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Concept Design for Low Noise, Highly Isolated, Single-String Pickups

Purpose

This design is made with the goal of creating a magnetic pickup for the electric guitar that is solely dedicated to receiving the signals from a single guitar string (that is, the string situated directly above the small pickup). The pickup will be isolated from the interfering signals of the other strings, as well as from external electromagnetic noise originating from such places as the power cables of an amplifier. To this end, the design will consist of a small pair of coils and permanent magnets in anti-parallel 'humbucker' configuration, connected in series with magnetic shielding around the sides of each coil. The incentive to channel the isolated signal of a single string is to be able to send individual signals through a multi-channeled audio jack and conduct signal processing on the musical contributions of each guitar string. While the design was made with the electric guitar in mind, the technology involved applies generally to electrical string instruments.

Background

The standard magnetic pickup coil (shown in figure 1) houses one to two permanent magnets or magnet protrusions per string, usually made of AlNiCo or NdFeB (Neodynium). The magnet(s) are set under a portion of the guitar string. Electrical guitar strings consist of iron or nickel alloys, allowing a portion of the string above the magnet to become magnetized.

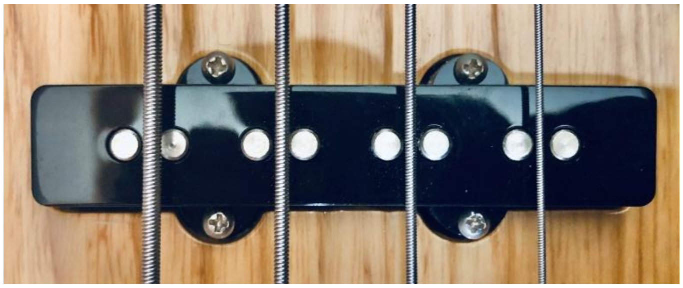

Figure 1: Conventional Electric Base Pickup

After the strings are plucked and henceforth vibrating, they emit changes or 'waves' from their induced magnetic fields with the same frequency as their own vibrations. These changes in the magnetic field are "picked up" by the wound conductive coil, whose cross section encompasses all instrument strings (in the picture the coil is covered by the plastic case). The changing magnetic field induces a voltage across the pickup coil, which is connected to a filter and preamp circuit within the guitar body. The magnetic coupling of the oscillating magnetized strings to the inductive copper coil thereby acts as the source of the signal for the electric-to-audio circuit of the instrument.

The conductive coil does not respond only to the magnetic waves emitted by the oscillating strings. It also receives signals originating from other sources, such as the AC voltage driving a power cable, microwaves emitted in a WIFI network, or RF waves from a radio broadcast. The "humbucker" design (shown in figure two) is meant to cancel out external signals, particularly the 60 HZ power that is in the range of the human hearing, while increasing reception of the signal produced by the strings. It instead utilizes two coils connected in series and two anti-parallel magnets per string.

Figure 2: Conventional "Humbucker" Pickup

'Antiparallel' is meant to indicate that one magnet has its north pole pointing in one direction and the other has its north pole pointing in the opposite direction. The coils must also be wired in series accordingly so that their voltages add when receiving signals from the string, but subtract when receiving noise.

The Single String Pickup

Major Components

The pickup is designed to receive the signal of an individual string, and must therefore be small on the order of 1cm in diameter, so that its coils do not overlap with any other strings. The primary components of the pickup include the "hard" (AlNiCo or NdFeB) magnet, the core, and the copper coils. The core is designed to contain an extruded cylindrical platform to house the magnet, and the copper wiring is wound around the core, forming a solenoidal inductor. It is standard for inductive elements to contain a core of permeable ferromagnetic material. However, such a core would not be suitable for two reasons. First, the nearby presence of the strong permanent will saturate most magnetically susceptible materials, vastly decreasing its permeability (μ) and thereby nullifying its purpose as an inductive core. Second, even with a material with a very high saturation threshold, there would still be a strong attractive force between the permanent magnet and the ferromagnet, once they were brought near one another. This would pose the mechanical challenge of securing the magnet and ferromagnetic core inside of the pickup in the proper orientation. Instead, a material without magnetic susceptibility is necessary.

