The Les Paul Electromechanical Pickup (D 2021)

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Abstract

As part of the Magnetic Transducer Innovations ISP in D 2021 we designed and built the first known prototype of the Les Paul Electromechanical Pickup. The pickup was designed based on Les Paul's patent and further adapted to modern day technological capabilities, going through numerous iterations and prototypes before a finalized pickup was tested and producing a signal. The following report documents each stage of the design process, manufacturing, and testing of the pickup. Special thanks to VJ Manzo, Scott Barton, Bob Palmieri, James Loiselle, Ian Anderson, Mitra Anand, and Robert Peralta for their valuable assistance and guidance for the duration of this project.

Background

This project was inspired by the 1959 patent by Les Paul for a magnetic pickup that, as a primary mode of generating signal, couples the motion of the string to that of the pickup's coil or magnetic core. While conventional pickups use the induced magnetization in the steel-nickel strings as the source for a varying magnetic field, Les Paul's invention proposed moving the pickup coil through the field created by the pickup's magnetic core. As seen in figures 2 and 3 of the patent, the guitar strings are notched into grooves on the pickup frame, and the nearby tailpiece of the guitar pinches the strings inward to tightly fit the strings in the grooves. In this way the pickup plays dual roles in the guitar, as mentioned as a generator of electric signal, but also as a bridge piece for the strings. Given a suitable method of suspending the pickup coil and separating its motional freedom from that of the pickup's magnets (not enumerated in the patent), string vibrations would be transferred to the pickup coil.

The primary deliverable of this project was to realize the essence of Les Paul's patent, making changes where necessary, but following close to the original design to remain within the scope of the patent. Auxiliary to this objective was the creation of a bill of materials and report to document the design process and propose steps for the continuation of the project.

Initial Designs

The design of this pickup went through many different iterations. As we referenced the patent, we tried to replicate the design outlined by Les Paul, which included a flexible substrate fixed to a base plate underneath the bobbin, causing the strings to force the pickup downwards. This model has the strings attached to the yoke by the tension of the strings exerting a force downwards, as well as a break angle from the yoke to the tailpiece. The bobbin moves relative to the fixed magnets on a base plate in this model. Examples of bobbins with different yoke types for this case are shown below in Figures 1 and 2.

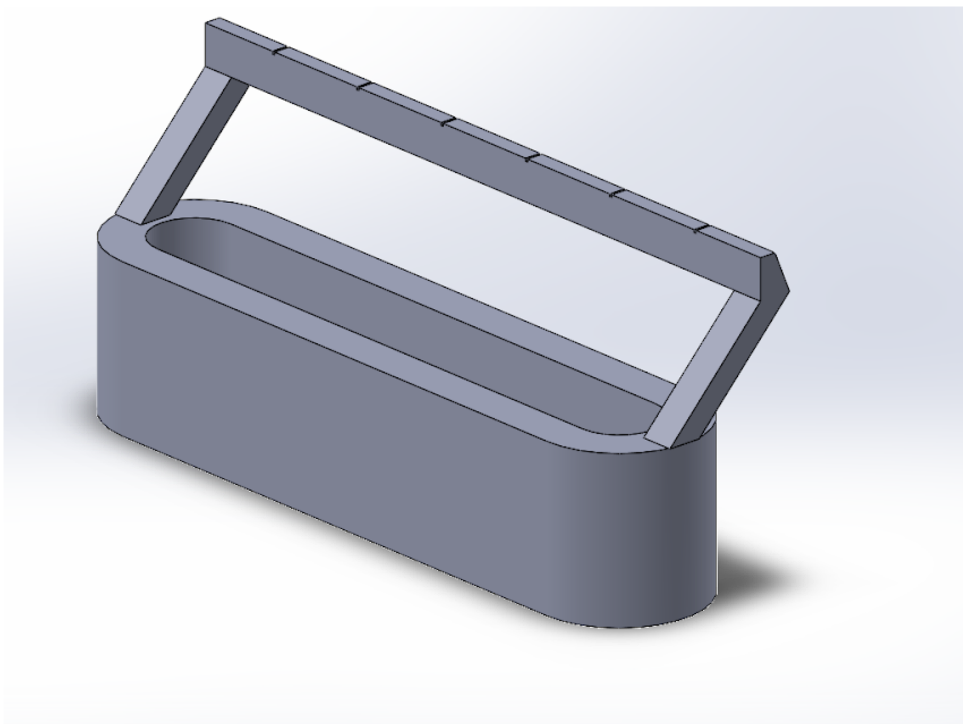


Figure 1: Initial design 1 with notches for strings.

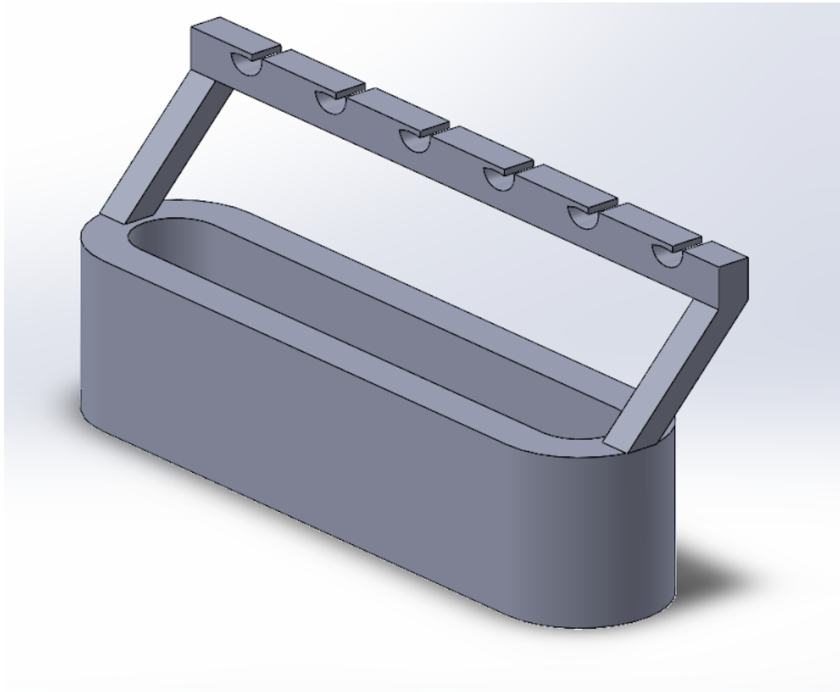


Figure 2: Initial design 2 with notches for strings.

In addition to this concept, we also developed the idea to have bearings for the magnets passing through the bobbin so as to restrict its side to side motion. The first iteration of this design is shown in Figure 3.

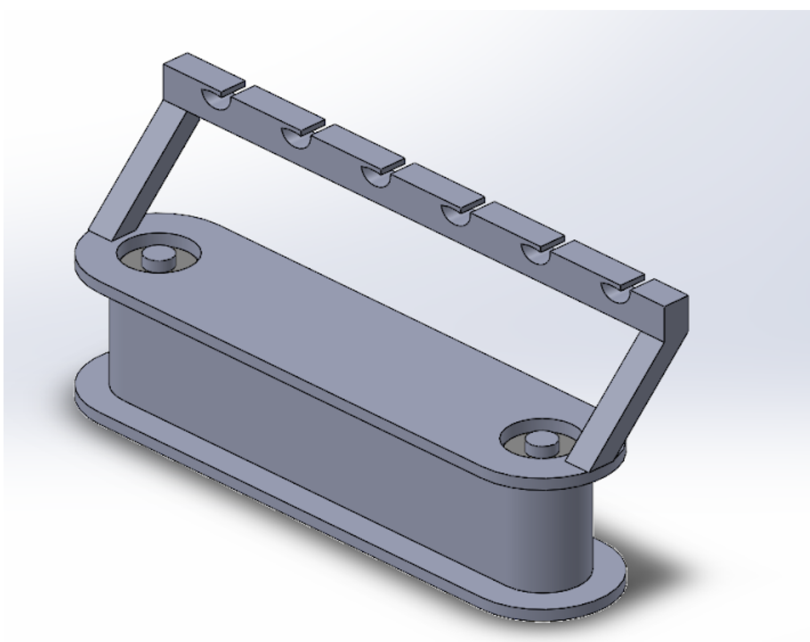


Figure 3: Bearing concept for magnets to prevent side-to-side motion.

The latter design was furthered to this model below (Figure 4), which had altered string grooves, and material removed to decrease the weight of the bobbin.

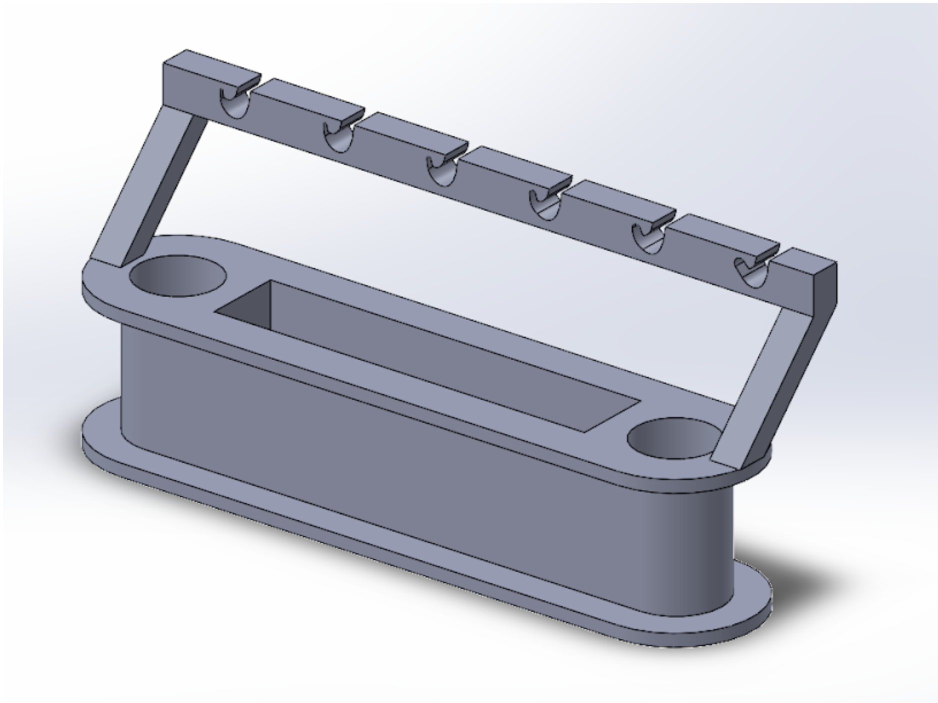


Figure 4: Reduced material bobbin.

A mockup of the bobbin component layering is shown in Figure 5.

