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Electromagnetic Field Analysis, Materials Characterization, and Advanced Modeling of Modern Guitar Pickups

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ELECTROMAGNETIC FIELD ANALYSIS, MATERIALS CHARACTERIZATION, AND ADVANCED MODELING OF MODERN GUITAR PICKUPS

A Thesis

by

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ABSTRACT

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This Thesis establishes the foundations of modern guitar pickup theory, enhancing current pickup design by an increase in voltage output, reduction of DC resistance, and a reduction of production costs. This research investigates factors that have received insufficient attention, such as the performance of different magnetic materials, magnet geometry, bobbin geometry, metal effects, etc. An equation to calculate the output of guitar pickups is developed. Additionally, this work constructs a modern pickup using the techniques developed in this thesis incorporating theory and advanced modeling techniques to simulate changes in performance and interactions with different magnetic materials and geometries. The new design developed in this study features 1200-1850 coil windings, 1.5K Ohms DC resistance, with a resulting output of 368 mV at 85.5 Hz. This work compares traditional pickups and four new experimental versions. The research discusses the relative costs and properties of three main magnet families: Neodymium, Ferrite, and Alnico. Neodymium magnets emerge as a promising choice, balancing cost and performance, particularly the N52 Neodymium magnet, which results in this study demonstrate it outperforms the industry standard Alnico 5.

DEDICATION

In addition to individual acknowledgments, I dedicate this thesis to the collective communities that have fueled my research endeavors.

To the Scientific Community, whose unwavering pursuit of knowledge in the realm of electromagnetics has expanded the boundaries of human understanding. Your dedication to advancing the frontiers of science has inspired this exploration into the application of electromagnetic principles in the electric pickup design.

To the Guitar Community, a diverse and passionate group of musicians, craftsmen, and enthusiasts, whose deep appreciation for the instrument has enriched the world of music. This thesis is an acknowledgment of the profound influence that the guitar, as an instrument, has on the lives of countless individuals worldwide. May our collective efforts in advancing pickup technology continue to inspire musicians and enthusiasts alike.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to several individuals who have been instrumental in the completion of this thesis.

First and foremost, I am extremely thankful to my thesis Chair of Committee, Dr Heinrich Foltz. Your continuous support, insightful guidance, and expertise in the field of Electrical Engineering have been invaluable throughout my career and research journey. Your mentorship has not only shaped the direction of this thesis but has also contributed significantly to my professional and academic growth.

I would also like to extend my appreciation to my thesis committee members, Dr. Nantakan Wongkasem and Dr. Hasina Huq. Your support and feedback have enriched the quality of my work. Lastly, thank you to my family and friends, whose firm belief in me has been a constant source of motivation.

This thesis would not have been possible without the collective support, guidance, and encouragement of these individuals. Thank you for your unwavering support.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND GOALS

Within electric guitars, guitar pickups are a cornerstone of music creation. It is the central device responsible for capturing the guitar strings movements and transforming them into electric signals. Currently, the world of guitar pickups has remained steeped in tradition with designs from the 1950s and 1960s still dominating the market. This enduring traditionalism has persisted, in part, due to a lack of comprehensive research and innovation within the field. This thesis, titled 'Electromagnetic Field Analysis, Materials Characterization, and Advanced 3D Modeling of Modern Guitar Pickups' embarks on a journey into the realm of guitar pickups. First it seeks to establish the foundations of modern guitar pickup theory and provide guidelines for contemporary pickup design. The research aims to investigate a range of factors that have received insufficient attention in the guitar industry, such as the performance of magnetic materials. Specific grades of Alnico and Neodymium will be studied with their respective magnetic properties, and how these properties such as permeability, coercivity, and magnetic strength affect the pickup performance. The performance of the pickup is based on several metrics such as the output voltage, number of coil windings, demagnetization characteristics, and DC resistance. These metrics are compared against current industry designs. Current designs feature depending on the pickup: 75- 300 mV output voltage, 1k Oe coercive force, 7,500-12,000 windings, and 6k-12k Ohms. Another goal of this thesis is to create a pickup that improves on these metrics by also documenting and understanding the connection between the parts that constitute the pickup and their respective electromagnetic. The ideal pickup would boast a higher output voltage, strong anti- demagnetization characteristics, lower DC resistance, and a smaller amount of coil windings. Together with this study a review of the most used current industry designs patents such as the humbucker (US Patent US2896491A) and single coil (US Patent US2455575A) will be analyzed.

Guitar Pickup Initial Overview

A guitar pickup is a fundamental component in an electric guitar, it is a sensor that converts the mechanical vibrations of the guitar strings, made from a ferromagnetic material, into electrical signals allowing them to be amplified through an amplifier and then a sound be played through an speaker. Dr. Lawing in his article "How does a Pickup really work" in figure 1 shows an illustration of the main components of a guitar pickup. The initial overview of the pickup serves as an introduction of the main components and the electromagnetic properties that must be considered in the pickup design.

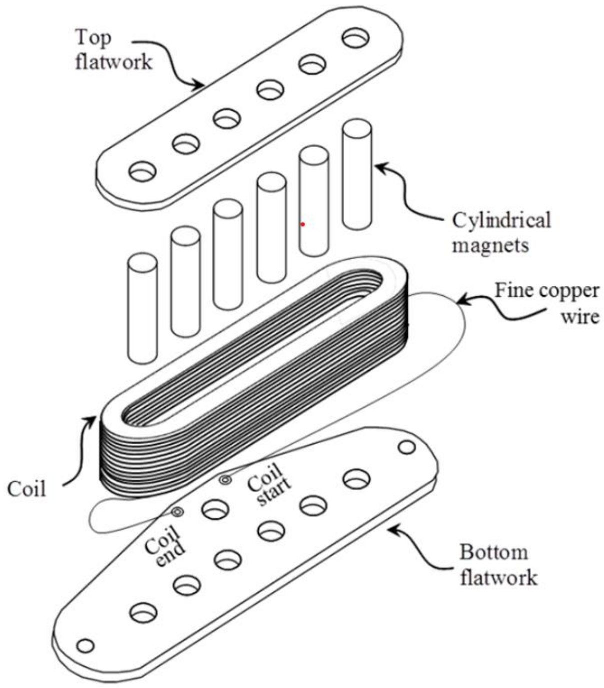

Figure 1: Guitar Pickup Overview.

Source: L. Scott. (2017). "How Does a Pickup Really Work?." Lawing Musical Products, LLC.

The breakdown of the main components is the following:

Coils: The coil windings, typically made of copper wire form a coil around a bobbin. When the guitar string vibrates, it induces a changing magnetic field in the coil, generating a small voltage able to be sent to an amplifier. The main parameter in consideration is the number of turns in the coil as an increase in the number of windings increases both the output voltage and the DC resistance which impacts the performance of the pickup.

Magnets and Pole Pieces: Positioned beneath the guitar strings, the magnet magnetizes the strings and creates a magnetic field. As the strings are played, they create movement within the magnetic field, inducing voltage in the coil windings. The pole pieces or metal cores help guide the magnetic flux through the coil but it’s important to note that not every pickup design use metal pole pieces and this is because magnets that are long enough can also serve as guides.

The main parameters in consideration are the magnetic strength and the coercive force of the magnet,

Bobbins: The bobbin is a spool or cylinder around which the coil windings are wound. It provides structural support and helps in maintaining the coil's shape. In figure 1, the bobbin is formed from the top and bottom flatwork, in the illustration shown the magnets are also conveniently used as columns to hold the coil. Excluding the core area, which is usually not considered part of the bobbin, the bobbin is usually made out of a non- magnetic material and does not offer an electromagnetic property and it’s mainly used as an structural support.

Covers: While not present in all pickups, a cover is often used as an aesthetic feature typically made from plastic, while it can also provide minimal protection to the coil windings it’s not a necessary component in pickup design, also because it’s usually made out of a non-magnetic material it does not offer an electromagnetic property.

The subsequent chapters of this thesis delve deeper into the electromagnetic properties of guitar pickups, examining the impact of each component on the overall performance. From the simulation and testing of magnet materials to the examination of different coil cores, each facet contributes to the goal of enhancing the pickup design process.

CHAPTER II

MAGNETOSTATICS AND MAGNETODYNAMICS IN PICKUP DESIGN

To comprehend the principles underpinning guitar pickups, a grasp of several fundamental areas is paramount. First, a guitar pickup is an electromagnetic sensor situated in the guitar body below the strings, within the beginning of the neck and the guitar bridge. It serves as a critical element responsible for converting mechanical vibrations into electrical signals.

Magneto Statics is a foundational component of electromagnetic theory, and it warrants exploration for the pickup design. In this static state, where charges remain fixed and currents exhibit no temporal changes, we reveal the pickup's initial state. Here a permanent magnet generates a magnetic field that wraps and magnetizes the guitar string, resulting in the establishment of a new magnetic field now around the string with the potential to generate voltage. When the string is played, the resulting mechanical motion produces a dynamic magnetic field or a magnetic field that is now moving. This dynamic magnetic field, in turn, induces voltage variations within the pickup's coil. This itself turns into the study of Magneto Dynamics, which is another component of electromagnetic theory and facilitates an understanding of the pickup's actual output characteristics, including its dynamic response range.

In this context, our research involves simulating various magnetic materials, encompassing both industry-standard options and experimental variants such as Alnico, ceramic, and neodymium. These simulations provide essential insights, including magnetic flux line distributions on cartesian coordinates and magnetic flux density at discrete locations. Such data serves as a foundation for selecting suitable magnet types and geometries and subsequently optimize the guitar pickup design.

Alnico Magnets in Guitar Pickup Design

Alnico magnets, an abbreviation for Aluminum/ Nickel/ Cobalt, assume a key role in the landscape of guitar pickups. These permanent magnets have established themselves as the industry standard for mid to high end electric guitars. Within the Alnico family, multiple grades exist, the ones mostly used in the design of guitar pickups are the Alnico II, Alnico III, Alnico V and Alnico VIII grades. Each grade exhibits similar but distinct magnetic properties, rendering them usable for guitar pickup design.

Alnico V: A Preferred Choice

Among the various Alnico grades, Alnico V stands out as the current preferred option for electric guitar manufacturers. Its preference can be attributed to its niche characteristics. Alnico V magnets offer a slightly elevated output compared to other Alnico grades, which contributes to a preference within the industry. Furthermore, they exhibit a better resilience to demagnetization, which is often a problem as Alnico magnets age. Demagnetization is the main reason Alnico magnets, for example in Single Coil guitar pickups, studied further in this thesis, are designed with high length-to-diameter ratio (L/D). The higher L/D contributes to improved resistance against demagnetization. Longer Alnico magnets with smaller diameters are less prone to demagnetization compared to shorter, thicker Alnico magnets. The disadvantage associated with this is adhering to a prescribed L/D ratio geometry, which results in increased material usage and subsequently higher production costs.

Historical Significance of Alnico Magnets

Studying the historical backdrop of Alnico magnets is pivotal in understanding their use on guitar pickups. The guitar manufacturing industry has embraced traditionalism, most of their designs have not changed since their major breakthroughs in the 1950's. It was around that time that alnico magnets were brought into the market, and it was then that their performance exceeded all other permanent magnets previously used. In his work "ALNICO permanent magnets" Achuta S Rao, PHD shows alnico magnet development compiled from US and international patents starting in 1931 with ALNICO III and ALNICO 8/ 9 in 1956.

Table 1: Alnico Magnet Grades, Properties, and Historical References.