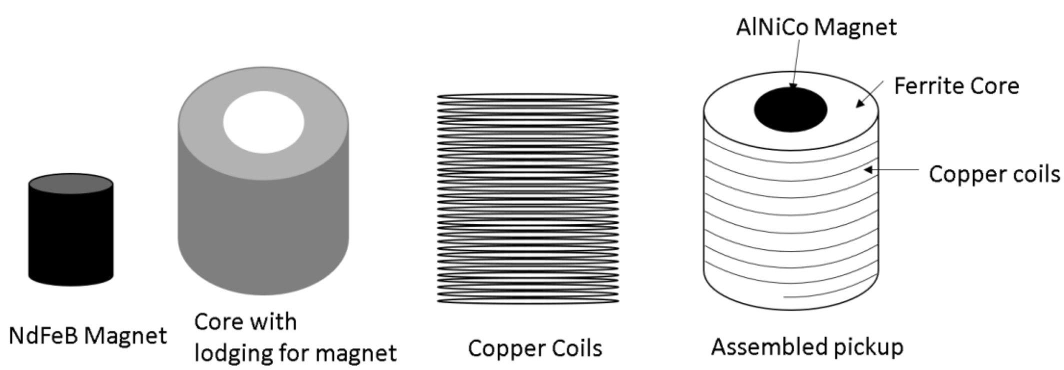

Figure 3: Major components of the pickup

The field from the AlNiCo magnet is the magnetization source for the strings on the instrument. The surface of the copper wiring is insulated (commonly termed magnet-wire) so that the coils form conductive loops instead of a conductive cylindrical surface.

Magnetic Shielding

A smaller inductor does not alone isolate the pickup from the magnetic fields of the other five strings. A strategy to increase signal isolation is to incorporate magnetic shielding around the sides of the pickup coil. A nickel alloy shell as show in in figure 4 can be used to isolate the pickup coil from the magnetic fields of the other magnetized guitar strings, as well as from the fields of environmental electromagnetic noise. The Nu series modular pickups [2] employ permalloy, a nickel iron-alloy (80% Ni, 20% Fe) often used in magnetic shielding applications. The image on the right illustrates how the flow lines of the magnetic field are directed along the curvature of the shield.

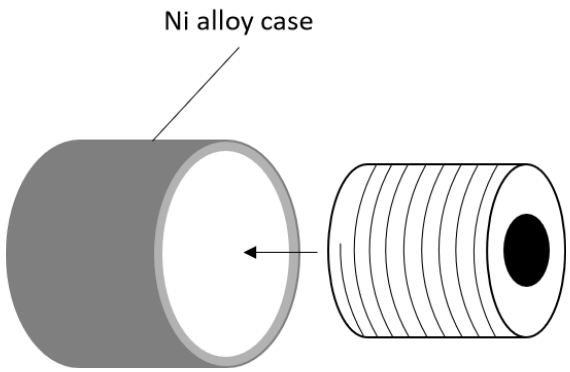

Figure 4: Magnetic shielding. Note that the top and bottom faces are unbounded.

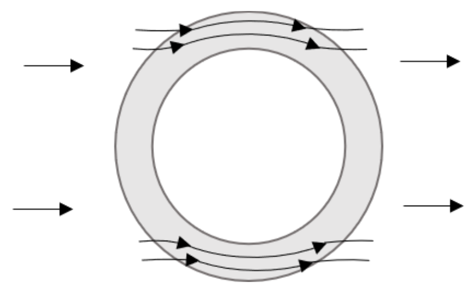

Figure 5: Top view with magnetic flow lines

Nickel and Iron alloys are appropriate materials for magnetic shielding because they have high magnetic permeabilities. Raw nickel has a relative permeability of near 100[1], raw iron near 200, and the particular atomic crystal structures in permalloy (achieved through specific heat treatment) provide it a relative permeability of near 8000 times greater than air[3]. A similar alternative to permalloy is mu-metal, which adds copper and chromium impurities to the nickel and iron to improve ductility. Attenuation of magnetic field strength within a bounded region increases proportionally with the relative permeability of the boundary material [4]. The specimen's thickness also contributes to its shielding capabilities. The effectiveness of the magnetic shielding is limited in that cannot be completely closed. The caps of the cylindrical pickup must remain unimpeded by the shielding material, as the pickup must be able to exchange ample magnetic flux with the guitar string. It must also be noted that shielding materials can be magnetized by the magnets present in each pickup, resulting in a reduction of their magnetic permeability, and hence their shielding capability. This interaction will be at a further distance than the previously discussed core, so the issues of saturation and magnetic force will be less prevalent.