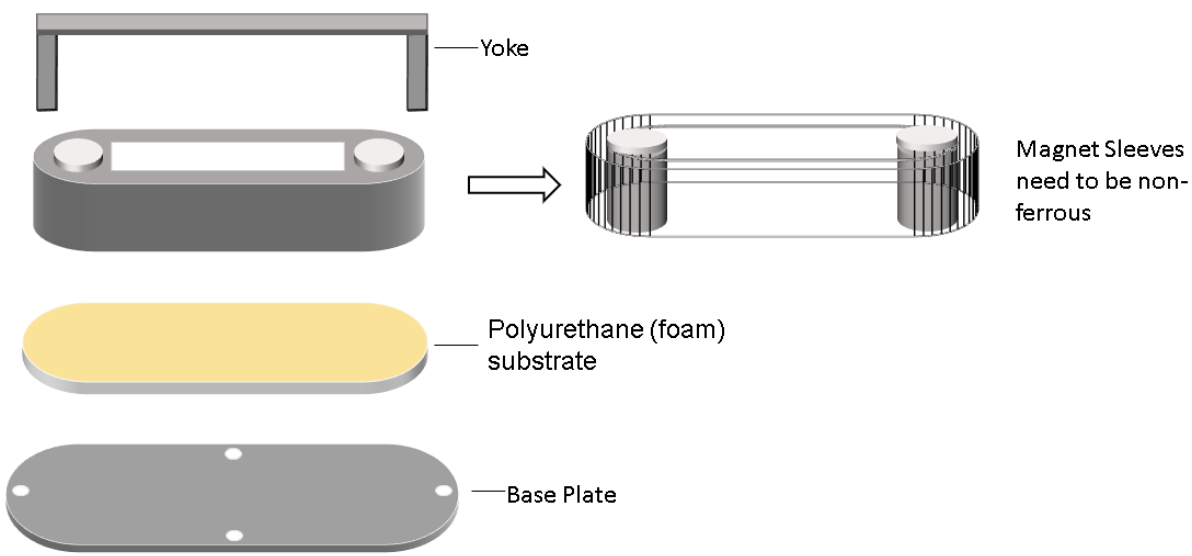


Figure 5: Early layout of bobbin components.

At this point in the process, the bearing design was decided to be the main focus. It went through another edit of string grooves as shown in Figure 6, sized to the gauge of each individual guitar string. This alteration coincided with a move away from the substrate idea and a move towards a zero downforce design, meaning the bobbin will hang freely from the strings, which will remain horizontal from nut to tailpiece. Additionally, a conversation was had to determine the type of bearing best suitable for this application. We ended up ordering ball bearings and sleeve bearings to see which one interacted with the magnets with the least amount of friction.

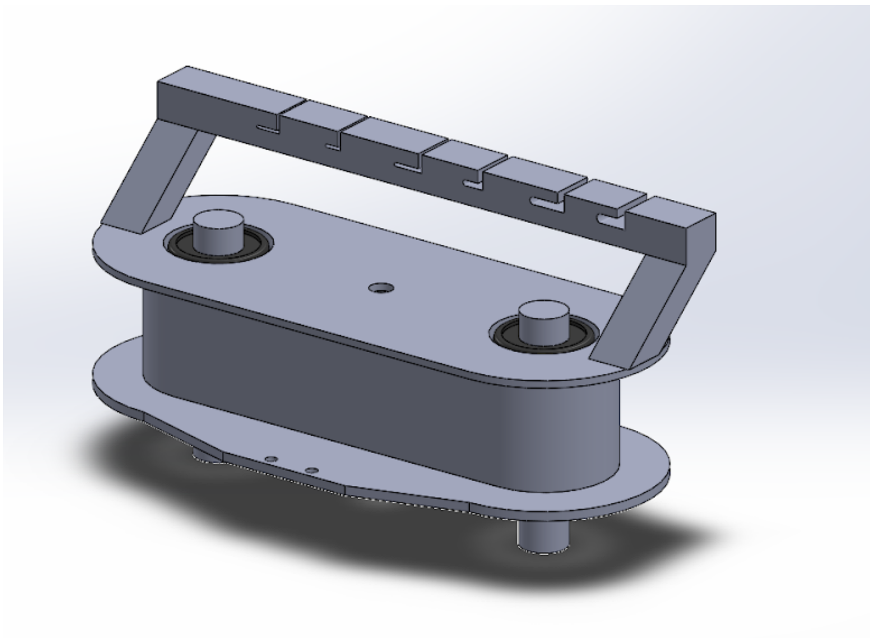
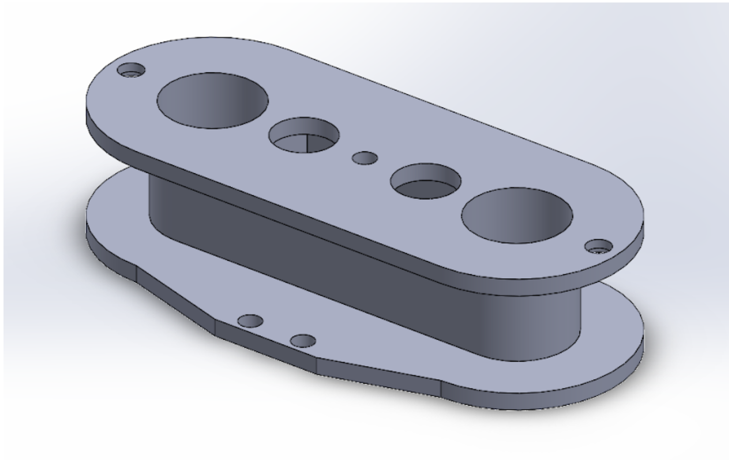
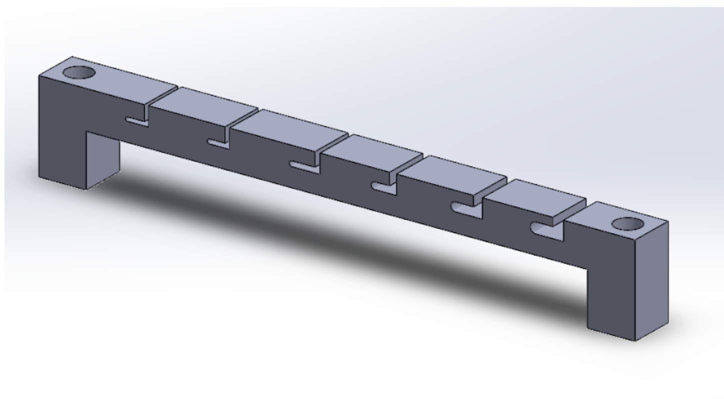


Figure 6: Bobbin design with string-specific notches on yoke, hole for coil winder shaft, and holes for the coil leads.

At this point, the topic of a modular yoke was discussed and incorporated into the design to allow for yokes of different materials to be tested without having to rebuild the whole bobbin each time. We also expected this to make manufacturing simpler. Additionally, two magnet clearance holes (without bearings) were included in the bobbin to produce a greater output signal. The middle of the bobbin is a hollow pocket designed to decrease the weight. This updated modular design is shown on the following page in Figures 7 and 8.





Figures 7 and 8: Modular bobbin and yoke.

This one piece bobbin was 3D printed, wound, and wired before moving to our final machined design. An example attempt is shown in Figure 9 on the following page. As depicted, it would be very difficult to attach the modular yoke to this bobbin as it stands.

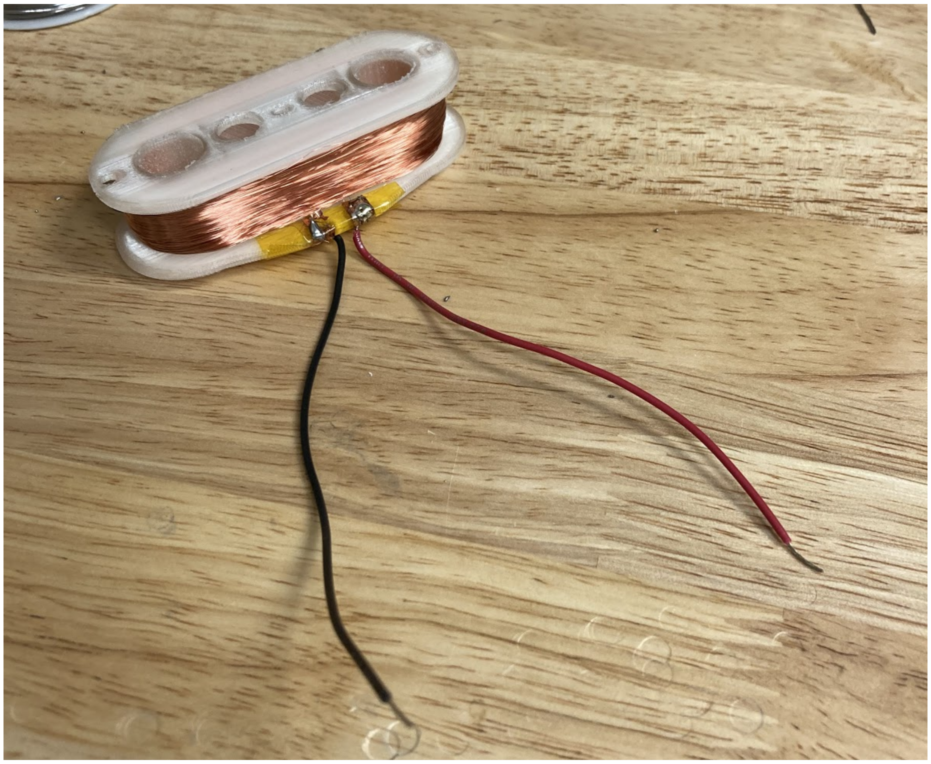


Figure 9: First “completed” pickup.

Finalized Design

Our finalized modular pickup design is composed of a two piece bobbin and a yoke. The two piece bobbin is necessary for removing the material on the interior of the bobbin with a machining process. Additionally, the two outer holes on the top piece of the bobbin are threaded so that the yoke can be attached using a 6-32 screw without the necessity of a corresponding nut that would interfere with the wound coil. Because of this design, the bobbin could no longer be 3D printed because the printer was incapable of producing the desired threads on such a small scale. The two pieces of the bobbin are fastened using 4-40 screws, and the SolidWorks models for each piece as well as the assembled version are shown below in Figures 10-12. The bobbin has four holes for magnets to pass through, the two outer ones being larger and toleranced appropriately to allow anodized aluminum sleeve bearings press fit into them. These bearings were chosen over the ball bearings because the neodymium magnets used produced a large magnetic force that actually ripped the balls out of the slots in the bearings. Neodymium magnets were chosen because we expected the movement of the coil relative to the magnets to be very small, so stronger magnets were needed to account for this lack of movement. We decided to use Delrin to build these portions of the pickup because it is a strong plastic that can be machined without deforming.

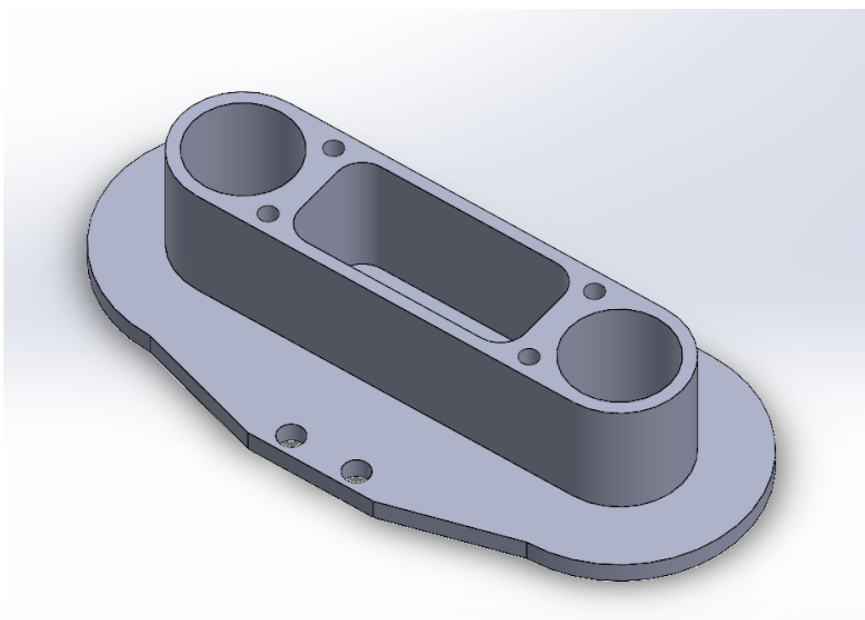


Figure 10: Bobbin bottom piece 3D model.

