications are still in the development opening new possibilities for product designers and engineers.

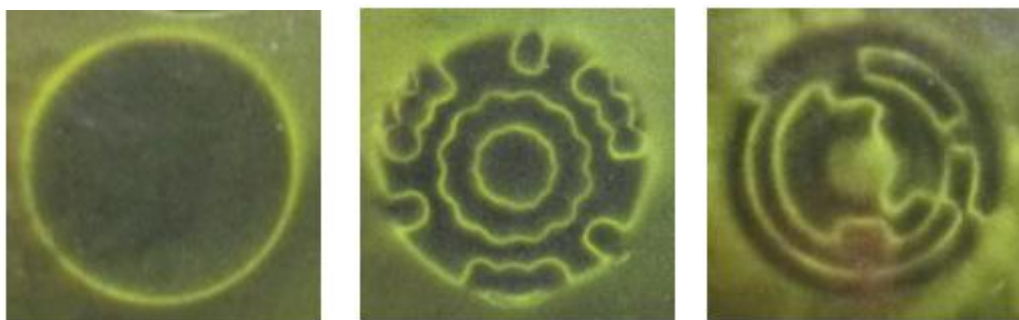


Figure 7.9 - Normal magnet, and polymagnets on the center and left, seen through a magnetic film.

Further study in this technology would allow for another means to innovate and create an even more differentiated and possibly efficient product.

Other Applications

During the research time, the author visited several local music shops and dealers with the goal of obtaining feedback on the concept, acquire new ideas and have an inside view of the needs and wants of consumers and suppliers.

One of the shops who collaborated with the authors work was the Impormusica. An established store that besides retail also integrates a music school. Consequence of that, the workers have more experience and a closer relation to the musicians and players necessities.

One of the said proposals was to create a magnetic fixation system that would allow the classical guitar pick-up system (an piezo electric pickup system like the one used in 4.2.2) to be readily placed via magnetic fixation, again with no permanent modifications to the instrument.



Figure 7.10 – Piezo electric pickup on the right, and piezo pickup installed on a classical guitar on the left.

A preliminary attempt was made by placing a S-20-20 magnet on the inside of the guitar, securing the pickup (made with ferromagnetic materials) into place, as pictured on Figure 7.10 with promising success.

This example goes to show that although the work here done, was focused on a strap system, the magnetic anchoring system may have other use case possibilities and its application might be broadened to other components and accessories.

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<Design of a musical instrument magnetic anchoring strap system>

Appendix A

MAGNETIC GUITAR STRAP

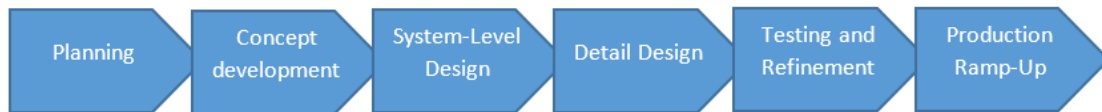
Executive summary

- **Brainstorming**

The first step taken, the group gathered and discussed personal ideas, the concept of a magnetic guitar strap was chosen.

- **Product development process**

The product development process was outlined with a minor description of each steps.



- **Bibliography research**

A description of the origins and evolution of the guitar strap is done.

- **Report planning**

This planning phase is divided into 4 stages:

- Identification of Opportunity;
- Assessment and Priority Setting;
- Planning of the available time and distribution of tasks;
- Mission Statement.