Two-Coil Anti-Parallel Configuration

(figure 6) The two magnets are oriented opposite one another, one with its north pole facing the steel string, the other with its north pole pointing away from the string. The two antiparallel dipoles form a magnetic quadrupole. The magnets will locally magnetize the iron in the steel guitar string. The inductors generate a voltage in response to a changing magnetic field, the source being the oscillating magnetized string. The two coils are connected in series.

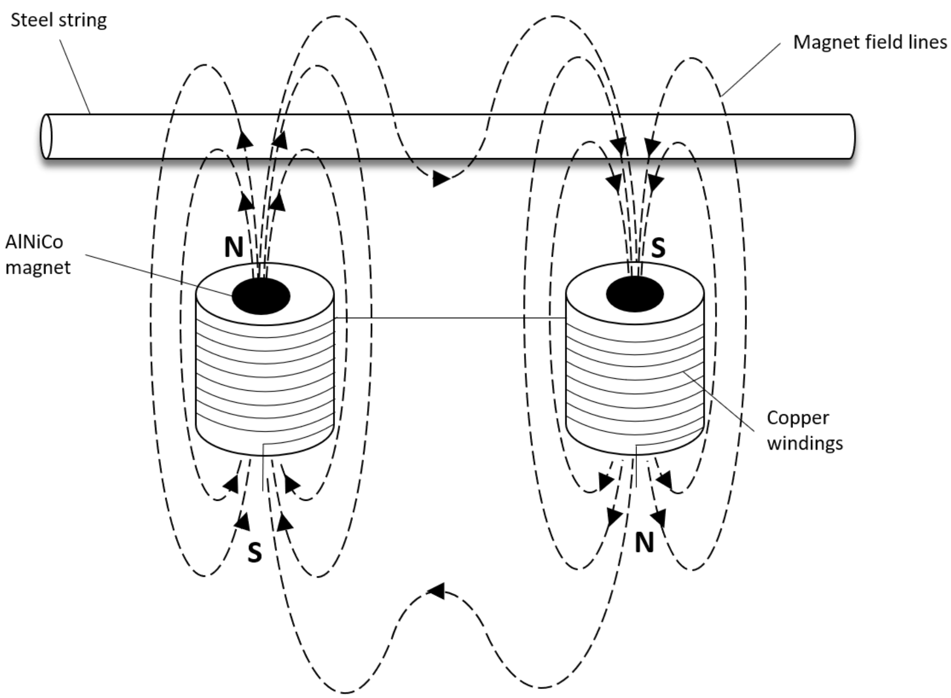

Figure 6: Magnetic Field Lines of Quadrupole Pickup

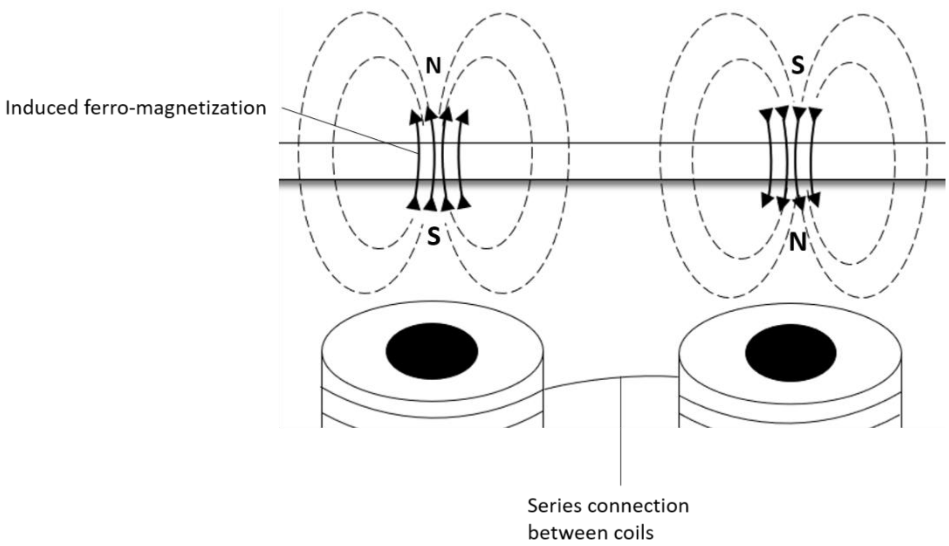

Figure 7: Magnetization of Guitar String

The two portions of the string are magnetized oppositely, forming antiparallel dipoles, also considered a quadrupole. As they are close together, their effects on objects further away will tend to cancel. However, objects in proximity (such as the copper coils) will dominantly experience the portion of magnetized string directly above them.

The strength of an induced magnetic dipole in a magnetically permeable material, in this case the steel or nickel strings of the guitar, depends the strength of the imposing magnetic field, coming from the permanent magnet in the pickup. Since the magnetic field strength of a dipole decreases proportionally with the distance cubed ($1/r^3$) [5], the magnetization of the string is effectively a local phenomenon, occurring on a small portion of the string above the magnet. At points at relatively far distances from the space between the induced quadrupole, the magnetic field strength of the quadrupole decreases with $1/r^4$ [5]. This means that the magnetic moments on the steel guitar string have less of an effect on pickup coils other than the oner directly below it.