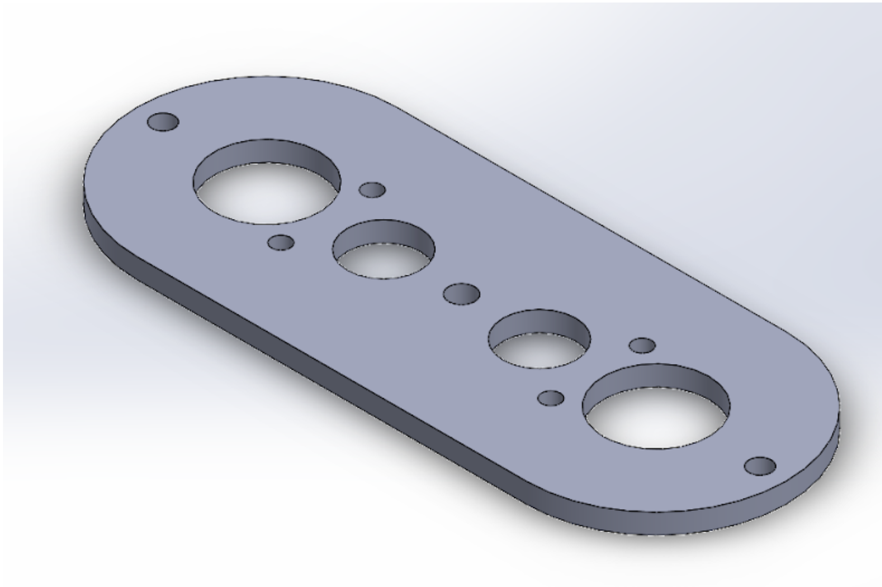


Figure 11: Bobbin top plate 3D model.

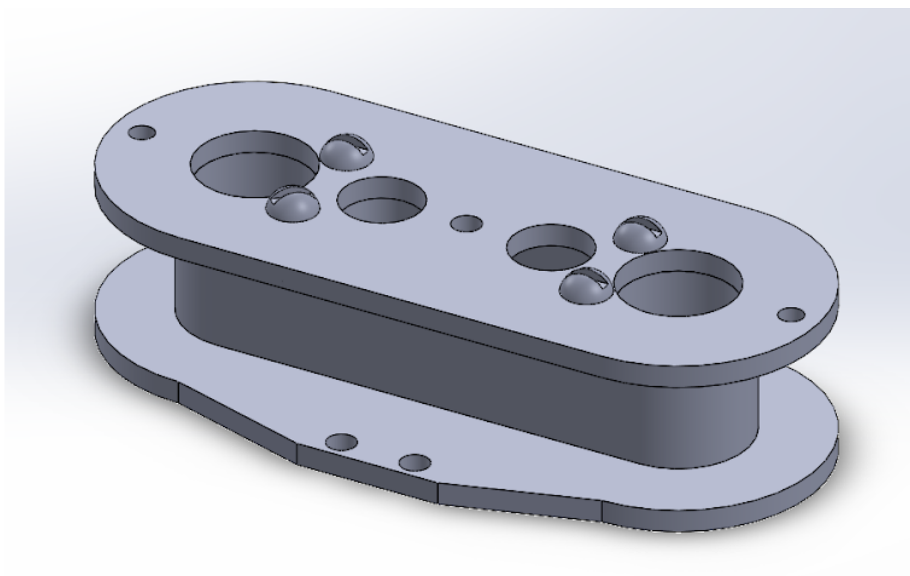


Figure 12: Bobbin assembly 3D model.

The finalized yoke design features six L-shaped grooves for the guitar strings to pass through. The design also has clearance holes in each support for the 6-32 screws to fasten the yoke to the bobbin. The grooves are mirrored across the middle so that the tailpiece pushes the strings towards one another and keeps them in their grooves. The grooves for the machined yoke are dimensioned exactly as the diameters of the strings. Using 10-46 gauge strings, these are 0.010”, 0.013”, 0.017”, 0.026”, 0.036”, and 0.046” from smallest to largest. This yoke is shown on the following page in Figure 13.

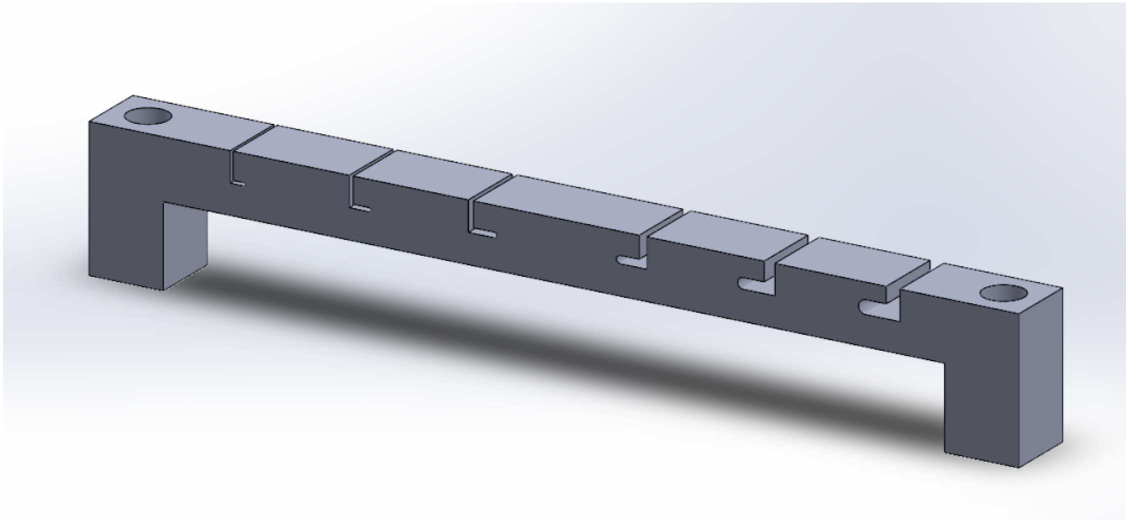


Figure 13: Yoke 3D model (for machining).

The grooves and clearance holes for the 3D printed PLA yoke are dimensioned larger than the diameters of the strings (by about 0.07” each) and the 6-32 screws to account for the tolerance of the 3D printer nozzle and thermal expansion of the material. Additionally, chamfers were added to the three smallest grooves on the face that rests on the printer bed due to extra material blocking the grooves on the first print layer. This yoke is shown in Figure 14.

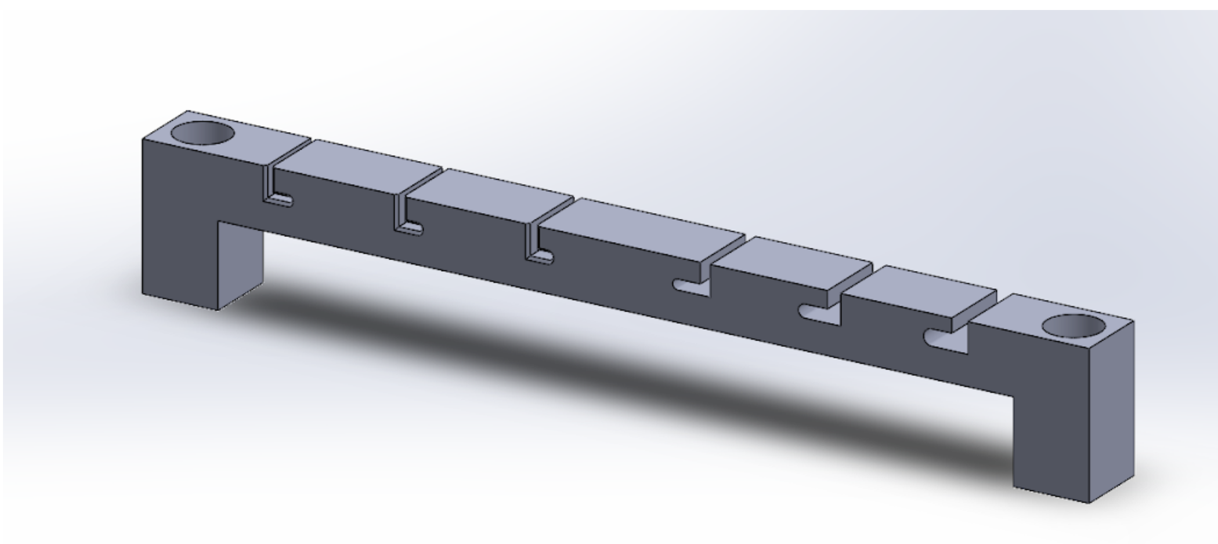


Figure 14: Yoke 3D model with chamfers on three smallest grooves (for printing).

On the following page is the SolidWorks assembly model of the final design including fasteners, excluding bearings (Figure 15).

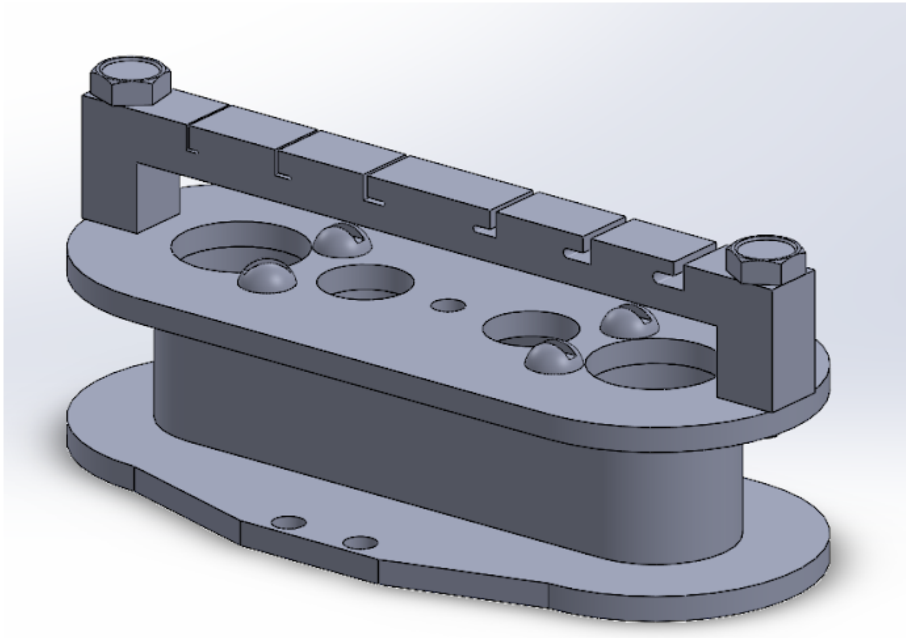


Figure 15: 3D model of final yoke-bobbin assembly.

In addition to the pickup design, we also had to design a way to incorporate this pickup into the guitar component testing rig with the addition of a tailpiece and block, as well as a new bridge block. The tailpiece has clearance holes on either end for ¼”-20 fasteners as well as six small holes for the strings to pass through but not the ball ends of the strings. The three holes on either side are equally spaced apart, but each set of three holes is squished together so that the strings lock into their grooves on the yoke. The tailpiece model is shown below in Figure 16.