Present Designation and Original Constituents	Year First Reported	Reference	Typical Properties		
			$(BH)_m$ (MGOe)	H_{ci} (Oe)	B_r (G)
Alnico 3 (Al, Ni, Fe)	1931	Mishima [1]	1.4	490	6800
Alnico 4 (Al, Ni, Co, Fe)	1931	Mishima [2] Ruder [3]	1.4	700	5500
Alnico 2 (Al, Ni, Co, Fe, Ti)	1934	Horsburgh and Tetley [4]	1.7	560	7300
New KS (Al, Ni, Co, Fe, Ti) (Alnico 12)	1934	Honda et al. [5] Ruder [6]	2.0	790	7200
Alnico 5 (Al, Ni, Cu, Co, Fe)	1938	Oliver and Shedden [7] Jonas [8]	5.5	640	12,500
Alcomax 3 (Al, Ni, Co, Fe, Nb)	1947	Hadfield [9]	5.0	670	12,500
Alnico 5 (Al, Ni, Co, Fe, Cu) crystal orientation	1948	McCaig [10] Bemius [11] Ebeling [12] Swift Levick et al [13]	6.5	680	13,000
Alnico 8 (Al, Ni, Co, Fe, Cu, Ti) and Alnico 9	1956	Koch et al. [14]	4.5 9.2	1450 1500	8500 10600

Source: S. Rao, Proceedings of Electrical/Electronics Insulation Conference, 1993, pp. 373-383.

Ceramic Magnets in Guitar Pickup Design

Ceramic magnets, scientifically known as ferrite magnets, are also important components within the realm of guitar pickups as they are the only other widespread used magnet in the market besides Alnico. This section offers an exploration of ceramic magnets, their properties, and their applications within the context of guitar pickups.

Ceramic Magnet Technical Details vs Alnico

Ceramic magnets are primarily composed of iron oxide, lending them their characteristic dark gray or black appearance. Their low production cost is matched by a set of robust magnetic attributes, rendering them a good choice for electric guitars. One of their most significant quantitative advantages is their high coercivity, exceeding 7,960 A/m or 10,000 Oersted's. This characteristic signifies the substantial external magnetic field required to demagnetize ceramic magnets, ensuring the long-term stability and performance of the guitar pickup vs an Alnico magnet which is more susceptible to demagnetization and limited in their geometry to a high L/D ratio. In terms of magnetic strength, ceramic magnets exhibit a field strength within the range of 0.024 to 0.4 Tesla (or 240 to 4,000 Gauss) depending on the specific composition and size, which is lower than the magnetic strength of most Alnico families.

Cost-effectiveness is the number one trait of ceramic magnets, making them a favored option for both manufacturers and musicians regarding affordable or lower end guitar models. The production cost is significantly lower compared to alternative magnet materials, thus reducing the overall cost of guitar production. The affordability of ceramic magnets ensures accessibility across various segments of the guitar market, especially for guitar players looking for an entry level instrument.

Ceramic Magnet Disadvantages

It is crucial to recognize the quantitative trade-offs associated with ceramic magnets. Their magnetic strength, while sufficient for most applications, falls short compared to other magnetic materials. The quantifiable consequence is in theory a marginally reduced output level. Perhaps by accident or convenience, manufacturing companies add a metal core to their ceramic pickup models, they do this mainly to fit the magnet into the standard pickup up bobbin and save production costs by not using Alnico magnets. The metal core serves to guide the magnetic flux closer to the strings, (different from Alnico single coil pickups which the rod magnets are the metal cores) they use a single ceramic bar magnet placed away from the strings below the bobbin. The metal core increases the magnetic strength of the pickup, but a more optimal alternative is to place the ceramic magnet closer to the strings and not below the bobbin for better performance. This phenomenon is explored and proven in further sections.

Feasibility of New Magnetic Materials (Neodymium)

The ascendancy of Alnico and Ceramic magnets during this era serves as a cornerstone in the critique of the guitar industry's stagnation. This thesis seeks to introduce new magnetic materials for study and assessment. We aim to challenge the status quo and inject fresh perspectives into guitar pickup design.

Neodymium magnets, renowned for their exceptional magnetic properties, have sparked substantial interest within the scope of this research due to their potential to deliver superior performance, cost savings, and innovative solutions in contrast to conventional alnico and ceramic magnets. This comprehensive exploration delves into the viability of integrating neodymium magnets into guitar pickups, encompassing an in-depth analysis that considers coercivity, demagnetization risks, advantages, trade-offs, and cost assessment.

Historical Background and Technical Details

Neodymium magnets, often referred to as neodymium-iron-boron (NdFeB) magnets, are a class of permanent magnets celebrated for their extraordinary magnetic properties. In the 1970s and 1980s, pioneering work by General Motors and Sumitomo Special Metals independently led to the development of neodymium-iron-boron magnets. These magnets harnessed the exceptional magnetic properties of neodymium, marking a significant milestone in the evolution of magnetic materials. Neodymium magnets are primarily composed of neodymium, iron, and boron, often denoted by the chemical formula Nd2Fe14B. They boast an exceptional magnetic energy product, often exceeding most Alnico families, making them significantly more powerful than their predecessors. Another important characteristic of neodymium magnets is their high coercivity, which means they are resistant to demagnetization. This attribute ensures that they can maintain their magnetization over prolonged periods, a key feature for their utility in many industries.

Current Industrial Applications of Neodymium Magnets

1. Consumer Electronics: The consumer electronics industry has significantly benefited from neodymium magnets. These magnets are widely used in smartphones, headphones, and speakers to create compact and high-performance audio components. This enables the production of slim and lightweight devices with exceptional sound quality.

2. Motors and Generators: Neodymium magnets find extensive use in the manufacturing of electric motors, generators, and servo motors in various industries. Their remarkable magnetic

strength not only enhances the efficiency of these systems but also enables miniaturization, a key advantage in modern engineering.

3. Medical Devices: In the field of medical technology, neodymium magnets play a pivotal role. Their powerful magnetic fields are utilized in magnetic resonance imaging (MRI) machines, facilitating precise and detailed imaging, essential for medical diagnosis and research.

4. Automotive Industry: The transition to electric and hybrid vehicles has relied heavily on neodymium magnets. They are used in traction motors, power steering systems, and regenerative braking, contributing to the increased adoption of green technologies and the reduction of greenhouse gas emissions.

5. Industrial Automation and Robotics: In the realm of industrial automation and robotics, neodymium magnets are integral. They are employed in tasks such as picking and sorting in manufacturing and assembly processes. Their strength and durability make them ideal for precision operations.

6. Wind Turbines: The renewable energy sector benefits from neodymium magnets, are found in the generators of wind turbines. These magnets enhance the energy production efficiency of wind power, playing a role in the transition to sustainable energy sources.

7. Defense and Aerospace: Neodymium magnets are utilized in defense and aerospace applications, including guidance systems and radar equipment. Their high magnetic strength contributes to the accuracy and reliability of these critical systems.

8. Audio Equipment: In the realm of audio equipment, neodymium magnets are employed in high-end headphones and loudspeakers. Their magnetic properties enable clear and powerful sound reproduction, catering to audiophiles and professionals alike.

Note neodymium magnets although heavily used in other industries are not currently used in the guitar industry hence the need for exploration and feasibility in this study.

Technical Details of Neodymium Magnets

Neodymium magnets, often colloquially referred to as "super magnets," characterized by their remarkable magnetic energy product, boasting a magnetic flux density typically ranging from 1.3 to 1.5 Tesla's. The high coercivity of neodymium magnets, around 1,000 to 1,300 kA/m, renders them resistant to demagnetization effects even in different environments, such as those featuring a stage or a musical studio. This high coercivity is a crucial aspect in ensuring the stability and longevity of guitar pickups.

The integration of neodymium magnets provides an array of advantages and trade-offs for guitar pickups. These include:

Advantages:

- Higher Magnetic Strength and High Coercivity: Neodymium magnets offer significantly higher magnetic strength per unit weight than any other magnet, in theory resulting in enhanced pickup performance, including increased output and sensitivity. Higher coercivity
- Cost Efficiency: Neodymium magnets are typically more cost-effective than alnico magnets, which can result in notable savings in the production of guitar pickups.
- Space Efficiency: Their compact size makes neodymium magnets ideal for applications where space constraints are a concern, such as single-coil pickups and mini-humbuckers.

Trade-offs:

- Heat Sensitivity: Neodymium magnets are more susceptible to heat than ceramic or alnico magnets, making proper shielding and heat management vital for preventing demagnetization in scenarios with elevated temperatures. Although most situations should be fine, leaving the pickup under direct sunlight for extended periods of time might result in issues without proper heat protection.

Permeability and Coercive Force

Understanding the relationship between permeability and coercive force is crucial for designing a modern guitar pickup. Permeability and coercive force are key parameters that characterize the magnetic behavior of materials, particularly in the context of guitar pickups where Alnico and Neodymium magnets will be compared. First, magnetic Permeability gauges how a material reacts when subjected to a magnetic field. It signifies how easily a material becomes magnetized when exposed to a magnetic field. This parameter is key particularly when choosing a core material for the guitar pickup. Coercive force, on the other hand, its a more important parameter for deciding on a magnet type, it measures a material's resistance to demagnetization. For guitar pickups, a higher coercive force is desirable to maintain reliability, preventing unintended loss of magnetization.

In the context of pickup design, the choice of a magnet type and core material is essential. Magnets with high coercivity are a better option because they are harder to demagnetize, for a guitar player this is important because it’s difficult to get to the magnets once the guitar is properly set up and because it’s not feasible to troubleshoot a pickup in situations where the guitar player is about to play. In the past demagnetization was a known problem and is the reason guitar pickups that use Alnico Magnets hold a high D/ L ratio, this is to try counter Alnico lower coercive force and ease of demagnetization characteristics, this would add however to substantial increase in material costs. Hard magnetic materials such as rare earth magnets and our pick of N52 Neodymium with their high coercivity (neodymium 12k Oe vs alnico 1k Oe) make a more attractive choice than Alnico as they are not prone to demagnetization and not limited to the D/L ratios alnico magnets have.

The core material could be different from the magnet, the role of the core material is to guide the magnetic flux through the coil and because it could be used in conjunction with a permanent magnet, a core material that is highly permeable is desired. Demagnetization with a core material is typically not an issue because it should be receiving constant magnetization from the permanent magnet. Materials such as different variations of steel with a permeability of 4k μx are favored as core materials due to their high permeability and their ease of magnetization.

CHAPTER III

CURRENT INDUSTRY PICKUP DESIGN

In the previous chapter, we explored the foundational elements of guitar pickups magnetostatics and magnetodynamics, with a particular focus on the various magnetic materials and their properties. In the next section current patents of the most popular pickup designs in the industry will be studied as well as an overview of a fundamental flaw with the current pickup design and how it stifles an improved version of a pickup.

Traditional Design: Single Coil Guitar Pickup

Manfred Zollner, in his book "Physik der Elektrogitarre" (Physics of the Electric Guitar), offers a foundational background on the structure of the components used. The standard single coil pickup (figure 1) (US Patent US2455575A) consists of three pairs of magnets usually Alnico V, which also serve as the inner columns of the pickup's bobbin. Traditionally, its coil windings are crafted from 41-44 AWG copper magnet wire, and the average number of windings hovers 7500- 9000. However, it's worth noting that with current pickup designs, slight variations in the number of coil windings are employed potentially expanding the range. For protection, a thin layer of electrical tape and a plastic cover encase the coil. While this cover may not provide EMI shielding, it offers essential safeguards against physical damage and contributes to the pickup's distinctive appearance. The outer screws, used to adjust the distance between the pickup and the strings, do not adhere to a specific standard. Nevertheless, it's important to acknowledge that a closer distance between the pickup and strings increases the voltage output, following Faraday's law. For the pickup to generate voltage, each string must interact with a magnetic field. The task of achieving this fall to the six alnico magnets. They magnetize the ferromagnetic material of the strings, generating a magnetic field around both the strings and the coil. The variation in this magnetic field induces a small voltage in the pickup, which is subsequently amplified by the guitar amplifier circuit. In the space of electric guitar pickups, single coil pickups are traditionally categorized as low-output and it is often seen as a disadvantage when compared to humbuckers (Humbuckers being the next type of pickup design studied). Additionally, they exhibit a higher susceptibility to interference from power lines and other electrical equipment, including lights and transformers. Nonetheless, single coil pickups offer distinct advantages. They are cost-effective, requiring fewer components, resulting in approximately 50% cost savings compared to humbuckers. Moreover, they are known in the industry for their clarity of sound, attributed to lower DC resistance and to a lesser extend lower capacitance.