Identification of Opportunity

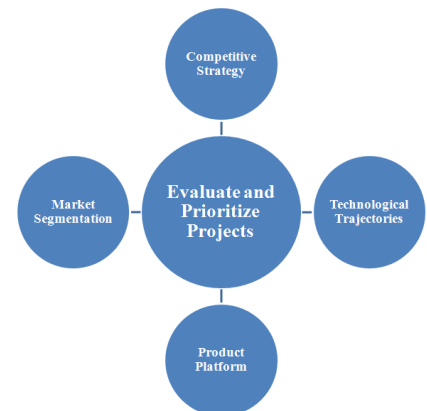
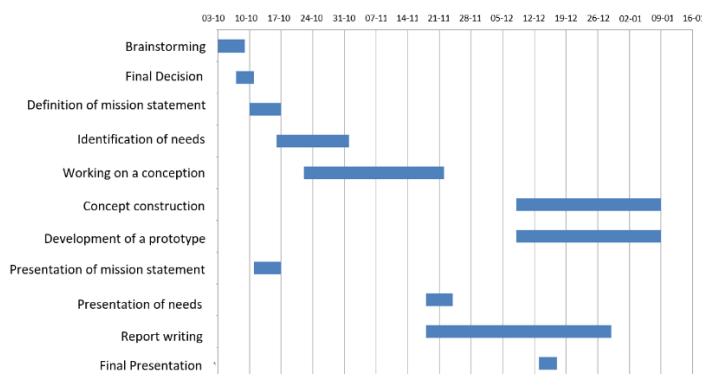
In the context of product development, opportunity means an idea for a new product. Ideas were filtered, considering constraints such as cost, time, specialized skills, etc.

Assessment and Priority Setting

Priorities set, and focus on the goal of making a strap that improves user experience and is user's friendly

Planning available time – Gantt chart

This chart illustrates the start and finish dates of the elements of the project.



Mission statement

Product description

Magnetic guitar strap for acoustic or classical guitar. Non-intrusive installation, with magnetic anchoring.

Benefit Proposition

The magnetic guitar strap provides, correct weight distribution on the shoulders, non-intrusive installation, discrete fitting with no visible evidences of the system when not in use.

Key Business Goals

- Make an ergonomic, cheap, functional and attractive product;
- Reach music retail stores;
- Increase awareness of the product in the music industry;
- Establish the brand as the reference in magnetic guitar straps;
- Have final prototype launch within 3 months;
- Prepare all documentations needed to ensure product in normal market.

Primary market - music stores (ex: LudiMusic, Riff, Gewa); retail stores (ex: Fnac, Guitar Center); guitar suppliers (ex: Fender, Gibson).

Secondary market - online distributors (ex: amazon); music schools.

Assumptions

- the magnets and the strap will be strong enough to withstand the guitar;
- the insertion of magnets inside the sound hole will not affect the sonic characteristics.