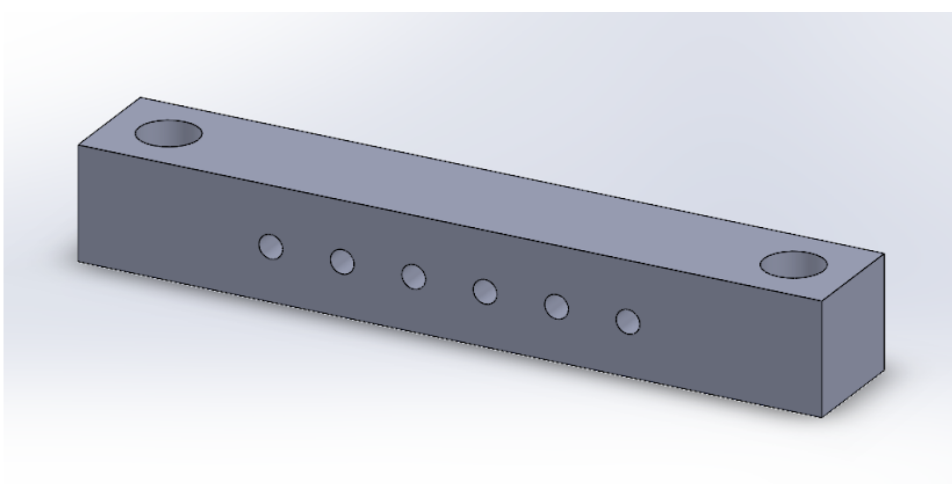


Figure 16: Tailpiece 3D model.

The tailpiece bridge block was designed to have ¼”-20 threaded inserts force fit into two holes for corresponding bolts and nuts to hold the tailpiece and allow its height to be adjusted.

This block model is shown below, as well as the assembled tailpiece test component (Figures 17 and 18).

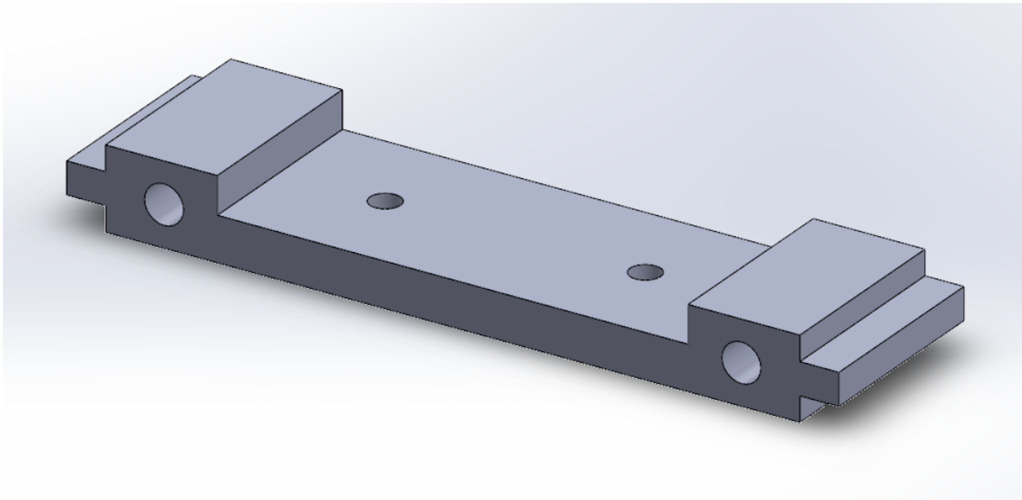


Figure 17: Tailpiece bridge block for guitar component test rig.

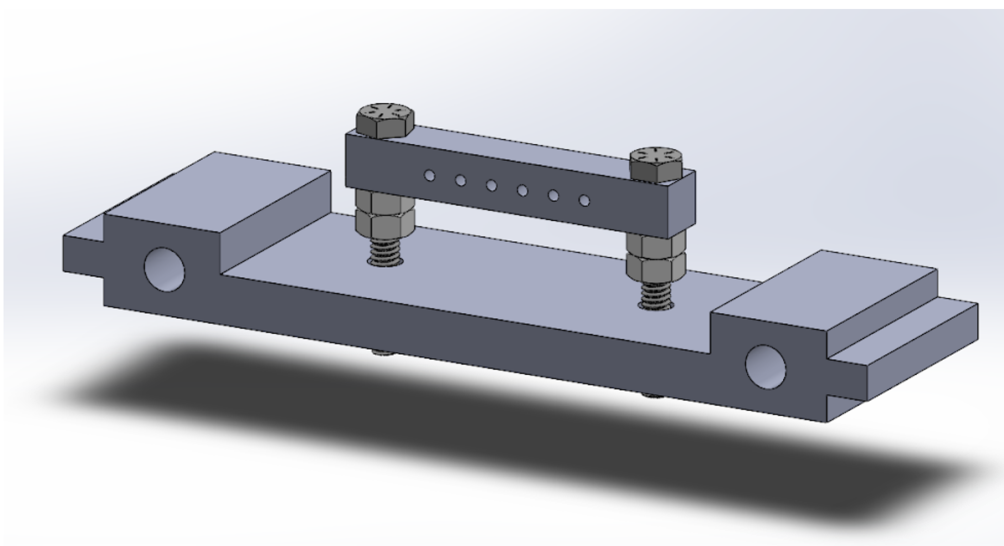


Figure 18: Tailpiece bridge block with tailpiece and threaded bolts.

The new bridge block had to account for the combined height of the pickup and the yoke, as well as the magnets so that they protruded through the entire bobbin. Four ¼" holes were placed on a lower surface to press fit the magnets. This block model is shown on the following page, as well as the assembled bridge test component (Figures 19 and 20).

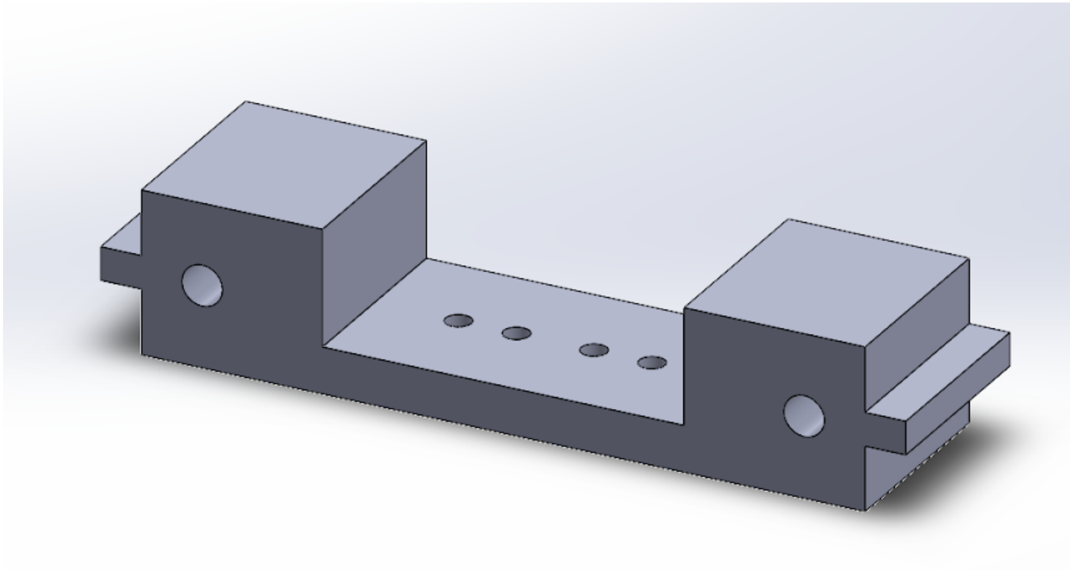


Figure 19: Pickup bridge block for guitar component test rig.

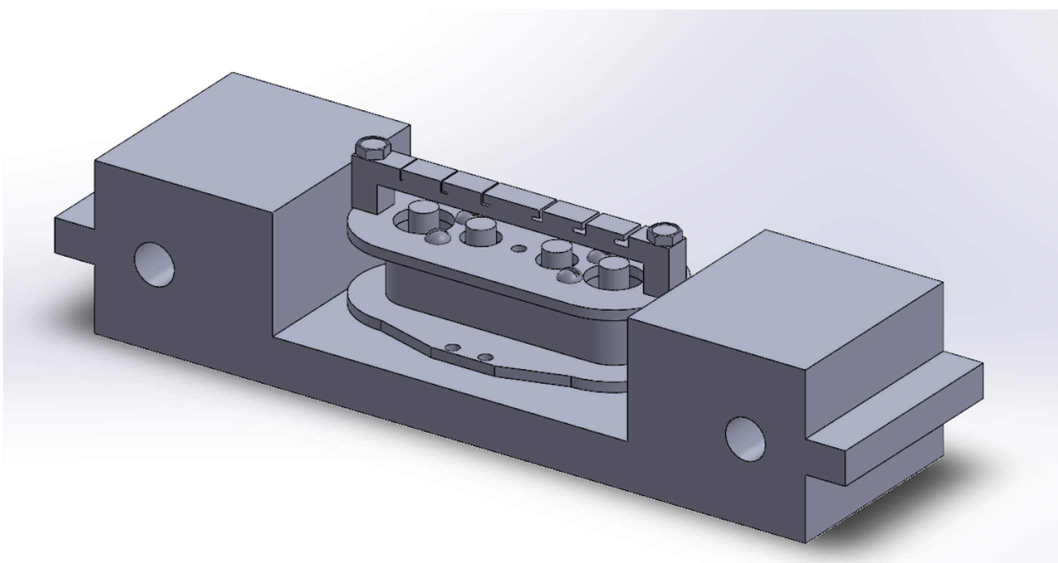


Figure 20: Pickup bridge block and pickup assembly with magnets.

Manufacturing Processes

Our finalized design utilized two manufacturing processes: CNC machining and 3D printing. CNC machining was used for the Delrin bobbin and aluminum yoke, and 3D printing was used for the PLA yoke.

CNC Machining

ESPRIT programs had to be created in order to machine the desired parts. ESPRIT is a CAM software that defines toolpaths for the machine tools. Within this software, you can also select the tools you wish to use, such as certain size drill bits and taps. The two bobbin pieces, tailpiece, and aluminum yoke profile (sans string grooves) were all machined on minimills from pieces of stock material.

The stock Delrin for the bobbin bottom piece was 1” thick by 1 ½” wide by 3 ¼” long. This part had to be machined in two operations and did not require any special fixturing. The first operation performed all of the features shown in the SolidWorks model, and the second operation flipped the piece 180° to face off the rest of the stock material on the underside. The machined bobbin bottom is shown in Figure 21. Two of them were made.

Figure 21: Machined bobbin bottom piece (Delrin).

The stock Delrin for the bobbin top piece was ¼” thick by 1 ½” wide by 3 ¼” long. This part had to be machined in two operations, and required special fixturing due to the thin nature of the stock. Masking tape was applied to the stock material and a scrap piece of aluminum, and the two pieces were super-glued together. This worked very well for both operations, and is allowed because the machine feeds and speeds are the same for Delrin and aluminum. The machined bobbin top is shown on the following page in Figure 22. Two of them were made.

Figure 22: Machined bobbin top plate (Delrin).

The stock aluminum for the tailpiece was ¾” thick by ¾” wide by 3 ¼” long. This part had to be machined in three operations, and did not require any special fixturing. The first operation milled part of the stock to the correct rectangular profile and cut the two clearance holes for the fasteners. The second operation flipped the piece 180° to face off the rest of the stock material. The third operation drilled the six holes for the guitar strings to pass through. The machined tailpiece is shown below in Figure 23. Two of them were made.