Traditional Design: Humbucker Guitar Pickup

The beginning of humbucking pickups can be tracked back to 1935 when Arnold Lesti patented a double-coil guitar pickup. Yet, it was Seth Lover's design (Reference US patent number US2896491A) popularized in the 1950s under Gibson PAF pickups that became widely used in the industry and the one studied. Variations of Seth Lover's pickup design are found in the industry, often differing only aesthetically or in the number of coil windings. It is important to note that various humbucking pickups, such as mini humbuckers, firebird pickups, or rail humbuckers, as they are commonly known exhibit slight deviations in bobbin size and pole piece configurations, but their overall operation and sonic performance closely follow Seth Lover's pickup design. Humbucking pickups offer notable advantages and disadvantages over single coil pickups. One of their most known features is that they boast a higher voltage output and exhibit a reduced susceptibility to interference thanks to their noise cancellation properties. Employing a common mode rejection technique and series connection of the coils enhances this noise-cancellation capability. However, it is important to acknowledge the trade-offs. Humbucking pickups are twice as expensive as single coil pickups, primarily due to the additional materials and labor involved in their construction. Furthermore, they are often perceived as having a duller sound in comparison to single coil pickups, primarily due to the increased DC resistance resulting from the series connection of both coils, effectively intensifying low pass filtering characteristics.

Flaws with Current Pickup Design

Why Output Voltage in Traditional Pickups Affect Sound Quality

In prior sections of this thesis, the foundational premise of crafting an electric guitar is deeply rooted in "tradition." Guitar manufacturers have by now built their brand around the notion that older equates to superior, a narrative perpetuated for decades. Marketing strategies have consistently reinforced the idea that vintage is synonymous with better. For the guitar industry, deviating from this narrative would not only contradict decades of branding but also challenge the very essence of their identity. Possibly the reluctance to alter this narrative stem from the potential revelation that what they've communicated their customer base for more than 80 years might not hold true, a realization that carries significant business implications, especially when applied to not only electric guitars but also to core components such as guitar pickups.

At its essence, the current guitar pickup design process remains simple, take an old guitar pickup archetype usually from the 1950’s or 1960’s, add a set of Alnico magnets (usually Alnico

V’s), and wound the coil. In the initial stages of pickup development, Alnico magnets were chosen for their superior performance which coincidentally, as explored in previous sections, were being developed around the same time as guitar pickups, aligning with the era's technological constraints. Experimentation led to the discovery that increasing coil windings could elevate output of the pickup to desired levels. However, a dilemma emerged as merely adding turns adversely affected the guitar pickup sound quality, resulting in a "dull," "muddy," or excessively bass-heavy sound as described by musicians of the era. This in turn would affect the electric guitar ability to perform its job in a band setting as the signal of the guitar would get mixed with other lower frequency-based instruments such as bass guitars, kick drums, or even pianos when their lower notes were being played. The compromise became common in the industry, with an increasing number of coil windings and DC resistance linked to a trade-off between output power and sound clarity.

For over 80 years, this approach has persisted without a thorough understanding from most musicians or even luthiers. While luthiers may understand the established method, questioning its origin reveals an adherence to tradition rather than informed decision-making. The failure to grasp the electromagnetic and electrical engineering intricacies of how a pickup works has led to a stagnation in design evolution. The inventors of the guitar pickup, who surprisingly had no formal background in engineering and pioneered pickups in the 1950s adhered to this methodology due to the limitations of their time. While their inventions were groundbreaking at the time, the subsequent shift in the industry from innovation to tradition has hindered substantial changes in pickup design even with technological advancements thus why this thesis aims to challenge the status quo.

Answering the first question of why increasing the number of windings significantly impacts the sound quality involves the understanding of the low pass filtering characteristics inherent in all guitar pickups. Elevating the number of coil windings increases DC resistance and capacitance, subsequently raising the threshold for lower frequencies to transfer to the output signal. The second question delves into the process of how to increase the pickup output without compromising sound quality. As explored in the upcoming chapter "Guitar Pickup Electromagnetic Theory," the output of the pickup is not solely dependent on the coil's turns but also tied to the magnetic properties of the magnet used. This aspect becomes a central focus in improving sound performance, output power, as well as a substantial reduction in costs and serves as the foundation for the research done in this study and the development of an improved pickup design.

CHAPTER IV

GUITAR PICKUP ELECTROMAGNETIC THEORY

The guitar pickup works under Faraday's law of induction, where a changing magnetic field induces a voltage in a coil given by the formula:

$$V(t) = N\,(\frac{d\Phi}{dt})$$

Where $V(t)$ is the induced voltage, N is the number of turns within the coil, $d\Phi$ is the change in the magnetic flux and dt is the change in time. When the string vibrates a in the magnetic field occurs inducing a voltage in the copper coil winding, the string by itself will not create a magnetic field unless it is magnetized first, this magnetization comes from the attachment of the permanent magnet to the guitar pickup. Because of this the string needs to be made from a ferromagnetic material and the magnet needs to be placed at a small distance under the string. Induced voltage can be higher without increasing the number of turns by increasing the magnetic flux, therefore keeping the DC resistance from increasing.

Although Faraday's law in its original form brings important insights it doesn't tell the whole story, the reason is because not every single coil winding is penetrated by the same amount of magnetic flux. The field that is produced at the string diverges and coil windings that are positioned closer to the string will experience a larger flux density change than those that are further away from the string.

Because of this, the formula below approaches closer to how the induced voltage could be calculated.

$$V(t) = (\frac{d\Phi_1}{dt} + \frac{d\Phi_2}{dt} + \frac{d\Phi_3}{dt} + \frac{d\Phi_4}{dt} + \frac{d\Phi_5}{dt} \dots \dots \dots \dots . \frac{d\Phi_n}{dt})$$

Where the each term correlates to one coil winding at different distances from the magnet, and n varies from 1 to N. To estimate the average changing flux for each turn, a 3D simulation is needed. With this, we can see the magnetic flux density at different cross sections and adapt as necessary. A possible solution comes in the bobbin design by reducing its length, moving the magnet further down the coil or inserting metal pole pieces to help guide the magnetic flux density through the whole of the coil.

String Movement and Velocity Effects

A key factor in Faraday's law is the rate of change of magnetic flux over time ($d\Phi/dt$). If plucking the string causes a change in the magnetic field, then this change will contribute to the induced voltage.

The string velocity is a decisive factor, it dictates the speed of the change in the magnetic field. A higher string velocity results in a more rapid change of the magnetic flux, consequently leading to a higher induced voltage. This relationship can be expressed mathematically by linking the rate of change of the magnetic flux to the change in the position of the string (dy). The resulting derivation establishes mathematically how the string movement influences the rate of change of magnetic flux and, subsequently, the induced voltage. Mathematically, this relationship can be defined as:

$$\frac{d\Phi}{dt} = \left(\frac{d\Phi}{dy}\right) x \left(\frac{dy}{dt}\right)$$

Where ($d\Phi/dy$) is the rate of change of the magnetic flux with respect to the position of the string (y) and (dy/dt) is the velocity of the string derived from the change in the string distance over time.

String Movement. Why 1D?

While the real movement of the guitar string is two-dimensional when attached to the guitar and plucked, it's critical to emphasize that the pickup sensor geometry is intentionally positioned perpendicular to the magnetic flux of a single dimension of the guitar string movement. This specific orientation implies that while only one dimension of the string movement is effectively captured by the pickup it does not interfere with the free hand movement of guitar players while they are playing. This is a crucial consideration in this thesis calculations, as the formulas are designed to only account for this dimension of the string movement. In our analysis, the variable 'y' will serve as a representative indicator for the effective string dimension that significantly influences the guitar pickup output.

Derived Equation for Guitar Pickup Output

By incorporating the principles of Faraday's law of electromagnetic induction and delineating the relationship between string velocity and its impact on the pickup system, it becomes feasible to create a new equation to calculate the output voltage generated by the pickup. The derivation comes as follows:

$$\frac{d\Phi}{dt} = \left(\frac{d\Phi}{dy}\right) x \left(\frac{dy}{dt}\right)$$

$$V(t) = (\frac{d\Phi_1}{dt} + \frac{d\Phi_2}{dt} + \frac{d\Phi_3}{dt} + \frac{d\Phi_4}{dt} + \frac{d\Phi_5}{dt} \dots\dots\dots\dots. \frac{d\Phi_n}{dt})$$

$$V(t) = [\left(\frac{d\Phi_1}{dy}\right) x \left(\frac{dy}{dt}\right) + \left(\frac{d\Phi_2}{dy}\right) x \left(\frac{dy}{dt}\right) + \left(\frac{d\Phi_3}{dy}\right) x \left(\frac{dy}{dt}\right)$$

$$+ \left(\frac{d\Phi_4}{dy}\right) x \left(\frac{dy}{dt}\right) + \left(\frac{d\Phi_5}{dy}\right) x \left(\frac{dy}{dt}\right) \dots\dots\dots\dots. \left(\frac{d\Phi_n}{dy}\right) x \left(\frac{dy}{dt}\right)]$$

Or

$$V(t) = \sum_{i=1}^{n} [\left(\frac{d\Phi_n}{dy}\right) x \left(\frac{dy}{dt}\right)]$$

This resulting formula calculates the output of the pickup and will give the user the ability to visualize how the guitar pickup performs, this formula takes taking into consideration the magnetic materials, string distances, the velocity of the string, and the coil windings. This equation, given as the summation of the rate of change of the magnetic flux with respect of the string position (y) times the velocity of the string for each coil winding element. In this study, this formula is used in combination with results obtained from electromagnetic simulations to predict the output of a guitar pickup and can be used as a tool to compare the performance of different guitar pickups or as a foundation for modern guitar pickup design.

CHAPTER V

ELECTROMAGNETIC SIMULATIONS

To successfully evaluate and optimize the pickup's performance, it was necessary to conduct a detailed electromagnetic simulation. This simulation will allow to not only visualize but also quantify the magnetic flux penetrating the coil within a cross-sectional area, and subsequently employ the formulas outlined in the previous chapter to gauge the pickup's performance. A 3D model of the existing Alnico V single coil design will be simulated, serving as our benchmark for comparison. This model will be compared to a series of experimental designs, enabling us not only to assess their feasibility but also to scrutinize their performance against an industry standard and against each other.

Design Archetypes

To carry out these electromagnetic simulations, CST Low-Frequency/Magnetostatic solver was chosen, and it provides a specialized tool for 3D modeling and electromagnetic simulations. In the following pages 5 design archetypes will be compared, note that the new experimental designs, will externally look similar but will both contain either an "air core", or a "metal core". Note that these 3D models contain only one simulated copper coil winding, this is to reduce CST computational time and because as results will show the flux is concentrated within the core area. The number of coil windings will later come into play during the "Expected Output Computation" section.

Traditional Design- Metal Core: Alnico V Single Coil

The choice of the industry single coil standard design as our benchmark was determined. This is an industry current design, prominent for its widespread adoption in the market, represents the best archetype to be evaluated. Furthermore, it facilitates a comparative assessment against other popular designs, such as the humbucker. A humbucker essentially comprises two single coil pickups connected in series. By scrutinizing and fine-tuning single coil pickup designs, one could also get general insights into the performance of humbucker-style configurations, which would be worth exploring in later studies.