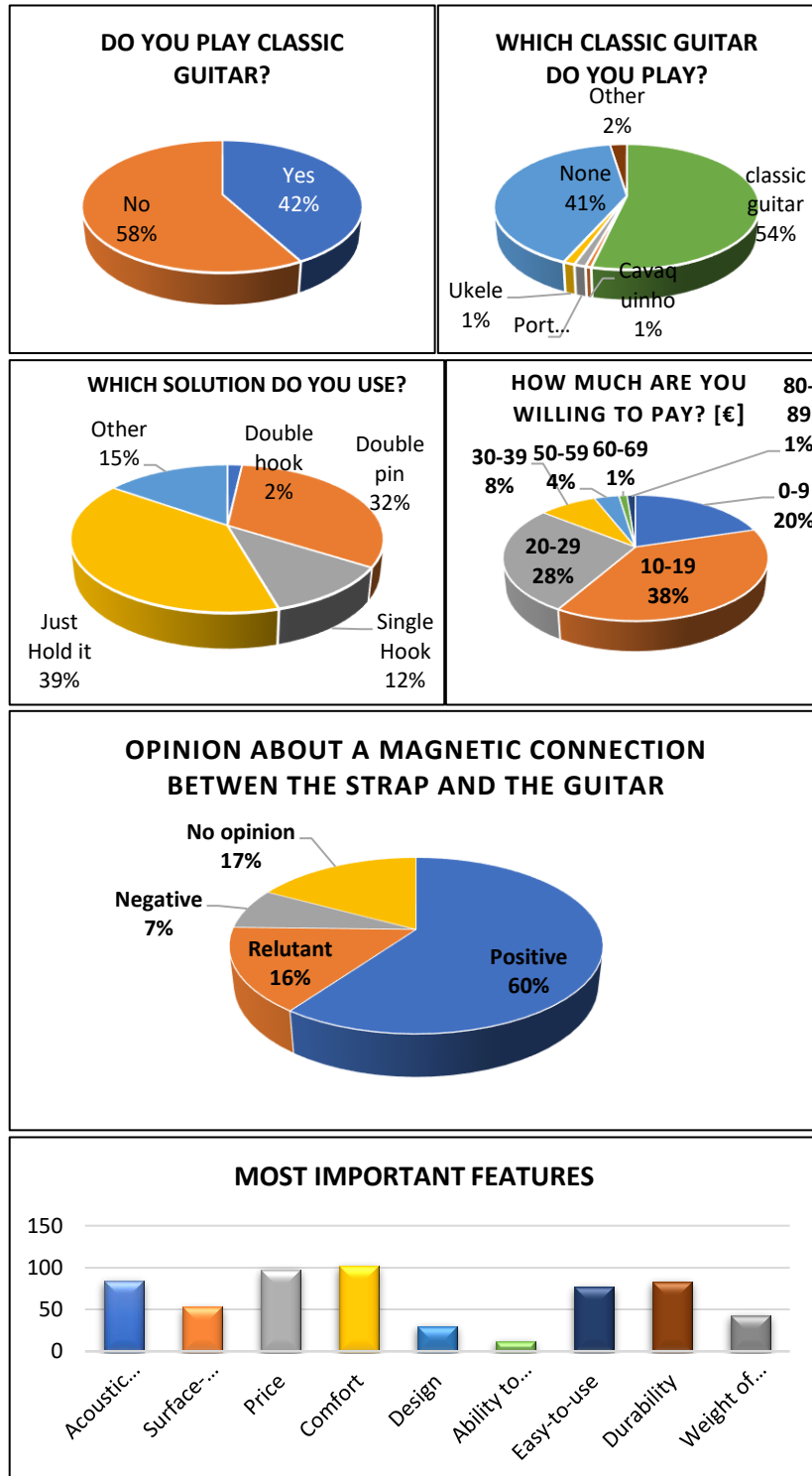
Constraints

- magnetic fields interference;
- price of the magnetic guitar strap;
- weight of magnets;

Stakeholders - musicians, music teachers, music students, music fans, guitar players.

Customer needs Identification

Surveys and interviews results



Product design

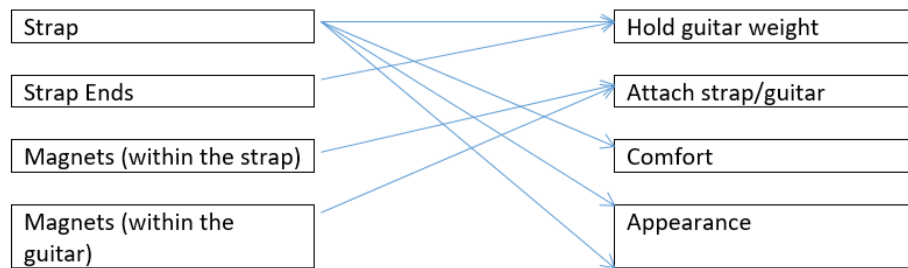
Market research

A description of the solutions available in the market namely, single and double hook, single and double pin guitar straps.

Patent Research

No magnetic guitar strap was found, and several guitar strap patents are displayed.

Modular System



Magnet choice

Considerations were done regarding the shape, size, strength and price. Selecting the S-20-10-N magnet.

Material Selection for the strap

A comparison is made between the different materials and nylon selected as the indicated for the application.

Establish Metrics and Units

Once all the needs are identified, the metrics were established as well as the units related to every characteristic needed for the product.

Link metrics to needs

The needs and all the metrics and respective units were linked together for a better understanding of the relation between them.

Benchmark on customer needs

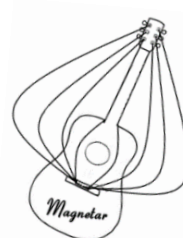
An evaluation of every identified need to each benchmarked product with qualitative grading.

Testing phase

Prototype Construction

Guidelines were made before building the product, and a description of its construction is done.