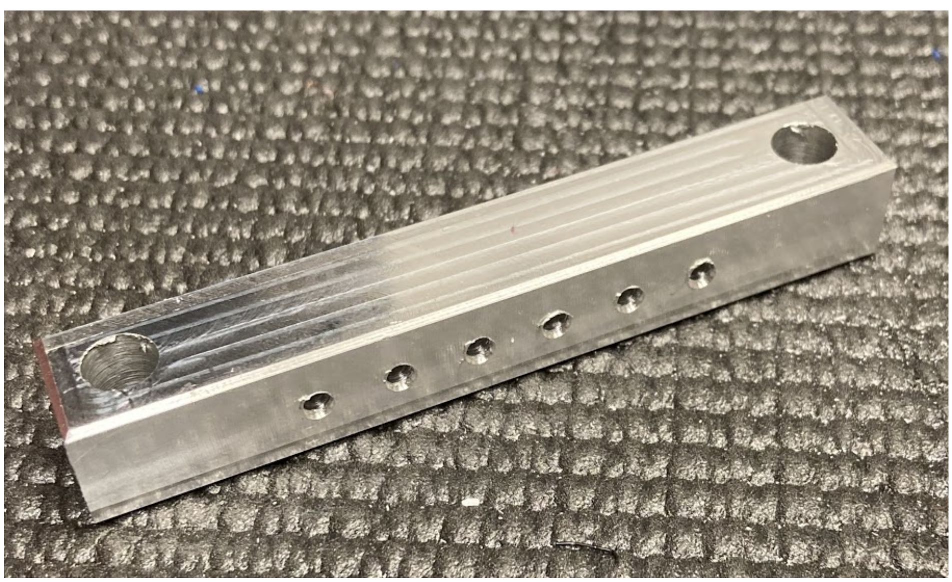


Figure 23: Machined tailpiece (aluminum).

The stock aluminum for the yoke profile was ⅜” thick by ¾” wide by 3 ¼” long. This part had to be machined in two operations, and did not require any special fixturing. The first operation cut the stock to form the two supports and drilled the clearance holes for the fasteners.

The second operation flipped the piece 180° to face off the rest of the stock material. The machined yoke profile is shown below in Figure 24. Two of them were made.

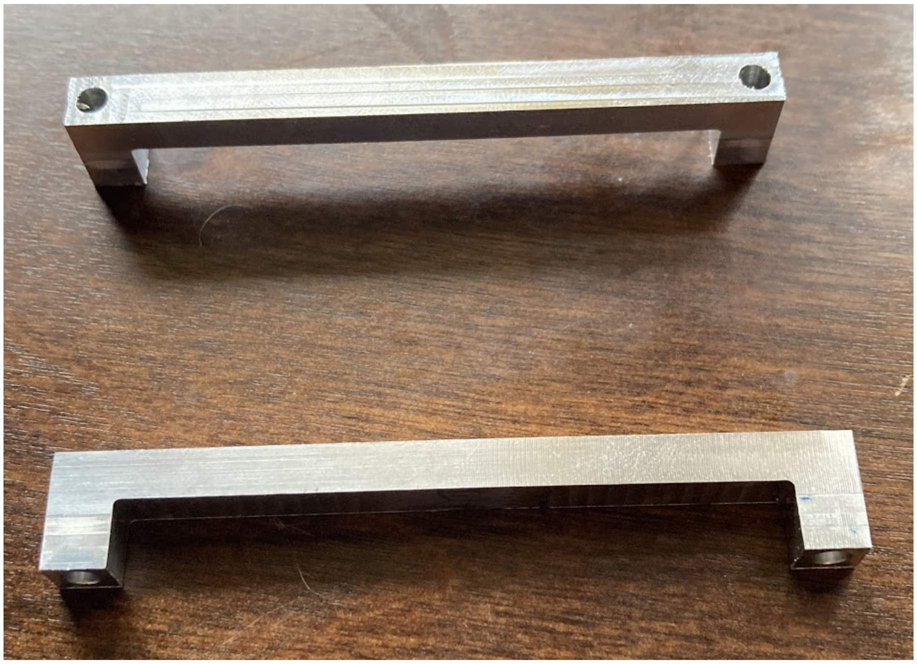


Figure 24: Machined yoke profile (without wire EDM notches, aluminum).

The string grooves in the aluminum yoke had to be machined using a wire EDM. This machine uses a very small wire with a diameter of 0.0098” to remove material from a part. This worked very well because the smallest groove on the yoke is 0.010”. The wire EDM yoke is shown below on the assembled pickup (Figure 25).

Figure 25: Machined yoke (aluminum) fastened to pickup.

3D Printing

The 3D printers at Foisie Makerspace were used to produce a plastic version of the yoke as well as the pickup bridge block and tailpiece bridge block for the guitar component test rig. We completed the full user training to get hand-on access to the printers in the full-user room, allowing us to bypass the long queues for the basic users.

The plastic version of the yoke was printed on either the Ultimaker3 or Ultimaker3 Extended, although the Ultimaker3 was able to produce higher quality grooves, particularly for the high E-string. So far, PLA was the only filament material tried. To improve the printer's ability to create the small, precise grooves on the yoke, we used the 0.25 mm nozzle/print-core (as opposed to the typical 0.4 mm print-core), with the printing profile set to high-quality (not available for Ultimaker3 Extended). For printer settings, we adjusted only the basic settings; the advanced settings are yet to be explored. The printer settings were as follows and are shown in Figure 26:

- 0.08 mm layer thickness
- 0.8 mm wall thickness
- 75% infill density
- 200°C printing temperature
- 60°C build-plate temperature
- "Skirt" adhesion type

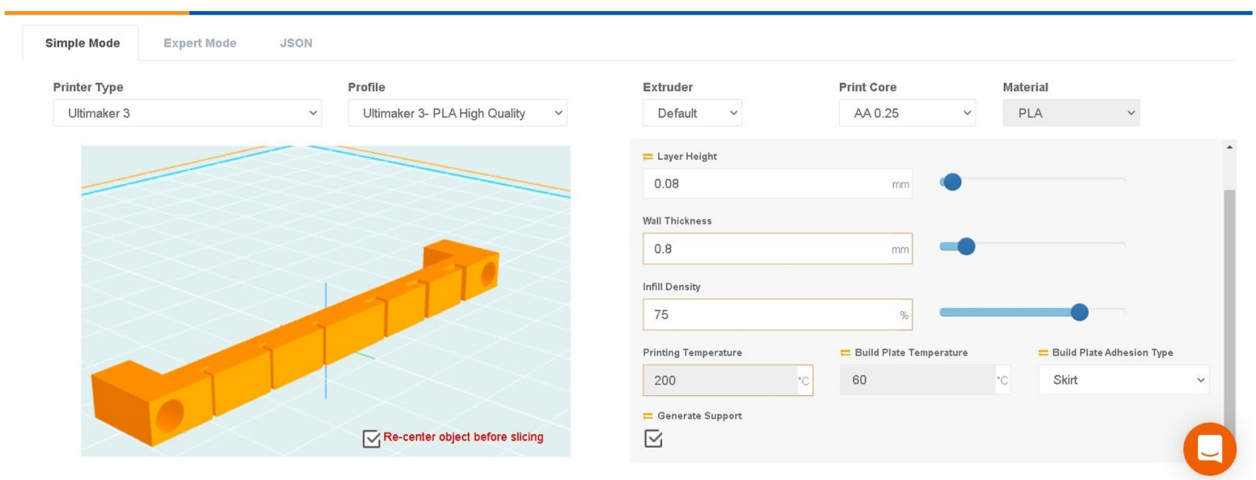


Figure 26: Capture of how the printer settings are selected in 3DPrinterOS.

When printing a component on a heated build-plate, the first layer often becomes "squashed" from the weight of the layers above it, causing it to slightly spread out over the build plate (this process is commonly known as elephant's foot). In the case of our yoke, with such small grooves (~.01"), the squashed first layer may spread out and come into contact with the opposite edge of the hole, thereby closing the grooves and making the yoke unsuccessful. Figure 27 on the following page is an example of how this affected an early yoke prototype.

Figure 27: Early printed yoke (PLA).

To eliminate this effect, chamfers were added to the three smallest grooves on the yoke as shown below. The chamfers elevate the edges of the holes so that they are not in contact with the printer bed. After the print is complete, the first layers of extruded filament indeed spreads out and covers the chamfers, so they are no longer apparent. Important to note: when the printer app 3DPrinterOS automatically loads and establishes the .stl file, it will not set the face with chamfers on the printer bed. However, 3DPrinterOS allows the user to simply rotate the part layout, so the chamfers can be set properly on the printer bed. Figure 28 below shows the yoke with the chamfers designed in SolidWorks, and Figure 29 shows the strings successfully fitting into the grooves on the yoke.

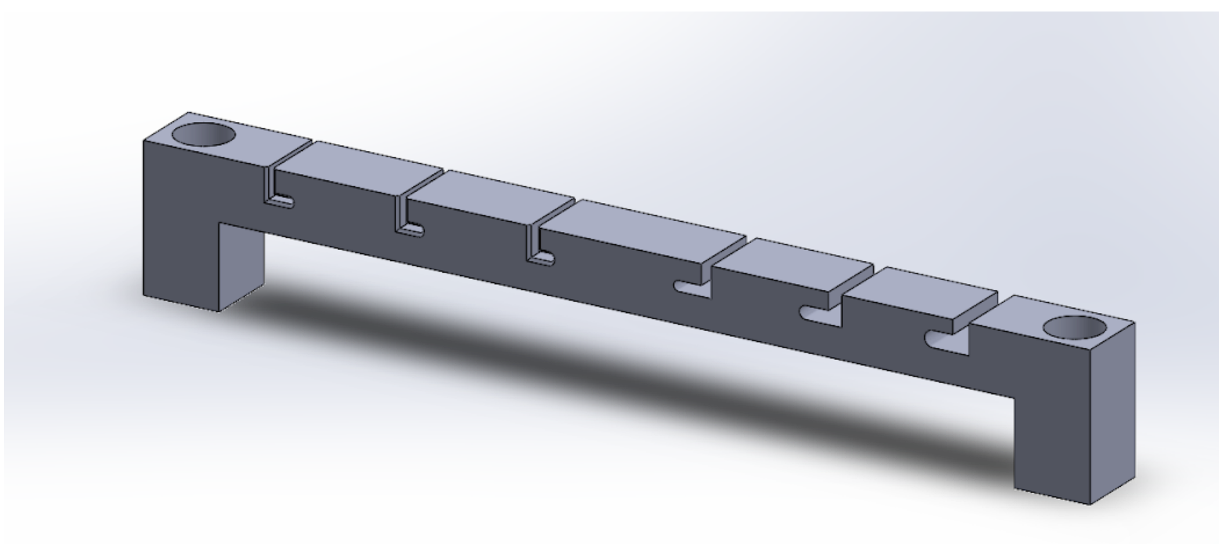


Figure 28: 3D model of yoke with chamfers.

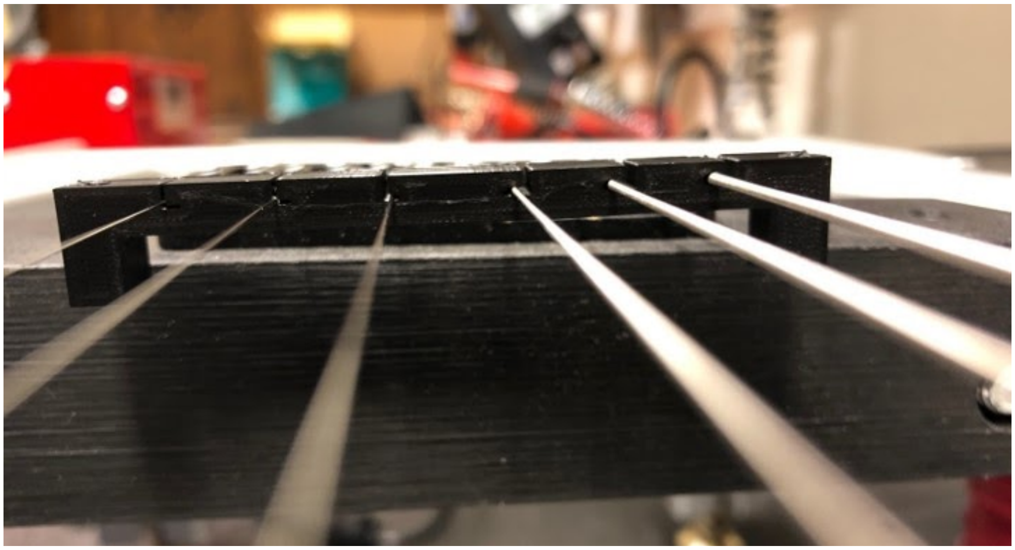


Figure 29: Printed yoke (PLA) with chamfers.