Dimensions and Magnetic Properties:

- Coil: 50.8mm Length x 17.8mm Width x 15.8mm Height
- Magnets: 6- 4.76mm Diameter x 16mm Height
    - Magnet Type: Alnico V
    - Coercive Force: 1k Oe
    - Permeability: 5- 6.7 μ_x
- Metal Core: 4.76mm Diameter x 16mm Height

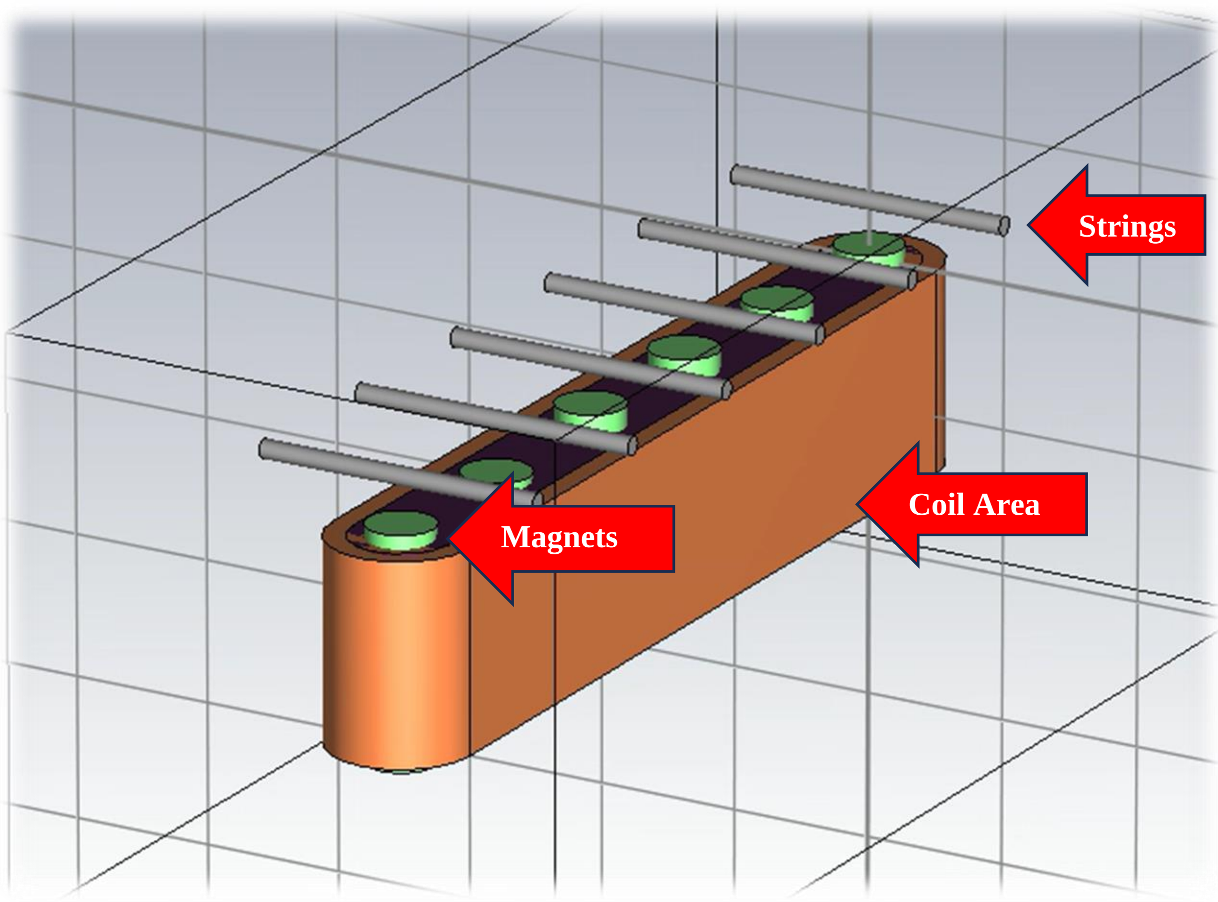

Figure 2: Metal Core: Alnico V Single Coil Magnet. Traditional Design. CST 3D Model.

New Design- Air Core/ Metal Core: Neodymium Single Magnet Set

The model presented in Figure 4 illustrates two closely related pickup designs, each with identical magnet configurations yet exhibiting distinct performance characteristics. The main difference between the two designs is that one design incorporates an air core, while the other incorporates a metal core. A full analysis of both designs will be conducted in this chapter, delving into the impact of the core material on key performance metrics.

Dimensions and Magnetic Parameters:

Air Core and Metal Core: Neodymium N52 Single. New Design:

- Coil: 50.8mm Length x 17.8mm Width x 12mm Height.
- Magnets: 6- 7mm Diameter x 2mm Height.
  - Magnet Type: Neodymium N52.
  - Coercive Force: 12k Oe.
  - Permeability: 1.05 μ_x.
- Metal Core: 2mm Diameter X 12mm Height.

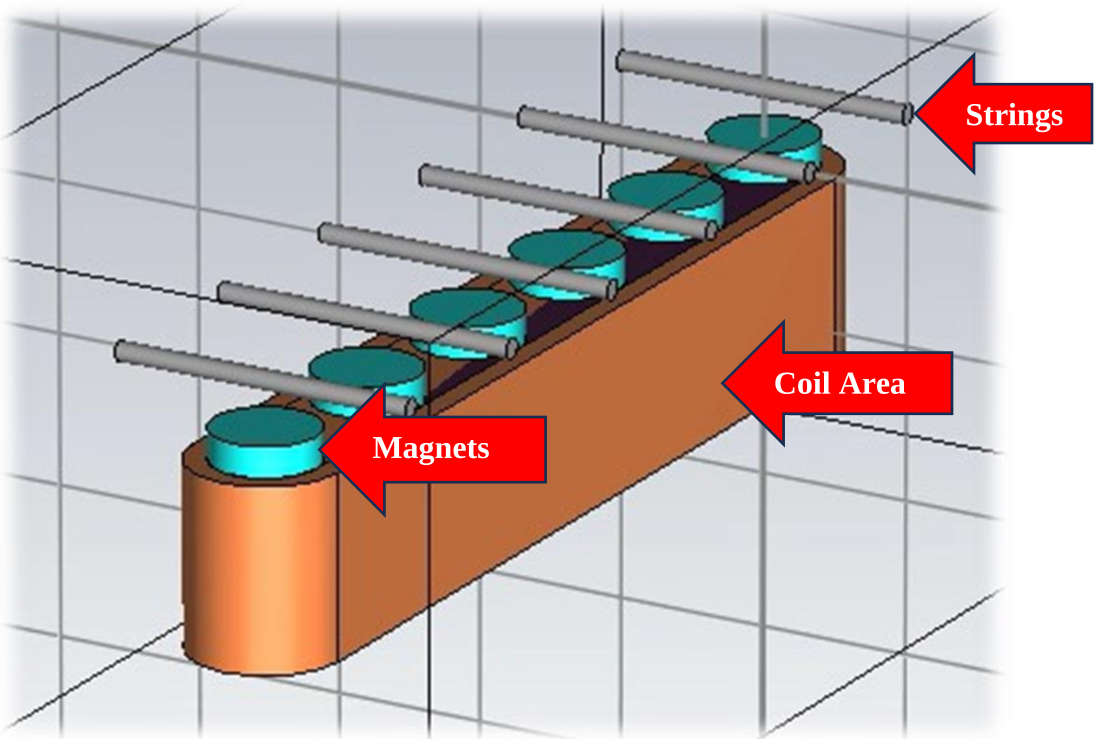

Figure 3: Air Core/ Metal Core: Neodymium Single Magnet Set. New Design. CST 3D Model.

New Design- Air Core/ Metal Core: Neodymium Double Magnet Set

The model presented in Figure 5 illustrates another two closely related pickup designs, each with the same magnet configurations but different from the design showed in figure 4, this design boasts a second set of neodymium magnets at the bottom of the coil. Similarly, a full analysis of the different designs will be conducted further in this chapter.

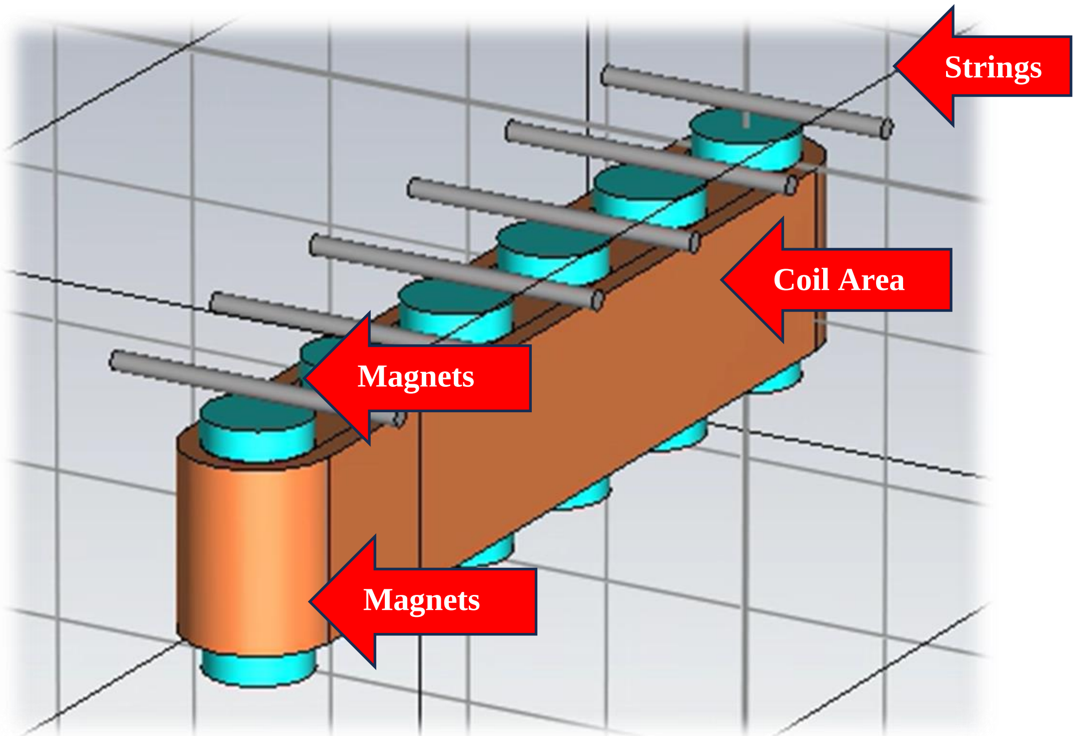

Figure 4: Air Core/ Metal Core: Neodymium Dual Magnet Set. New Design. CST 3D Model.

Dimensions and Magnetic Parameters:

Air Core and Metal Core: Dual Magnet Set. New Design:

- Coil: 50.8mm Length X 17.8mm Width X 12mm Height.
- Magnets: 12- 7mm Diameter X 2mm Height.
    - Magnet Type: Neodymium N52.
    - Coercive Force: 12k Oe.
    - Permeability: 1.05 μ_x.
- Metal Core: 2mm Diameter X 12mm Height.

Simulation Results: Data Collection

The data collection process involved the examination of the five distinct pickup archetypes through a series of ten simulations, with each simulation encompassing three collection points and two different string positions, denoted as y1 and y2, positioned 2mm and 3mm away from the pickup, respectively. As it’s not feasible to collect the magnetic flux density for each coil winding, the flux density information was obtained at three critical cross-sections to approximately evaluate the pickup sensibility at each section. The magnetic flux density information will be used to calculate the rate of change of the magnetic flux dΦ using the equations shown in the theory section of the thesis.

The first cross- section, Cross Section A, is situated 1mm below the initiation of the coil, and it provides insights into the magnetic flux density in the coil's initial region.

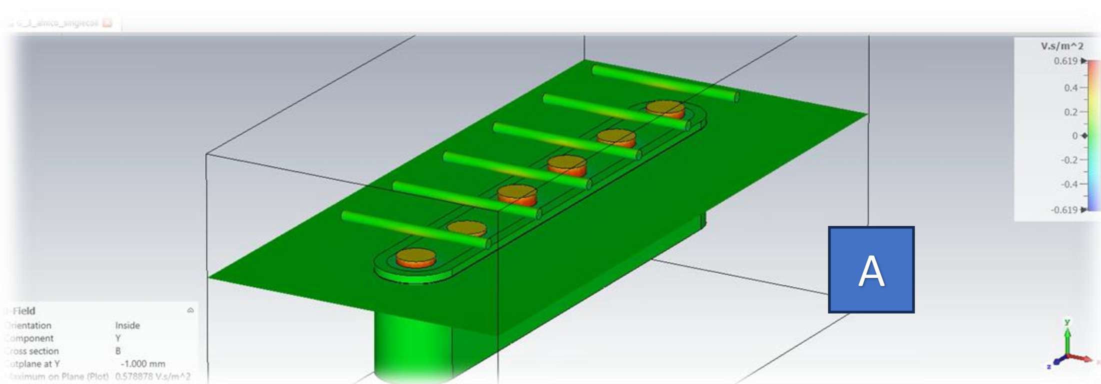

Figure 5: Cross Section A.