The two-coil humbucker configuration causes the voltages of the two coils to add when receiving magnetic waves generated by the string, while the voltages generated from most electromagnetic noise entering the open the cross sections of the coils will cancel. This result can be explained of with close examination of Faraday's Law of electromagnetic induction applied to the pickup-system.

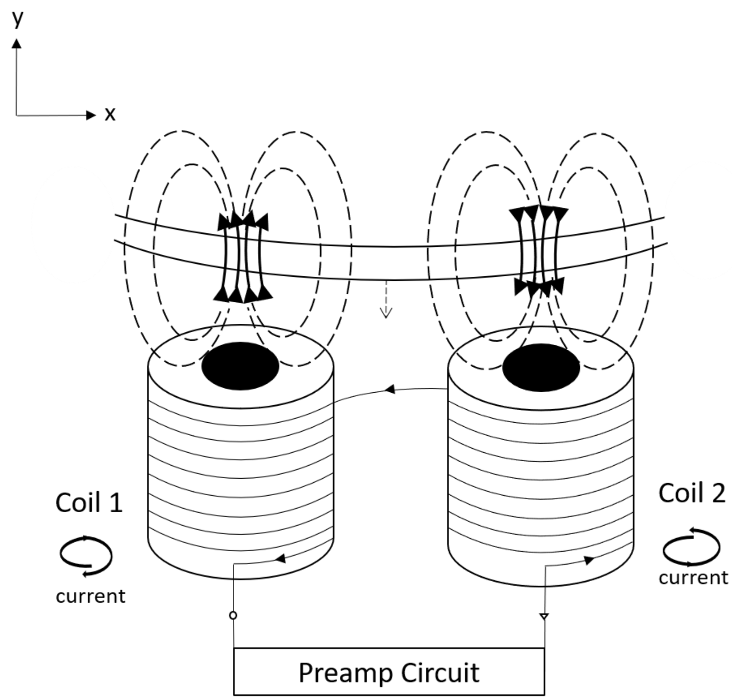

Figure 8: Analysis of two-coil, quadrupole pickup

Take the case where the string's motion is downward, as shown in figure 8. The magnetic flux through coil 1 is increasing in the +y direction, while the flux through coil 2 is increasing in the –y direction. This means that the loops of coil 1 will have an induced voltage clockwise, driving current downward across coil 1. The induced voltage across the loops of coil 2 will be counter-clockwise, driving current upward across coil 2. This means that the voltages generated by coils 1 and 2 will add constructively, due to the series connection being between the upper loops of both coils.

Now take the case where an electromagnetic wave passes through the coils, but its wavelength is longer than the distance between the coils. Now the magnetic flux through the loops of both coils will be changing in the same direction, so the induced voltages will add destructively (cancel).