Making of a logotype



Appendix B

On this appendix, there is a full description of the used magnets properties provided by the manufacturer.



Data sheet article Q-10-10-04-N

Technical data and application safety

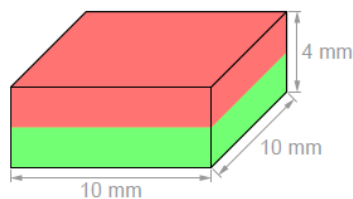
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www.supermagnete.pt
support@supermagnete.pt

1. Technical information

Article	Q-10-10-04-N
Shape	Block
Side 1	10 mm
Side 2	10 mm
Side 3	4 mm
Tolerance in size	+/- 0,1 mm
Direction of magnetisation	parallel to side 3
Pole faces	10 x 10 mm
Material	NdFeB (Neodymium Iron Boron)
Type of coating	Nickel (Ni-Cu-Ni)
Strength	approx. 2,2 kg approx. 21,6 N
Weight	3,04 g
Manufacturing method	sintered
Magnetisation (Grade)	N40
Max. working temperature	80°C
Curie temperature	310 °C
Residual magnetism Br	12600-12900 G 1.26-1.29 T
Coercive field strength bHc	10.5-12.0 kOe 860-955 kA/m
Coercive field strength iHc	≥12 kOe ≥955 kA/m
Energy product (BxH)max	38-40 MGOe 303-318 kJ/m ³



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Exempt from registration according to REACH.



Data sheet article Q-20-10-05-N

Technical data and application safety

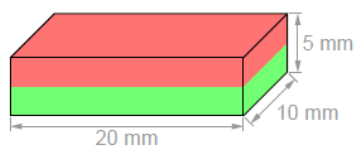
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1. Technical information

Article	Q-20-10-05-N
Shape	Block
Side 1	20 mm
Side 2	10 mm
Side 3	5 mm
Tolerance in size	+/- 0,1 mm
Direction of magnetisation	parallel to side 3
Pole faces	20 x 10 mm
Material	NdFeB (Neodymium Iron Boron)
Type of coating	Nickel (Ni-Cu-Ni)
Strength	approx. 3,8 kg approx. 37,3 N
Weight	7,6 g
Manufacturing method	sintered
Magnetisation (Grade)	N42
Max. working temperature	80°C
Curie temperature	310 °C
Residual magnetism Br	12900-13200 G 1.29-1.32 T
Coercive field strength bHc	10.8-12.0 kOe 860-955 kA/m
Coercive field strength iHc	≥12 kOe ≥955 kA/m
Energy product (BxH)max	40-42 MGOe 318-334 kJ/m³



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Exempt from registration according to REACH.



Data sheet article W-05-N

Technical data and application safety

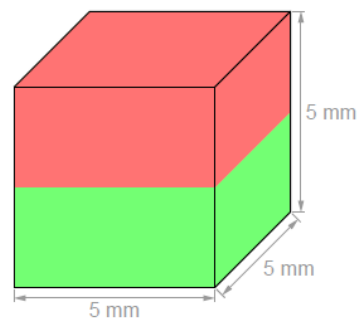
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www.supermagnete.pt
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1. Technical information

Article	W-05-N
Shape	Cube
Length	5 mm
Tolerance in size	+/- 0,1 mm
Material	NdFeB (Neodymium Iron Boron)
Type of coating	Nickel (Ni-Cu-Ni)
Strength	approx. 1,1 kg approx. 10,8 N
Weight	0,95 g
Manufacturing method	sintered
Magnetisation (Grade)	N42
Max. working temperature	80°C
Curie temperature	310 °C
Residual magnetism Br	12900-13200 G 1.29-1.32 T
Coercive field strength bHc	10.8-12.0 kOe 860-955 kA/m
Coercive field strength iHc	≥12 kOe ≥955 kA/m
Energy product (BxH)max	40-42 MGOe 318-334 kJ/m ³



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Appendix C

On appendix B can be consulted all the information regarding mechanical and physical properties of SL 7810 stereolithography resin.