Cross Section B, positioned 6/8mm below the coil, is aimed to capture flux dynamics within the midsection of the coil.

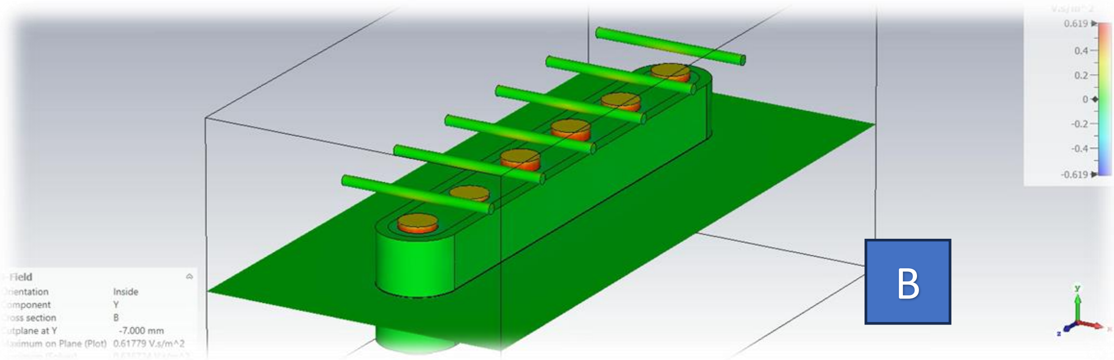

Figure 6: Cross Section B.

Cross Section C, located 1mm above the termination of the coil, facilitates the examination of the magnetic flux density near the coil's endpoint.

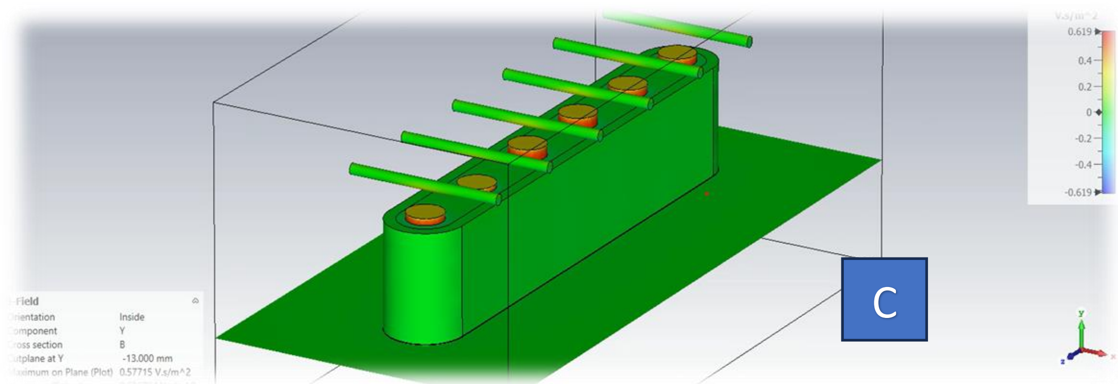

Figure 7: Cross Section C.

This data collection strategy allowed for an analysis of the magnetic behavior at different points and positions within the pickup complete area and it’s necessary to calculate the rate of magnetic flux change. The results were documented in the following table:

Table 2: Magnetic Flux Density Data Collection Table.

							B Field (T)			
Design	Format	Magnet	Type	Core	String Position	Distance S-P (mm)	Max	Point A	Point B	Point C
New	Dual Magnet Set	Neodymium	N52	Metal	Y2	3	2.19821	2.12394	2.05982	2.16868
New	Dual Magnet Set	Neodymium	N52	Metal	Y1	2	2.211866	2.1501	2.06572	2.16951
New	Dual Magnet Set	Neodymium	N52	Air	Y2	3	1.19826	0.277404	0.0645615	0.227577
New	Dual Magnet Set	Neodymium	N52	Air	Y1	2	1.01428	0.290534	0.0697308	0.229528
New	Single Magnet Set	Neodymium	N52	Metal	Y2	3	2.23219	2.03331	1.52972	0.567246
New	Single Magnet Set	Neodymium	N52	Metal	Y1	2	2.27232	2.07034	1.55269	0.579016
New	Single Magnet Set	Neodymium	N52	Air	Y2	3	0.995805	0.283861	0.0363158	0.00865707
New	Single Magnet Set	Neodymium	N52	Air	Y1	2	1.33282	0.274559	0.0391782	0.00864588
Traditional	Rod Magnet Set	Alnico	V	Metal	Y2	5	0.618834	0.576337	0.61777	0.577497
Traditional	Rod Magnet Set	Alnico	V	Metal	Y1	4	0.636724	0.578889	0.617828	0.577204

To quantify the magnetic flux change ($d\Phi n/dy$) with respect to the string position, the rate of change of dB. Averages were computed for the change in magnetic flux across Cross Sections A to C. The use of averages in this context provides an approximation of the pickup magnetic flux responsiveness to the guitar string position as it moves. This approach estimates a measure of the dynamic magnetic behavior across different sections of the pickup, facilitating meaningful comparisons and insights between the different guitar pickup archetypes.

Table 3: Magnetic Flux Density Change (mT).

							Change (mT)			
Design #	Design	Format	Magnet	Type	Core	Position	Change A	Change B	Change C	Average
1	New	Dual Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	26.16	5.9	0.83	10.96
2	New	Dual Magnet Set	Neodymium	N52	Air	(Y1-Y2)	13.13	5.1693	1.951	6.75
3	New	Single Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	37.03	22.97	11.77	23.92
4	New	Single Magnet Set	Neodymium	N52	Air	(Y1-Y2)	-9.302	2.8624	-0.01119	-2.15
5	Traditional	Rod Magnet Set	Alnico	V	Metal	(Y1-Y2)	2.552	0.058	-0.293	0.77

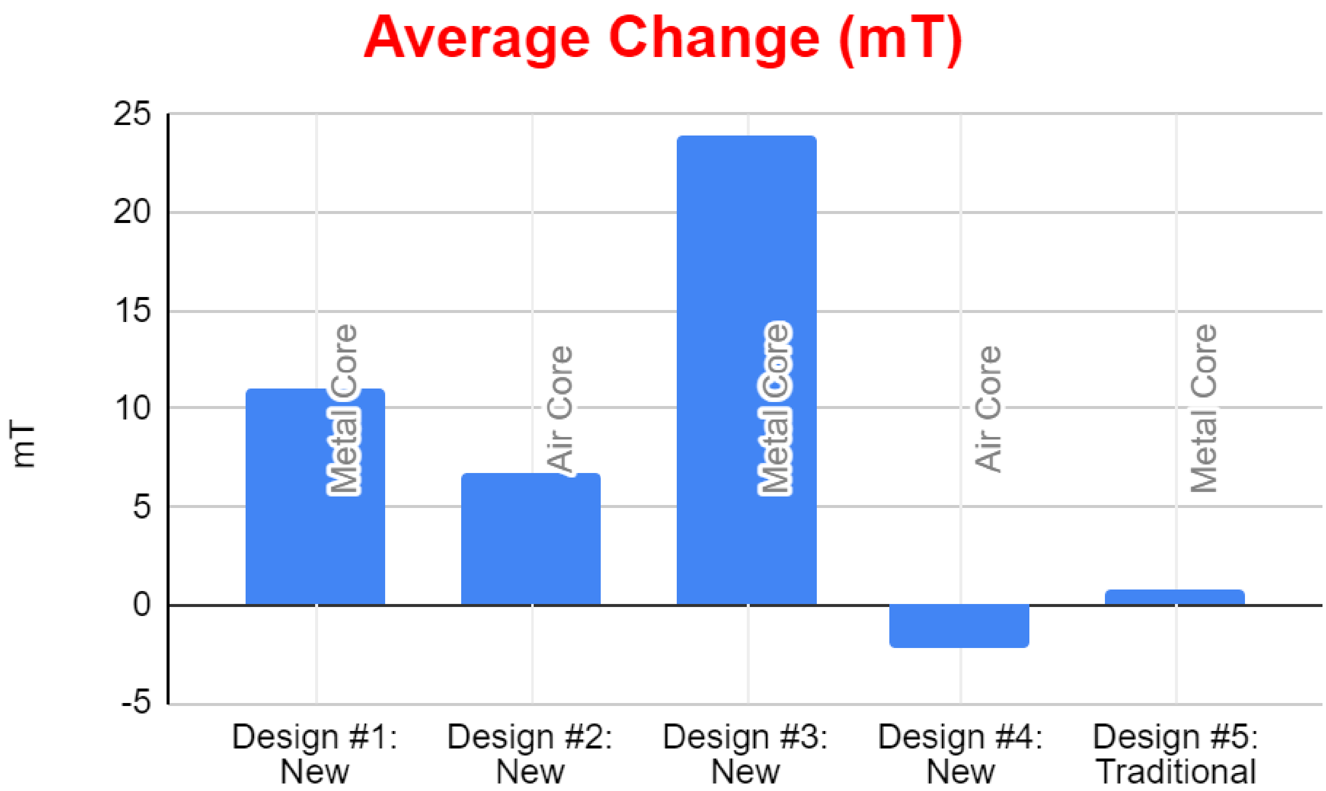

Figure 8: Average Change in mT for all designs.

Finding: Air vs Metal Core Archetype

When conducting a comparative analysis between air core and metal core pickups, it becomes evident that air core pickups have more leakage of flux per turn as one moves farther down the coil, particularly when lacking an additional set of magnets at the bottom. The introduction of a metal core into the pickup design aimed to investigate its effectiveness in guiding the magnetic flux through the coil. The choice of a metal core for all designs is a pick of 1010 steel which has a permeability of 4k μ_x

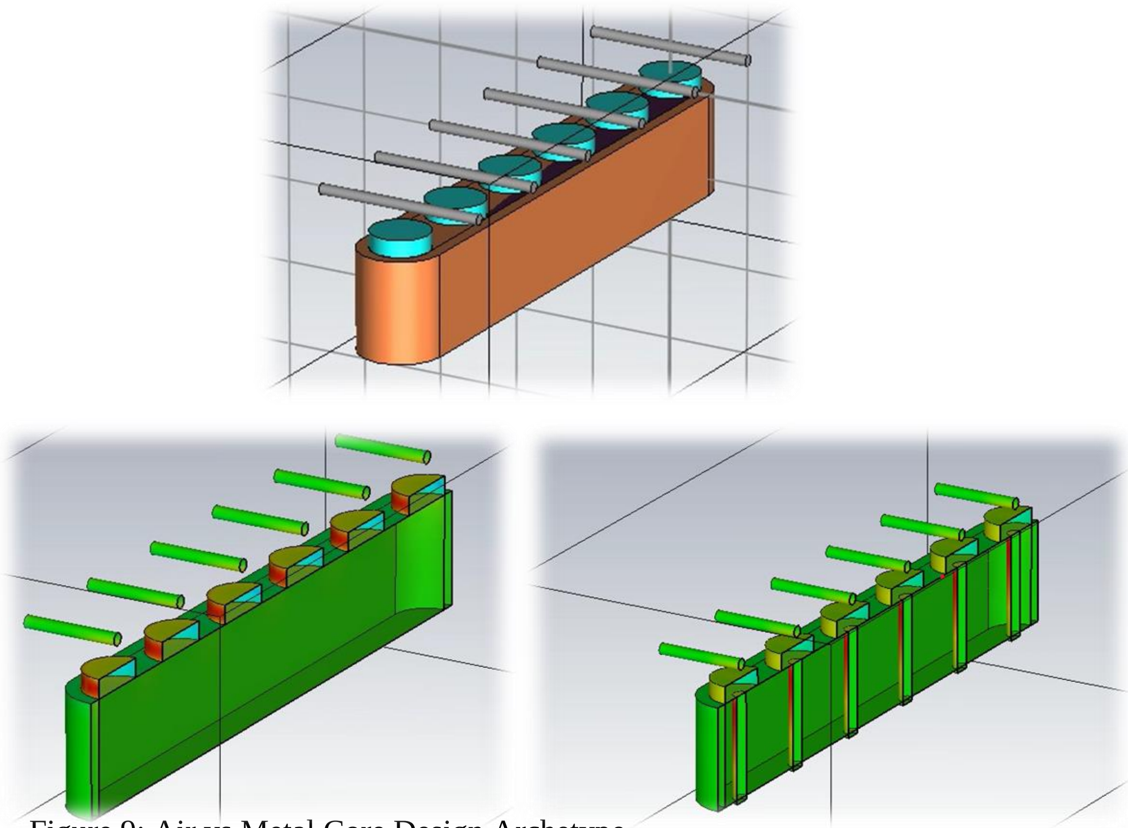

Figure 9: Air vs Metal Core Design Archetype.