The pickup bridge block and tailpiece bridge block for the test rig have less precise specifications, and could therefore be printed quickly on the TAZ6 with default settings. To reduce printing time, the “fast” printing profile can be selected as well. Figures 30 and 31 are images of the bridge blocks.

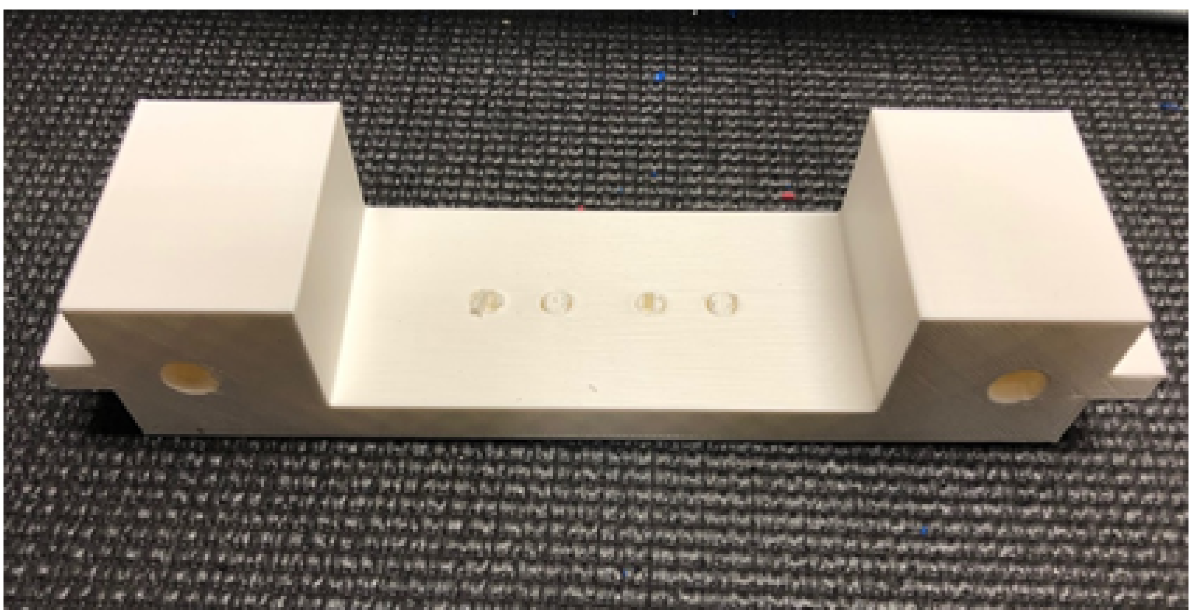


Figure 30: Printed pickup bridge block (PLA).

Figure 31: Printed tailpiece bridge block with threaded inserts (PLA).

Assembly

Pickup Assembly

The pickups were wound with 8000 or 9000 turns of 42 gauge copper enameled "magnet" wire. We used the Mojotone pickup winder in the G11D Guitar Lab in Riley Commons. The strand of wire was held tight by hand, and gradually guided back and forth along the length of the bobbin as the shaft rotated. See tutorials for the Mojotone winder at [Guitar Pickups - vjmedia (wpi.edu)]() or [Mojotone Pickup Winding Machine](). With 9000 turns, we measured a coil resistance of ~8 kΩ and an inductance of 31.4 H.

The bobbin assembly is very simple, and utilizes just four 4-40 nylon screws to fasten the two bobbin parts together. The assembled bobbin (unwound) is shown below in Figure 32.

Figure 32: Machined bobbin assembly.

For one of our machined bobbins, we press fit sleeve bearings into the two outer holes that fit the ¼" magnets. This was done with an arbor press.

Once the coil is wound, wires need to be soldered to the start and the end of the coil. Because Delrin has a melting point lower than the temperature that the soldering iron heats up to, a layer of protection needed to be placed before the coil was wound and a contact could be secured. In order to do this, we adopted a "sandwich" method to solder safely and effectively. First, a piece of polyimide tape was placed on both sides of the coil holes, acting as an insulator, and poked through the holes. On top of this layer, a small piece of copper tape was folded over and poked through both coil holes to form an electrical contact to solder the wires to. This so-called sandwich is shown in Figure 33.

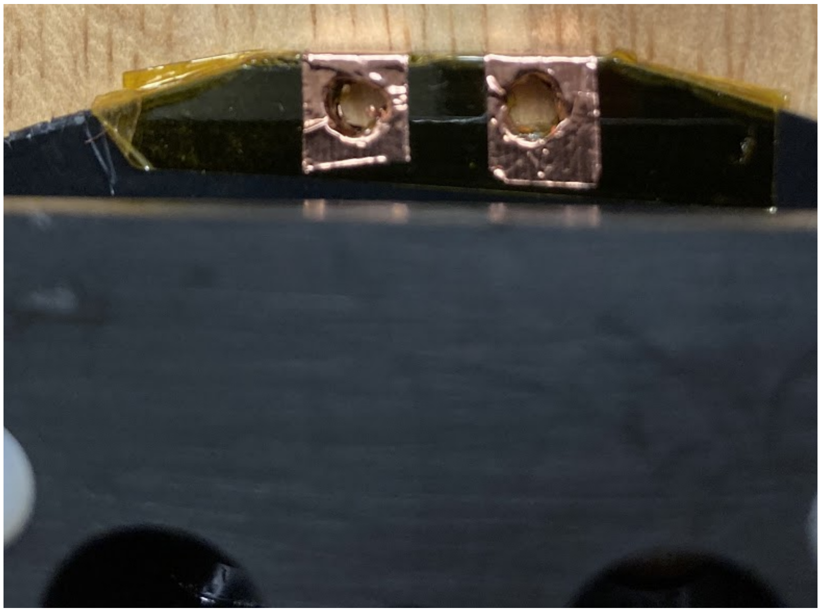


Figure 33: “Sandwich method” for soldering coil leads.

Once the coil was wound and soldered, wires were soldered to it. The wound and soldered pickup with bearings is shown below in Figure 34.

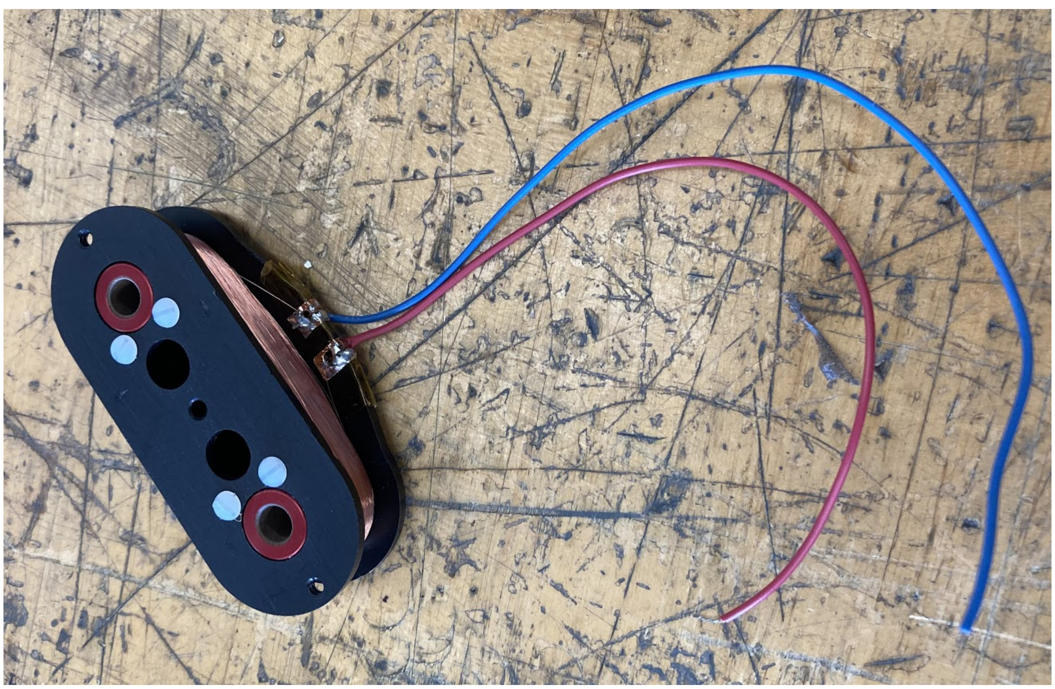


Figure 34: Pickup with bearings (no yoke).

Finally, the yoke was fastened to the bobbin top piece using 6-32 screws. The wires were soldered to a ¼” input jack for testing purposes. The fully assembled pickups, one with bearings and one without, are shown below in Figures 35 and 36.

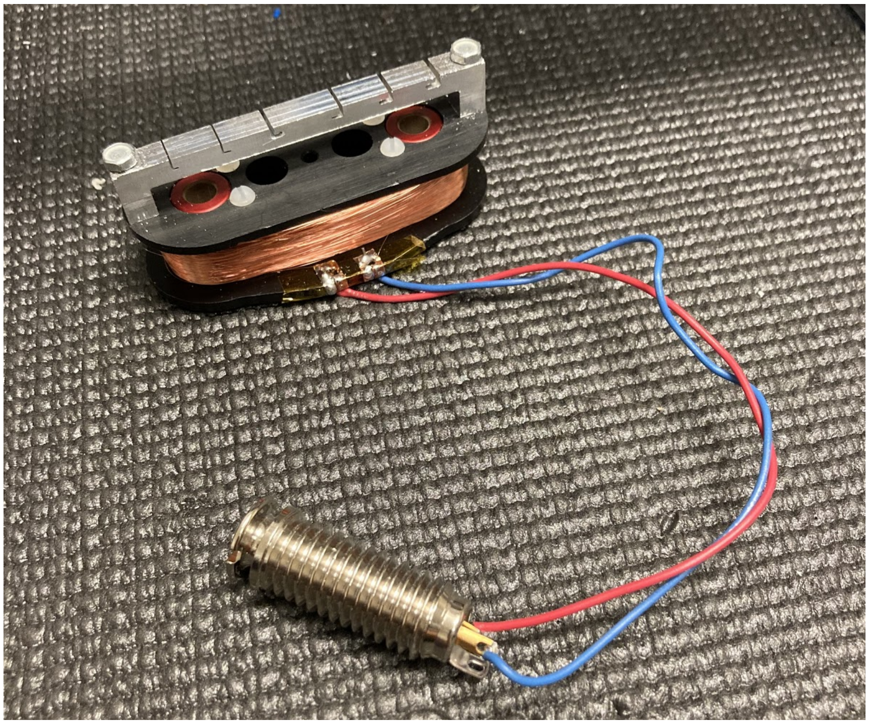


Figure 35: Assembled pickup with bearings and aluminum yoke.