Accura® ABS White (SL 7810)

ABS Class

Rigid and tough white plastic to simulate and replace CNC-machined ABS articles

Post-Cured Material

MEASUREMENT	CONDITION	METRIC	U.S.
Tensile Strength (MPa/PSI)	ASTM D 638	46-48	6670-6960
Tensile Modulus (MPa/KSI)	ASTM D 638	2290-2400	332-348
Elongation at Break (%)	ASTM D 638	8-14	8-14
Flexural Strength (MPa/PSI)	ASTM D 790	74-76	10730-11020
Flexural Modulus (MPa/KSI)	ASTM D 790	2040-2120	296-307
Impact Strength (J/m /Ft-lbs/in)	ASTM D 256	24-47	0.45-0.88
Heat Deflection Temperature	ASTM D 648 @ 66 PSI	51 °C	124 °F
Coefficient of Thermal Expansion (CTE)	ASTM E 831-93 25-50 °C	96	53
Glass Transition (Tg)	DMA, E"	63 °C	145 °F
Hardness, Shore D		86	86

Features

- Rigid and tough
- Functional assemblies
- Short-run production parts

Liquid Material

MEASUREMENT	CONDITION	VALUE
Viscosity	@ 30 °C (86 °F)	210 cps
Penetration Depth (Dp)		5.6 mils
Critical Exposure (Ec)		9.9 mJ/cm ²
Color		White
Solid Density	@ 25 °C (77 °F)	1.16 g/cm ³
Liquid Density	@ 25 °C (82 °F)	1.13 g/cm ³

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Appendix D

This appendix includes a complete example of the listening test questionnaire. The test was done in Portuguese.

Sons de Guitarra

Este Questionário requer audição de diferentes ficheiros de áudio. Os mesmos tem que ser acedidos aqui:

https://drive.google.com/drive/folders/0B70qETyqXo_4clZIYkRmR01CV1k?usp=sharing

Cada ficheiro de áudio contém 5 notas e uma duração aproximada de 1min, uso de headphones é recomendado.

**Obrigatório*

1.

Endereço de email *

2.

Após audição do Ficheiro 1, Notou alguma diferença entre as diferentes notas? *

Marcar apenas uma oval.

- ☐ Sim
☐ Não

3.

Caso tenha respondido que sim na resposta anterior, tente descrever as diferenças que ouviu (opcional)

4.

Após audição do Ficheiro 2, Notou alguma diferença entre as diferentes notas? *

Marcar apenas uma oval.

- ☐ Sim
☐ Não

5. **Caso tenha respondido que sim na resposta anterior, tente descrever as diferenças que ouviu (opcional)**

6. **Após audição do Ficheiro 3, Notou alguma diferença entre as diferentes notas? ***
Marcar apenas uma oval.

☐ Sim
☐ Não

7. **Caso tenha respondido que sim na resposta anterior, tente descrever as diferenças que ouviu (opcional)**

8. **Após audição do Ficheiro 4, Notou alguma diferença entre as diferentes notas? ***
Marcar apenas uma oval.

☐ Sim
☐ Não

9. **Caso tenha respondido que sim na resposta anterior, tente descrever as diferenças que ouviu (opcional)**

10.

Após audição de todos os Ficheiros (pode repetir se achar necessário) em qual crê ouvir mais ou maior diferenças? *

Marcar apenas uma oval.

- ☐ Ficheiro 1 *Pare de preencher este formulário.*
- ☐ Ficheiro 2 *Pare de preencher este formulário.*
- ☐ Ficheiro 3
- ☐ Ficheiro 4 *Pare de preencher este formulário.*
- ☐ Não consegui ouvir diferenças nenhuma *Pare de preencher este formulário.*

Avaliação Qualitativa

11.

Numa escala de um a cinco como classificaria as diferenças escutadas no Ficheiro 3 *

Marcar apenas uma oval.

	1	2	3	4	5	
Pouco perceptível	☐	☐	☐	☐	☐	Muito evidente

☐ Pretendo receber uma cópia das minhas respostas.

Com tecnologia