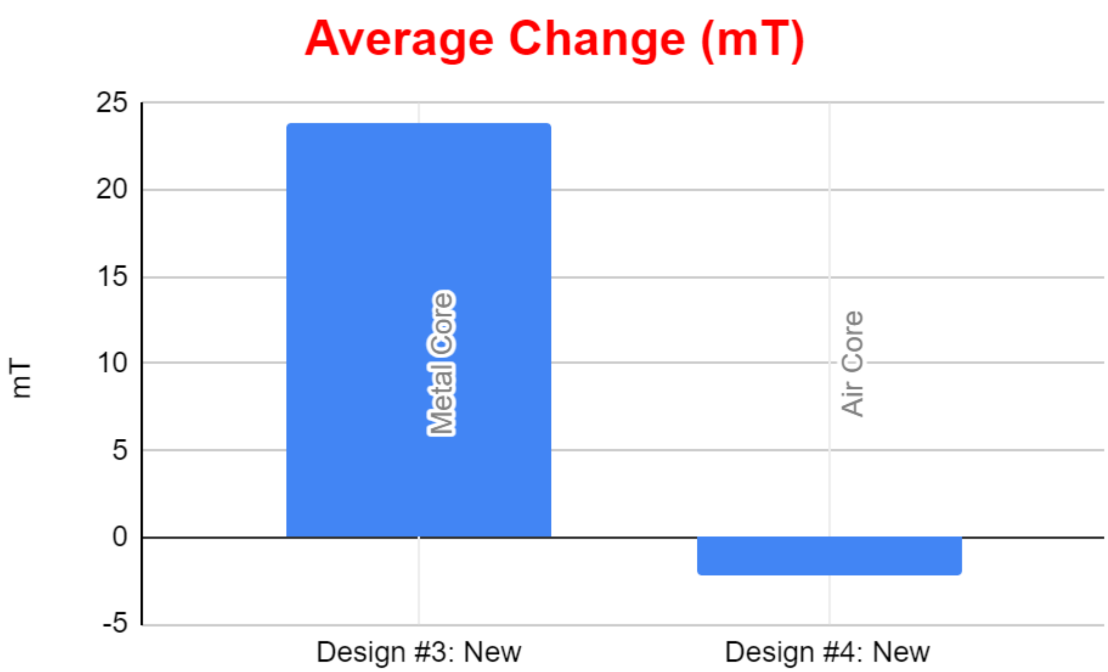

Figure 10: Single Magnet Set, Air vs Metal Core Average Change (mT).

Table 4: Single Set, Air vs Metal Core Parameter Table.

							Change (mT)			
Design #	Design	Format	Magnet	Type	Core	Position	Change A	Change B	Change C	Average
3	New	Single Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	37.03	22.97	11.77	23.92
4	New	Single Magnet Set	Neodymium	N52	Air	(Y1-Y2)	-9.302	2.8624	-0.01119	-2.15

The initial observations suggest that pickups with a metal core outperform their air core counterparts. The metal core appears to address the flux leakage experienced in air core pickups, making it a promising solution to counteract these inefficiencies together with making the bobbin shorter in length compared to the traditional design. The metal core's ability to enhance the guidance of magnetic flux through the coil contributes to improved performance, demonstrating its potential as a viable and beneficial component in pickup design with the added benefit of potentially reducing the number of windings in the coil and compensating it with a higher $d\Phi$.

Finding: Single vs Dual Magnet Set Archetype

In the context of comparing single-set versus dual-set magnets in pickups, it becomes apparent that the magnetic field is stronger in dual-set pickups, particularly as it approaches the bottom magnets, which aligns with the expectations. However, an interesting observation emerges when assessing the magnetic flux change: it is not necessarily stronger in the dual-set magnet configuration. This is important because it means that even though the magnetic flux density is larger all across the board in the dual magnet set pickup, increasing the number of magnets or changing its configuration to having more magnets at the bottom it doesn’t necessarily means that the pickup is going to perform any better or like in this case, it could perform worse. This, however, could also be affected by the bobbin geometry, if the coil is any longer than in the 3D model, having another set of magnets at the bottom could help.

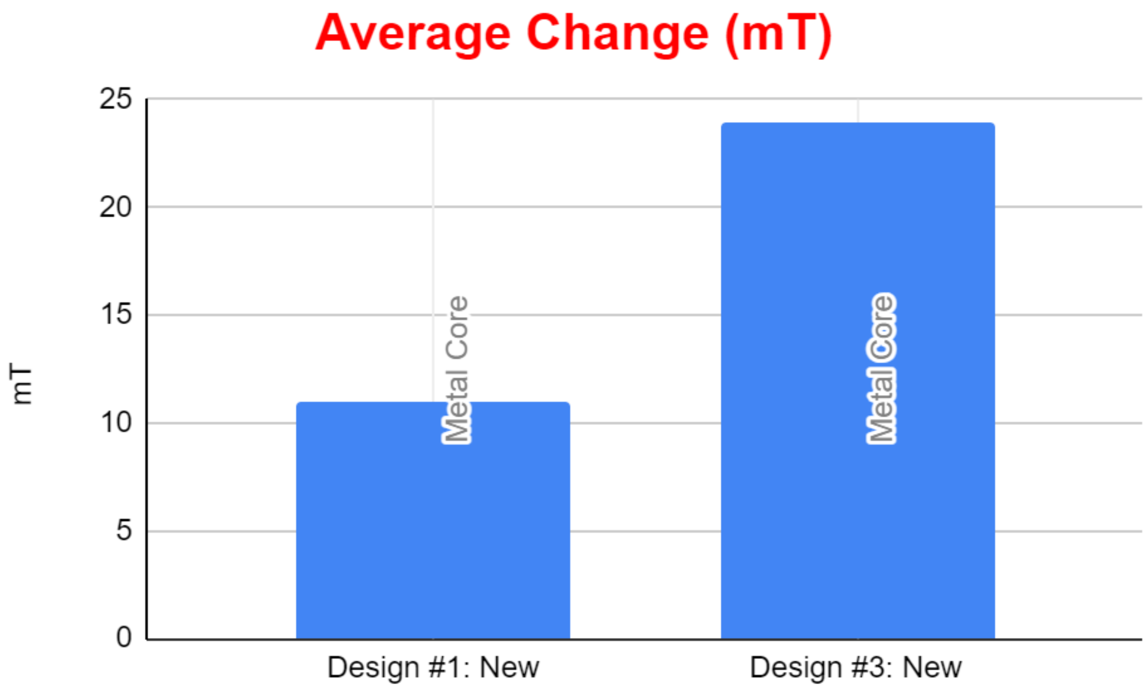

Figure 11: Single vs Dual Magnet Set Design Average Change.

Table 5: Single vs Dual Magnet Set Parameter Table.

							Change (mT)			
Design #	Design	Format	Magnet	Type	Core	Position	Change A	Change B	Change C	Average
1	New	Dual Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	26.16	5.9	0.83	10.96
3	New	Single Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	37.03	22.97	11.77	23.92

Surprisingly, the single-set metal core pickup exhibits a noteworthy advantage overall. Despite the anticipated increase in magnetic field in the double-set configuration, the rate of change in the magnetic flux with respect to string movement does not exhibit a corresponding increase. This insight leads to the conclusion that the single-set metal core pickup appears to be the more efficient and effective choice, offering robust magnetic characteristics without incurring the additional expense associated with incorporating another set of magnets at the bottom.

Finding: Traditional vs New Design Archetype

The Proposed design #3 combines Neodymium's inherent low permeability by integrating these magnets with a high-permeability 1010 steel metal core. This combination leverages Neodymium's magnetic potency and strong demagnetization properties with a high permeability metal core, ensuring efficient magnetization and guide of the magnetic flux density through the complete coil. Now comparing the best performing new design (#3) and the traditional design (#5) from the simulated results, notable differences emerge. Design #3, featuring Neodymium N52 magnets with a 2x12 mm metal core showcases a remarkable average rate of change of 23.92 mT. Across all cross sections (A, B, C), the magnetic flux variation is consistently higher with values through each cross-section A, B, C being 37.03 mT, 22.97 mT, and 11.77 mT respectively. In contrast, Design #5, employing Alnico V magnets with a metal core in the same position, exhibits a lower average rate of change at 0.77 mT. The magnetic flux variations in cross sections A (2.552 mT), B (0.058 mT), and C (-0.293 mT) are notably less pronounced.

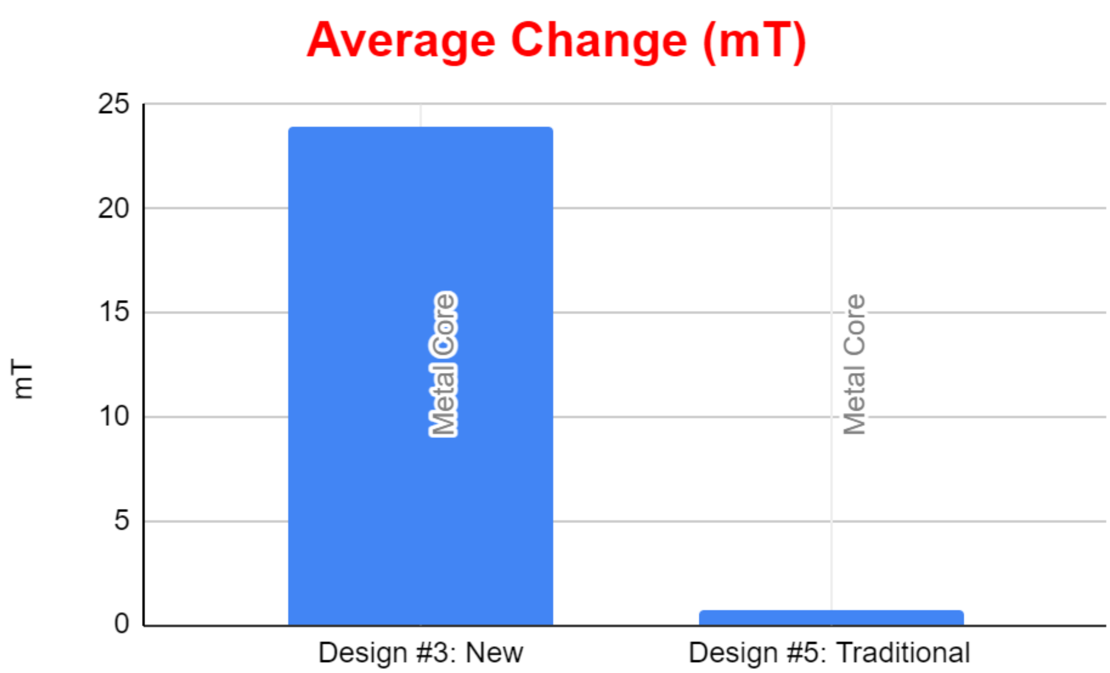

Figure 12: Traditional vs New Design Average Change.

Table 6: Traditional vs New Design Parameter Comparison Table.

							Change (mT)			
Design #	Design	Format	Magnet	Type	Core	Position	Change A	Change B	Change C	Average
3	New	Single Magnet Set	Neodymium	N52	Metal	(Y1-Y2)	37.03	22.97	11.77	23.92
5	Traditional	Rod Magnet Set	Alnico	V	Metal	(Y1-Y2)	2.552	0.058	-0.293	0.77

This analysis highlights the superiority of Design #3, emphasizing the impact of Neodymium N52 magnets in achieving a more potent and consistent magnetic flux change across all cross sections. The higher magnetic strength of neodymium contributes to the enhanced performance of the guitar pickup system when compared to the traditional Alnico V pickup of Design #5.