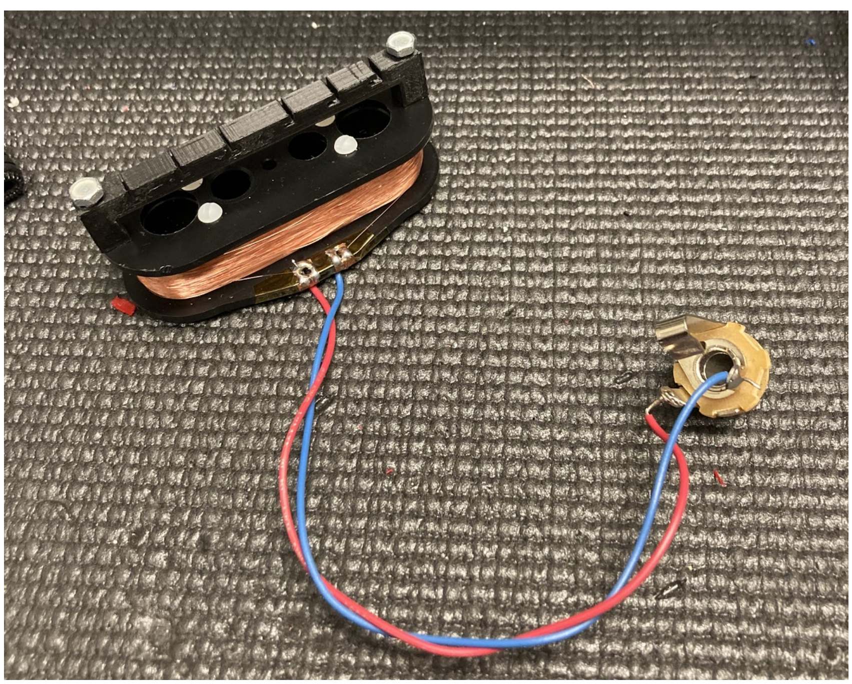


Figure 36: Assembled pickup with PLA yoke, no bearings

Test Rig Components

On the pickup bridge block, the support material from printing was removed with a flathead screwdriver. The magnets were then force fit into the holes using a hammer. Since the nickel plating on neodymium magnets is brittle, a thick piece of cloth was placed over the magnet. If a steel hammer is used, this cloth will also help prevent the hammer from sticking to the magnet, although it does not remove the entirety of the attractive force. Therefore, a rubber mallet would be much better suited for hammering strong magnets. This bridge block was added to the rails on the guitar rig.

On the tailpiece bridge block, the support material was removed by hammering through the holes with a screwdriver. The threaded inserts were then force fit into the holes. The holes had to be filed until wide enough to initialize the fit, after which the inserts were hammered into place. The bolts were put through the aluminum tailpiece and fastened underneath with two hex nuts each. The remaining length of the bolts were threaded through the inserts on the tailpiece block, and fastened underneath with one hex nut each. This allows the user to adjust the height of the tailpiece. This bridge block was added after the bridge block onto the rails of the guitar rig.

Testing

The RME UFX in Lab G11D was used as the audio interface during testing. Inputs 9 and 10 on the RME were used to sample the incoming signal. The gain was adjusted in TotalMix, the software that interfaces with the RME (installed on the iMac in G11D). A gain of 45 dB was found to be the maximum achievable without inducing clipping. Outputs 1 and 2 are connected to the two speakers in G11D (Atomic MKII Neo Amplifiers), and could be used to hear the response from the pickup in real time.

Audio signals were sampled in Ableton Live (also installed on the iMac in G11D). Ableton Live allows the user to implement real-time filtering onto the incoming signal, although for most of our tests we recorded the raw signal, allowing replication and signal-processing to be completed in post.

The pickup was tested for both its electric response and its acoustic response. The strings on the test rig were tuned to E2, A2, G3, B3, and E4. For the electric response, a ¼" cable was connected from the jack on the pickup to input 9 on the RME. During recording, a single string was plucked once and allowed to oscillate until it came to rest. This was repeated for each of the 6 strings on the test rig. The pickup on the test rig is shown in Figures 37 and 38.

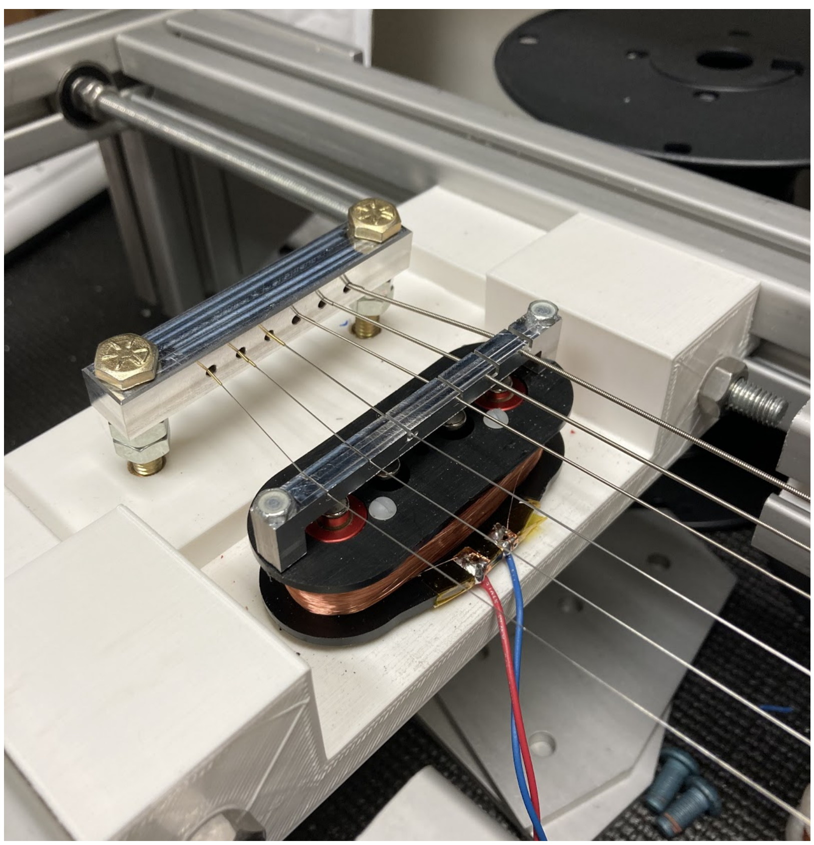


Figure 37: Pickup and tailpiece setup on test rig

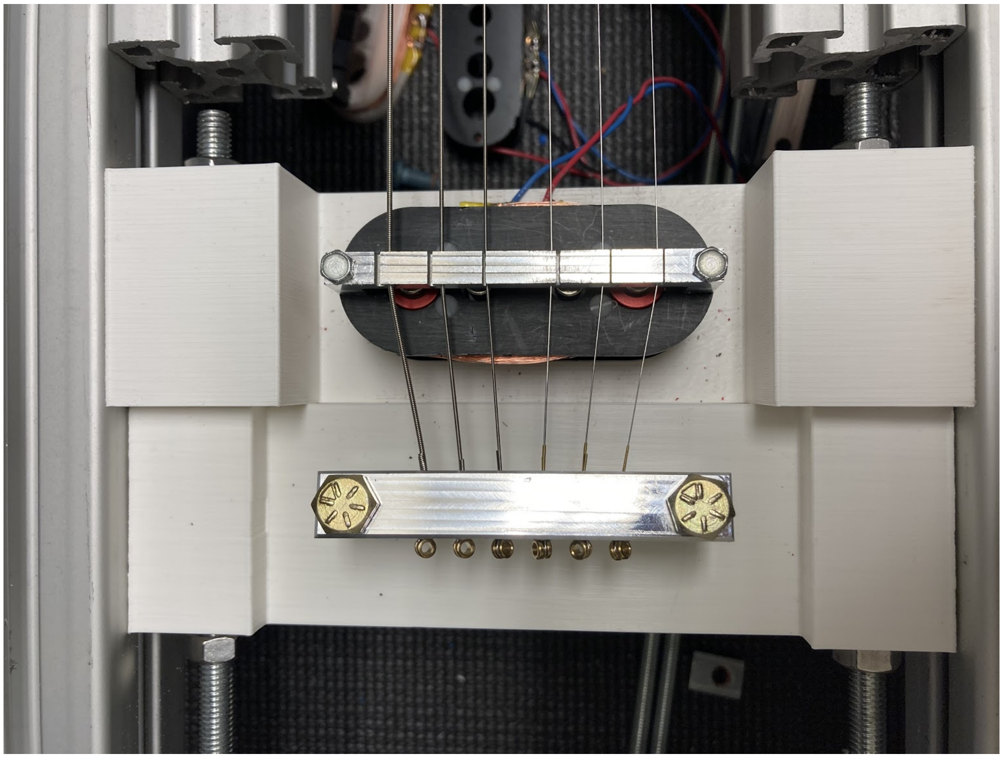


Figure 38: Bird's eye view of pickup on test rig.

As expected with a 9000 turn, large-area, single-coil pickup, the noise level was considerably high. The noise was sampled by itself so that the appropriate filters could be designed. As seen in Figure 39, the noise consisted of particular multiples of 60 Hz, the largest being 180 Hz, 540 Hz, and 60 Hz. Notch filters with low bandwidth can be designed to eliminate the noise, although care must be made not to attenuate any harmonics from the strings themselves.

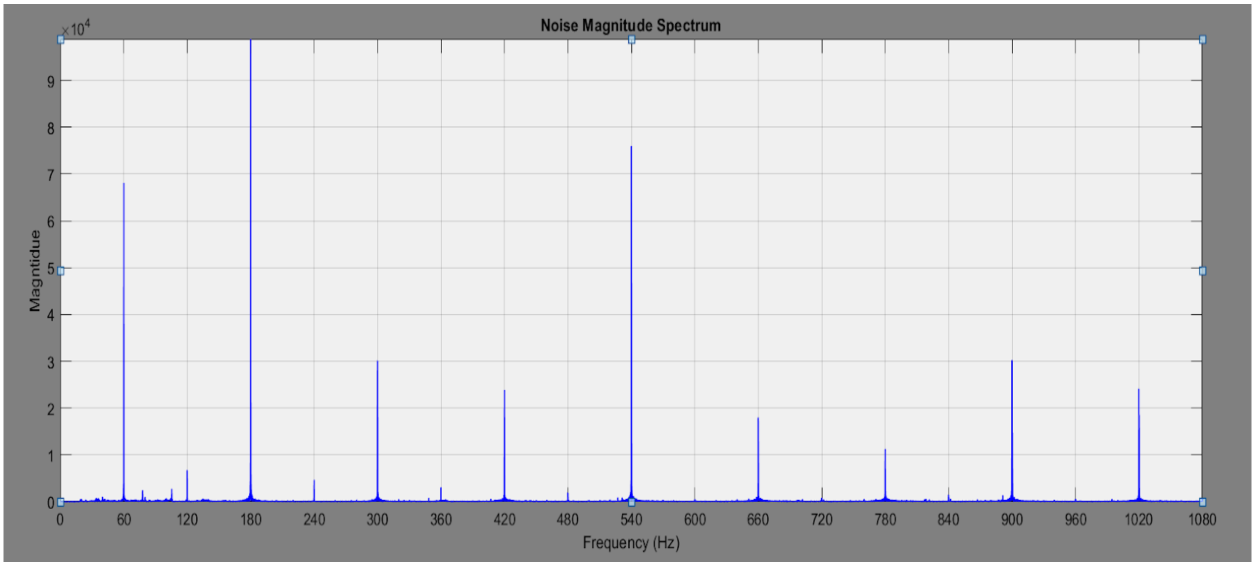


Figure 39: Magnitude spectrum of noise.

With the acoustic response, a microphone was connected to input 10 on the RME using a XLR cable. The microphone was held 6” laterally and 6” vertically from the yoke, as shown below in Figure 40.

Figure 40: Microphone placement for acoustic response.

During recording, a single string was plucked once, and allowed to oscillate until it came to rest. This was repeated for each of the 6 strings on the test rig.