Spacing

In the event that ideal isolation between strings and other pickups is not achieved, the spacing between the pickups can be increased. The illustration below shows two methods for increasing the spacing between pickups. With a magnetic quadrupole pickup, the field strength decreases with $1/r^4$. It should be noted that the frequency response of the string can vary across different points along the length of the string, and it is often desired to have one set of pickups positioned near the neck of the guitar and another positioned near the bridge of the guitar.

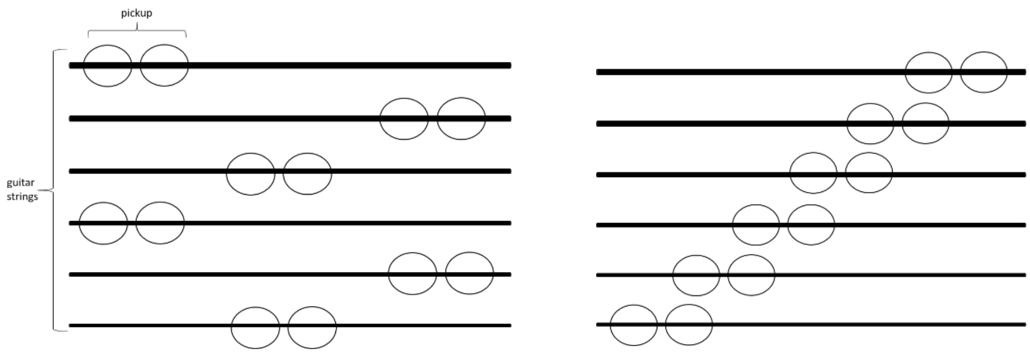

Figure 9: Examples of increasing the distance between pickups

Reception Efficiency

The smaller inductive area of the single-string pickup means less power transfer between the string and the pickup, resulting in a weaker signal. To increase the inductance of the pickup coil, more windings are necessary, and thus a smaller wire gauge is used. This leads to a greater resistance of the coil. The Nu series uses 46 AWG magnet wire with a total resistance of 400Ω and 1300 turns. A design with two coils, keeping the length of each pickup the same and requiring the same number of total turns, allows for the wire thickness to be doubled. This halves the resistance. Having two coils also increases the energy transfer between the strings and the pickup. Overall, the signal strength generated from the two-coil-system will be stronger than that of the single-coil.

Conclusion

The two coil, antiparallel dipole configuration with magnetic shielding affords an ultra-low-noise pickup system that is isolated to the signal contribution of a single magnetized string. The smaller coil size will generate a weaker signal than that of a conventional pickup, although having two coils will improve signal reception compared to one coil. The pickups can be positioned in line as normal, or spaced farther apart if more isolation is required.

References

[1] GSU.edu. “Hyperphysics”. http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html

[2] Cycfi Technologies. “Nu Series Modular Pickups”. https://www.cycfi.com/store/

[3] H.D. Arnold, G.W. Elmen, Permalloy, an alloy of remarkable magnetic properties, Journal of the Franklin Institute, Volume 195, Issue 5,1923,Pages 621-632, ISSN 0016-0032, https://doi.org/10.1016/S0016-0032(23)90114-6. (http://www.sciencedirect.com/science/article/pii/S0016003223901146)

[4] J.D. Jackson, *Classical Electrodynamics*, 2nd edition. Wiley, 1975.

Original patent application by Arnold Lesti for two coil, two dipole pickup system: https://docs.google.com/viewer?url=patentimages.storage.googleapis.com/pdfs/USRE20070.pdf

This means that placing the pickups farther apart decreases the field strength of magnetized strings on other pickup coils, for the same reason that a magnetic dipole strength decreases with $1/\mathbf{r}^4$.

Placing pickup coils farther apart, however, causes complications with the sound of the string, since the mechanical vibrations of the string differ across points along the length of the strings. It also requires non-conventional slots for the pickups to be cut on the bridge of the guitar.

One strategy to accomplish this is to position the pickups farther away from each other on the bridge of the guitar, as opposed to the conventional 6-string pickup that places it magnets in a line perpendicular to the strings.

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html

[2] H.D. Arnold, G.W. Elmen,Permalloy, an alloy of remarkable magnetic properties, Journal of the Franklin Institute,Volume 195, Issue 5,1923,Pages 621-632, ISSN 0016-0032,

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