Expected Output Computations- In this segment, the projected output of the pickup will be calculated utilizing the equations formulated in "Chapter IV: Theory," in conjunction with the results obtained from simulating Design #3 (Single Magnet Set - Neodymium N52 - Metal Core). Design #3 stands out as our best performing pickup and serves as the foundational model for the physical prototype.

As explained previously in this chapter, because it’s not feasible to obtain the magnetic flux density values for each of the coil windings, the change in flux density will be averaged using the three cross-sections (A-C) to approximately assess comprehensive the pickup overall sensibility.

$$Avg\ dB = \ 0.0239\ T$$

When calculating the rate of change of the magnetic flux with respect to the string position ($\frac{d\Phi}{dy}$) the core area will be the parameter taken into consideration. This is because the field is concentrated within the cores and not within the extended coil area.

$$Effective\ Area = (Number\ of\ Cores)\ x\ \pi\ x\ (Core\ Radious)^2 = 6\ x\ \pi\ x\ .001^2$$

$$= 1.8x10^{-5}m^2$$

$$d\Phi = dB\ x\ E.Area = .0239\ T\ x\ 1.8x10^{-5}m^2 = 4.5x10^{-7}Wb$$

$$\frac{d\Phi}{dy} = \left(\frac{4.5x10^{-7}}{.001}\right) = 4.5x10^{-4}\ Wb/m^2$$

The string velocity was approximated by measuring the string displacement distance and its estimated period T, the period is calculated by its formula $T = {}^{1}/_{f}$. The frequency chosen for the experiment is 85.5Hz and the string displacement dy measured roughly 3mm.

$$\frac{dy}{dt} = \frac{.003}{(\frac{T}{2})} = .003\ x\ 85.5\ x\ 2 = .51\ m/s$$

The induced voltage is computed by multiplying the rate of change of the magnetic flux with respect to the string position ($d\Phi/dy$) by the velocity of the string (dy/dt). The resulting induced voltage approximates the average voltage induced per coil winding.

$$Induced\ Voltage = \frac{d\Phi}{dy}\ x\ \frac{dy}{dt} = 2.3x10^{-4}\ Volts\ per\ turn$$

The total induced voltage is dependent on the number of coil windings. In this case, the number of turns significantly influences the resulting output voltage of the guitar pickup. For this computation a value of 1200 coil windings will be utilized, as it is the estimated number of turns for the physical prototype. The result is then multiplied by 2, considering we are dealing with a peak-to-peak voltage. It's important to note that the number of turns can vary depending on the specific pickup design.

$$Total\ Induced\ Voltage = Coil\ Windings\ x\ Volts\ per\ Turn\ = 1200\ x\ 2.3x10^{-4} =\ 276\ mV$$

$$Pickup\ Output\ Voltage = V_{pk-pk} = 276\ x\ 2 = 552\ mV_{pk-pk}$$

CHAPTER VI

NEW DESIGN PHYSICAL PROTOTYPE DEVELOPMENT

This chapter delves into the implementation of the theoretical models developed in this thesis, focusing on the creation of a physical prototype for a modern guitar pickup having as a foundation the mathematical equations and the simulation results explored from the previous chapters. 3D printing, soldering, and the development of a coil winder were necessary to bring a prototype to life. Fusion 360 was the software used for the 3D modeling of the guitar pickup bobbins, the coil winder structure, and the copper wire feeding system. They were printed on a Prusa MK3S+. Accompanying this chapter is a visual showcase, featuring images of the 3D model of the coil winder, the physical coil winder, the feeding systems, and the jig designed for testing purposes. These visuals offer a comprehensive overview of the physical process of the development and testing of the guitar pickup.

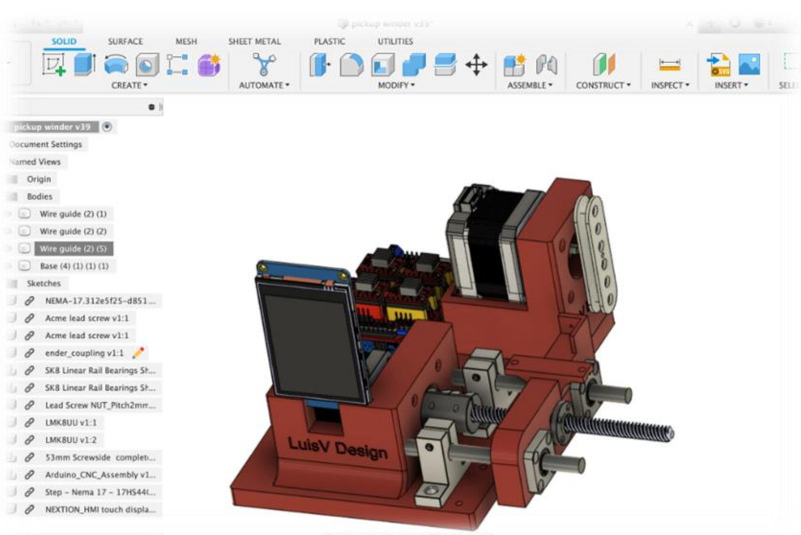

Figure 13: Coil Winder Design 3D Model.

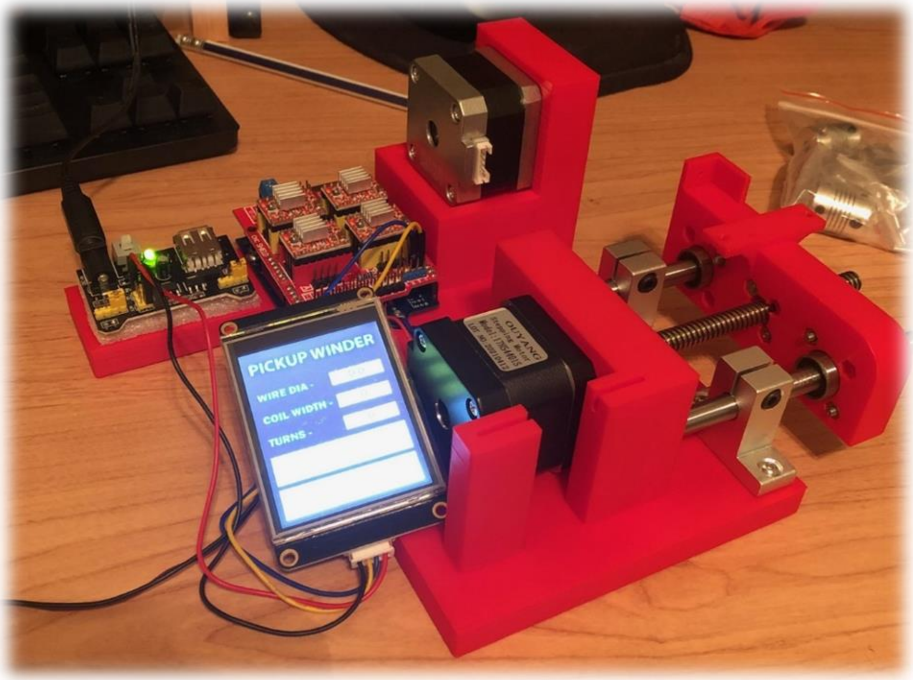

Figure 14: Coil Winder 1st Prototype.

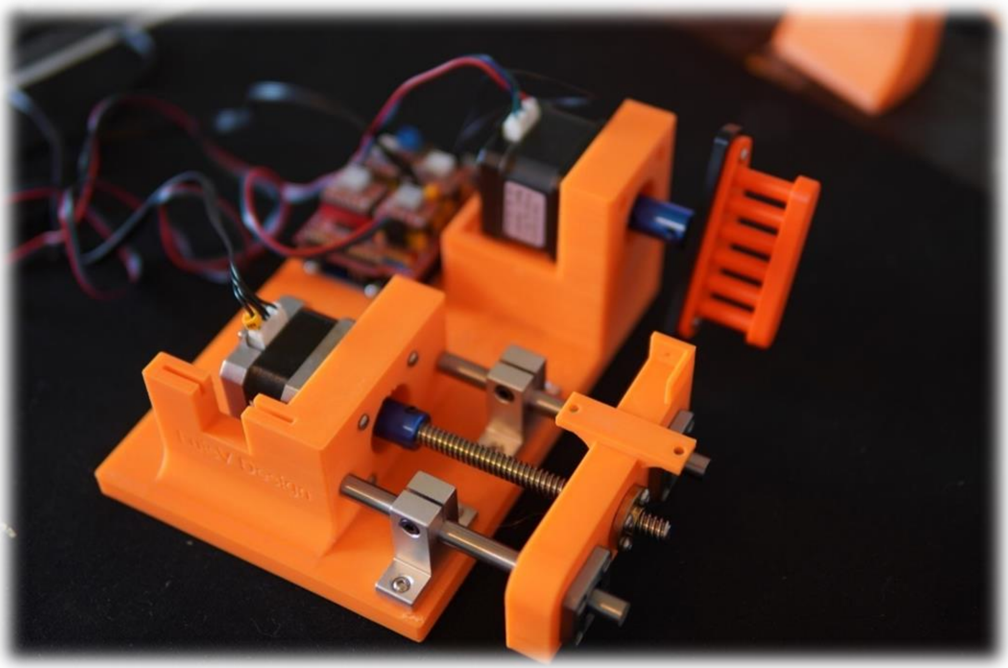

Figure 15: Coil Winder 2nd Prototype.

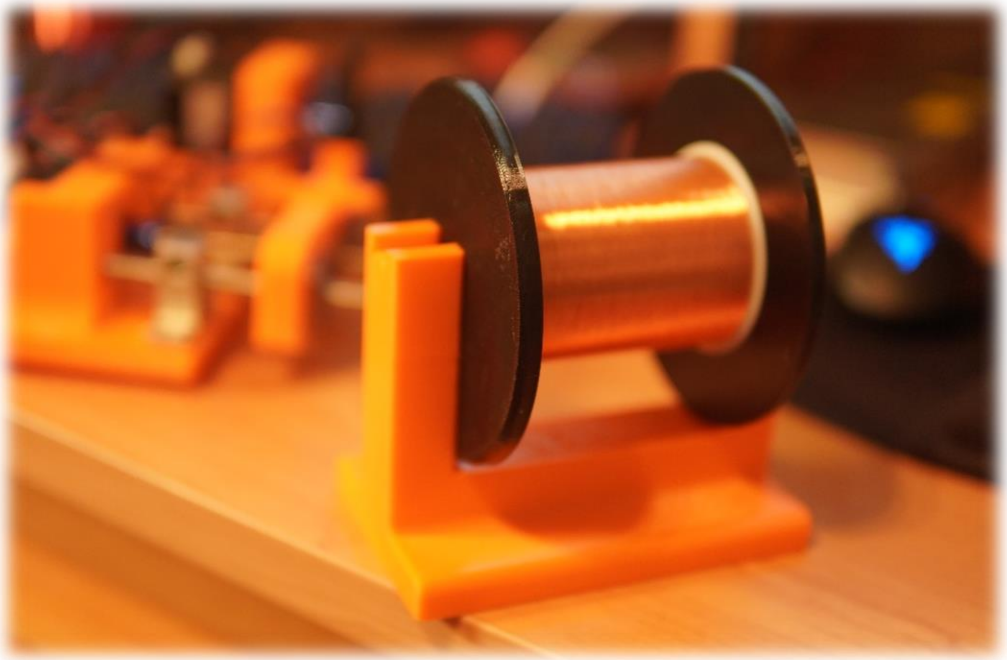

Figure 16: Copper Wire Feeding System.

Prototype Characteristics and Dimensions

The prototype, based on Design #3 from Chapter 5 “Electromagnetic Simulations” (Single Magnet Set - Neodymium N52 - Metal Core), showed new features. The coil measured 50.8mm in length, 17.8mm in width, and 12mm in height. The N52 Neodymium magnet, crucial to the design, has dimensions of 7mm in diameter by 2mm in height, and an estimated 1200-1850 coil windings with a DC Resistance of 1.5K Ohms. The metal core boasts a diameter of 2mm and a length of 25mm. Note that certain limitations arose during the physical implementation, mostly regarding the number of coil windings and the unavailability of 1010 steel for the intended material of the metal core as well as the intended dimensions of 2mm x 12mm. This could cause slight deviations.

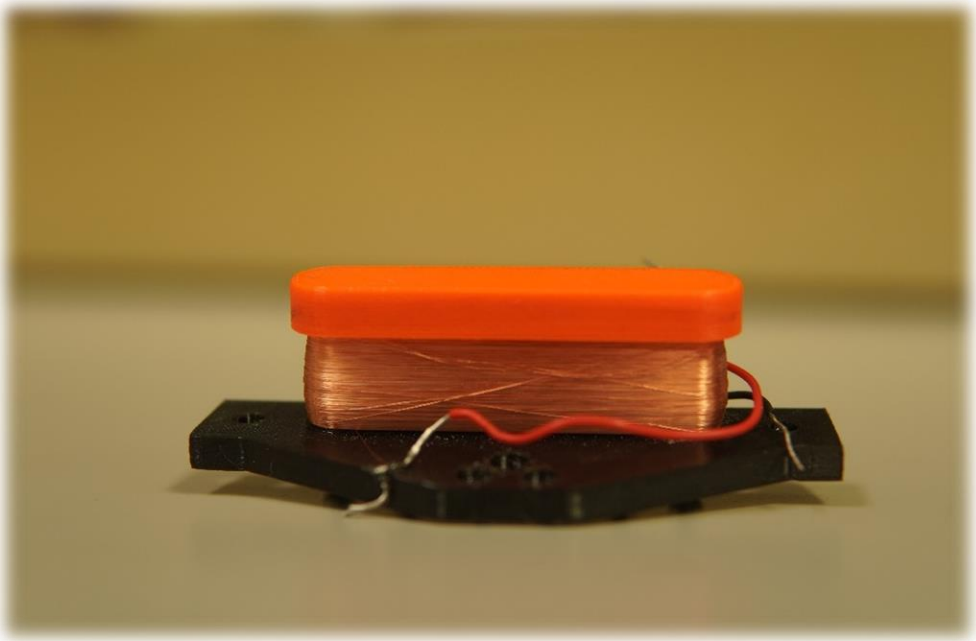

Figure 17: Guitar Pickup Prototype. New Design. Based on Design #3.

Testing and Validation

To validate the performance of the prototype, a jig was constructed for controlled testing conditions. The physical guitar pickup was connected to a Tektronix TBS1202C oscilloscope for comprehensive testing. This test provided valuable insights into the real-world behavior of the prototype.

Figure 18: Electric Guitar Jig Testing.

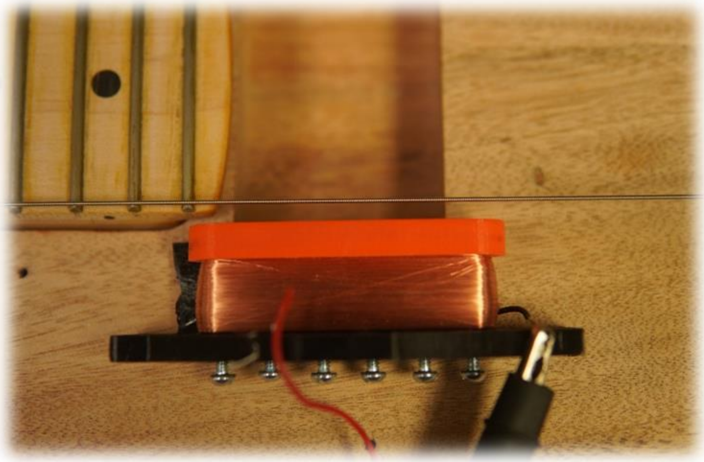

Figure 19: Prototype Pickup Testing.

The testing of the pickup horizontally alongside the string is to engage all six cores emulating a strumming of the six electric guitar strings. It was placed perpendicular to the movement of the string to get the full effect of the magnetic flux in a normal electric guitar set up.

Physical Pickup Waveforms and Low Pass Filtering Effects

The waveform results from the experimental guitar pickup, showcasing a peak-to-peak voltage of 368mV at a frequency of 85.5 Hz, the snapshots of the oscilloscope offer valuable insights into the electrical performance of the design. This measurement reflects the response of the pickup to the movement of the guitar string, aligning with the principles of Faraday's law. The induced voltage, a consequence of the changing magnetic field due to string movement, provides a quantitative representation of the pickup's ability to convert the string movement into an electrical signal.

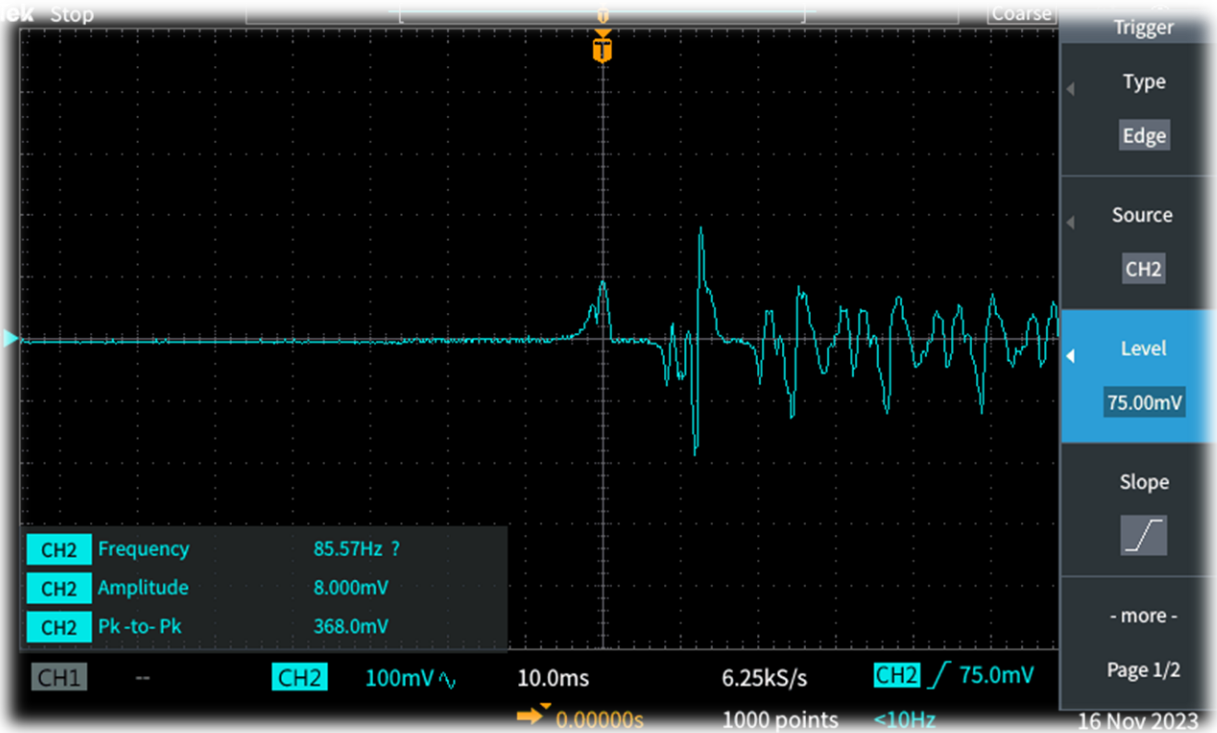

Figure 20: Guitar Pickup Prototype Oscilloscope Waveform Results.

The DC resistance of the experimental pickup, recorded at 1.5K ohms (1200-1850 coil windings) is a crucial parameter influencing its tonal characteristics. A lower DC resistance often correlates with a brighter and more cost-efficient pickup. Comparing these results to traditional Alnico V single-coil or humbucker designs, a noteworthy consideration is the peak-to-peak voltage or the output of the pickup. Traditional pickups such as some humbucker designs may reach voltages of 300mV, but they require 10,000 or more coil windings or an elevated DC resistance (10k+ Ohms) to achieve such levels. It's essential to be aware that increasing the coil windings or DC resistance will introduce a higher number of lower frequencies into the output signal due to the guitar pickup low pass filtering characteristics.

The low pass filtering nature of guitar pickups means that as the coil windings or DC resistance increases, an increased amount of lower frequencies are allowed into the output signal.

This alteration impacts the tonal performance, potentially increasing the bass response but also affecting the electric guitar ability to perform its role effectively as the guitar signal could overlap or mix with other instruments in band setting such as bass guitars, a kick drum, or the lower notes of a piano. Therefore, the experimental pickup's design featuring a lower DC resistance while still maintaining a strong peak to peak voltage output represents an effective approach to balancing tonal characteristics and power, offering a lot more flexibility in comparison to traditional designs as there still a lot of room to increase the number of turns with the new design.

Deviations: Simulation vs Physical Prototype

In comparing the simulated and real-world performance of two guitar pickups based on design #3, we observe a deviation in peak-to-peak voltage values. The simulated output registered at $552mV_{pk-pk}$, while the real-world experiment yielded $368mV_{pk-pk}$. The primary factor that could be contributing to this disparity is the number of coil windings. The simulated pickup adheres strictly to a predefined winding count, while the real-world experiment introduces some level unpredictability, in part from limitations encountered during the development winder and the motors skipping steps, potentially leading to a discrepancy in the winding numbers. In this instance, the actual number of coil windings in the physical prototype may be significantly less than the simulated value. Nevertheless, it is essential to recognize that despite the limitations with the coil winder the new pickup design not only demonstrated functionality but also outperformed the traditional Alnico V design by a substantial margin, highlighting its promising potential in the realm of guitar pickups.

CHAPTER VII

CONCLUSION

This thesis embarked on a transformative exploration of guitar pickups, driven by the aspiration to modernize their design and transcend the industry's tradition. The journey culminates in a resounding backing of modern prototyping tools such as electromagnetic software, additive manufacturing, as well as the understanding of electromagnetic theory and the development of new mathematical equations for guitar pickups.

Central to this thesis's findings is the revelation regarding a new design, referred to in this thesis as the “Single Set Metal Core Pickup” employing N52 Neodymium Magnets. This design not only showcased superior efficiency but also demonstrated significant cost advantages over the traditional counterparts. The embrace of new materials and design principles positions this new approach as a promising leap forward in the evolution of guitar pickups. The efficiency gains and cost-effectiveness observed in the simulations and the physical prototype lend empirical support to the thesis's overarching argument of establishing the foundations of modern guitar pickup theory and provide guidelines for contemporary pickup design.

Although this thesis research provides a solid foundation, there are promising directions for future work. First improving the reliability of the guitar pickup prototype to be able to withstand continuous use on an electric guitar. Another promising avenue of future work includes the research of other core and magnetic materials to better understand their impact on the pickup's performance. This could include exploring different alloys, composites, or materials with unique electromagnetic properties.

As this thesis draws to a close, it leaves a resonant call for the guitar industry and the guitar community to embrace change. Through research and practical experiments, this thesis aspires to pave the way for a new era in guitar pickup design, one that acknowledges tradition but embraces the limitless possibilities of advancements in technology.

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BIOGRAPHICAL SKETCH

Luis A. Villarreal holds a bachelor's degree in electrical engineering, which he earned in May 2017 from the University of Texas at Rio Grande Valley and a master's degree in electrical engineering from the same institution, obtained in December 2023. Alongside his academic pursuits, Luis's professional journey spans across diverse industries, including electrical, aerospace, and automotive. This broad range of experiences has equipped him with a comprehensive understanding of engineering applications and challenges.

Beyond his engineering endeavors, Luis has nurtured a lifelong passion for playing the electric guitar, a pursuit that began in childhood. This enduring interest has not only enriched his personal life but has also found expression serving as the lead guitarist for the Baptist Student Ministry at UTRGV, showcasing his walk with God, love for music, and his passion for engineering. Luis's story is one of continuous growth, where academic pursuits, professional endeavors, and personal passions converge. Contact: Luis.A.Villarreal02@utrgv.edu