Analyzing the Signals

By looking at the magnitude spectrum of the audio samples, we can quantitatively analyze the response of the pickup, as well draw a quantitative comparison between different yoke types (aluminum and PLA). Both yokes produced particular undertone artifacts, often consistent across plucks of different strings. The undertone artifacts from the aluminum yoke were of greater magnitude and different frequencies than those of the PLA yoke.

Of the artifacts generated with the aluminum yoke, most pronounced were those of the high E string, which was tuned to near 329.6 Hz (E4). In the magnitude spectrum of the E4 string (aluminum), we see the expected spike near 329.7 Hz, a first harmonic of the same amplitude at 659.3 Hz, and a third harmonic of lower amplitude at 988.2 Hz. However, there are also spikes at 79.98 Hz (at an even greater magnitude than the primary note!), 89.98 Hz, and 110.4 Hz. These low frequency artifacts were present on most of the samples from the aluminum yoke, at exactly the same frequencies, as seen in Figures 41-46. An exception can be seen in the E2 string, which still had the dominant 78.98 Hz artifact, but had a band between 78 and 100 Hz which overlapped with the fundamental note (81.38 Hz).

Aluminum Yoke (no bearings) Spectra

In the following "Magnitude" on the Y-axis has no objective units

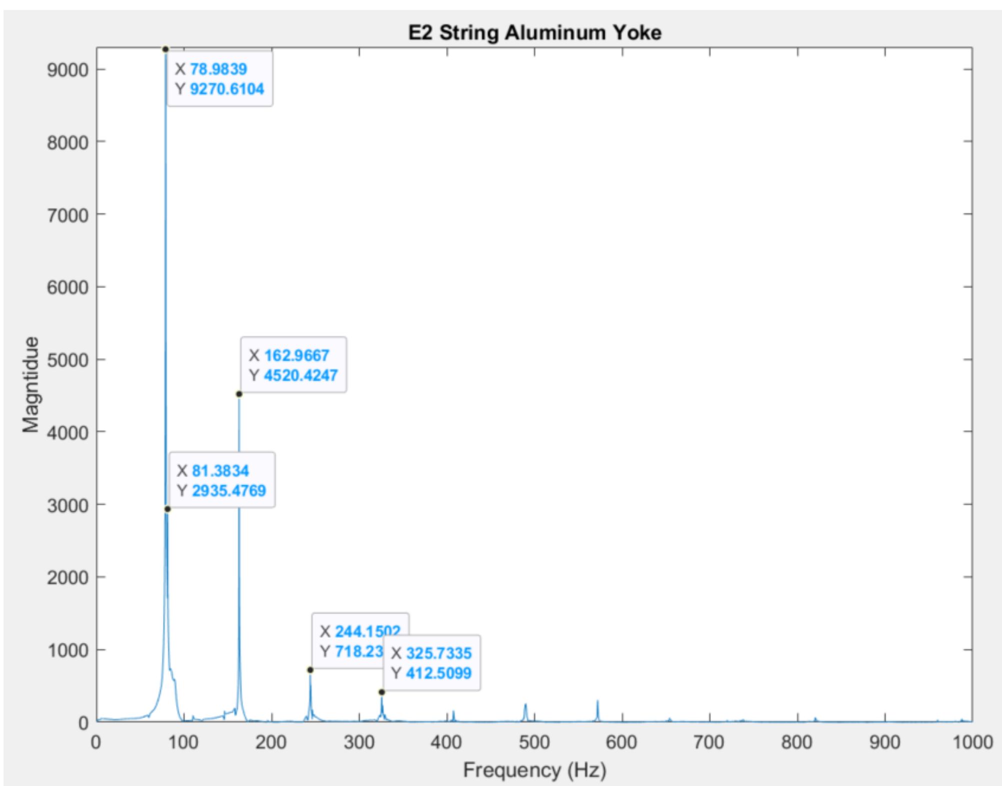


Figure 41: E2 string (aluminum yoke, no bearings).

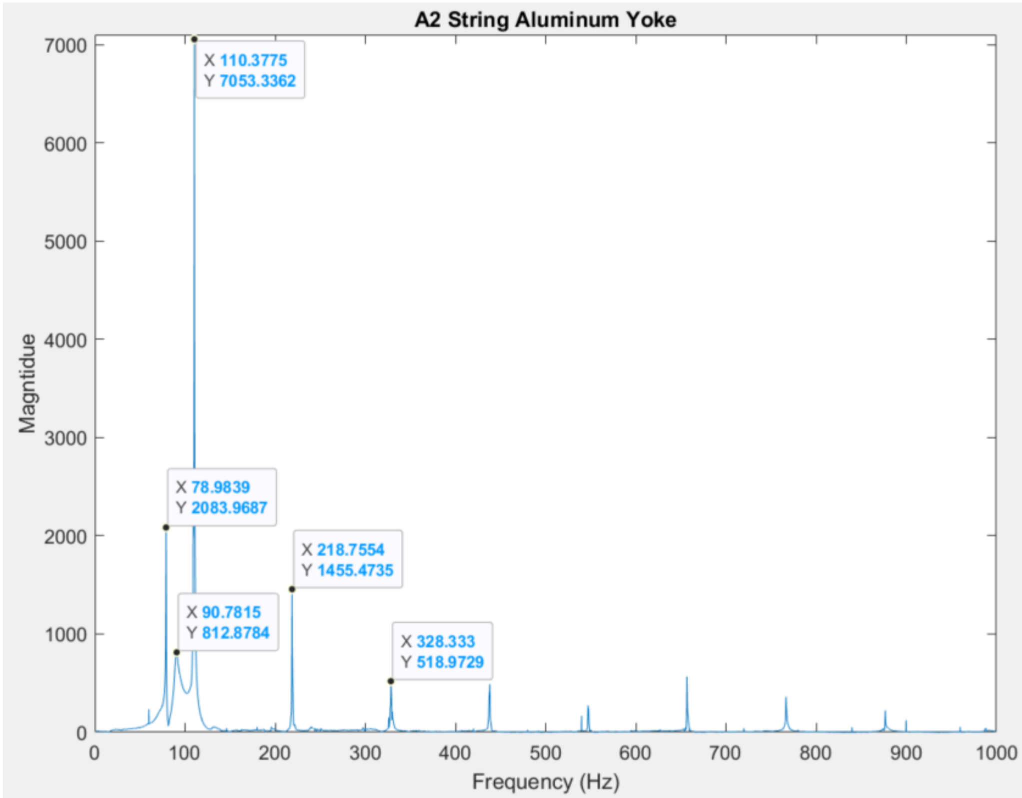


Figure 42: A2 string (aluminum yoke, no bearings).

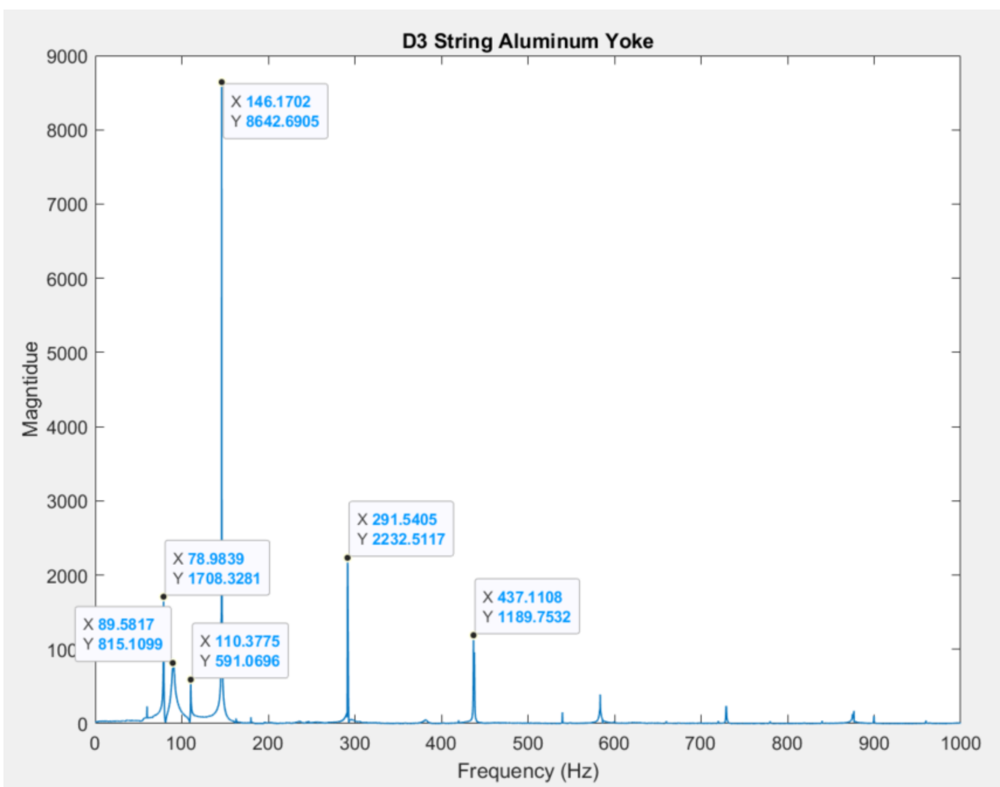


Figure 43: D3 string (aluminum yoke, no bearings).

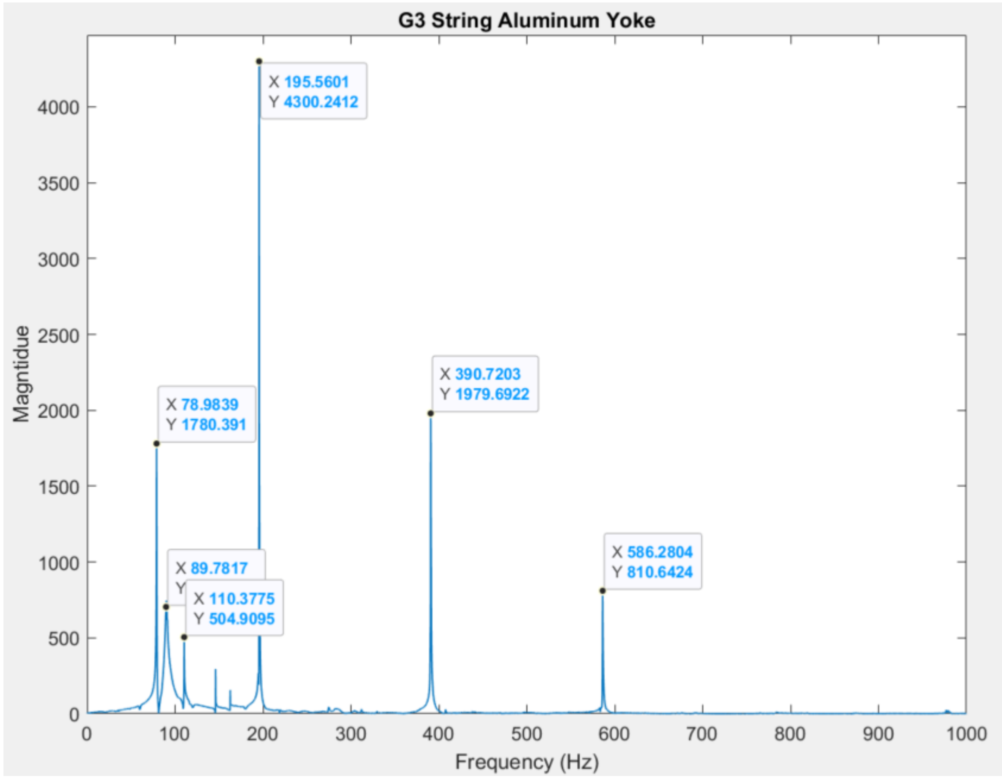


Figure 44: G3 string (aluminum yoke, no bearings).

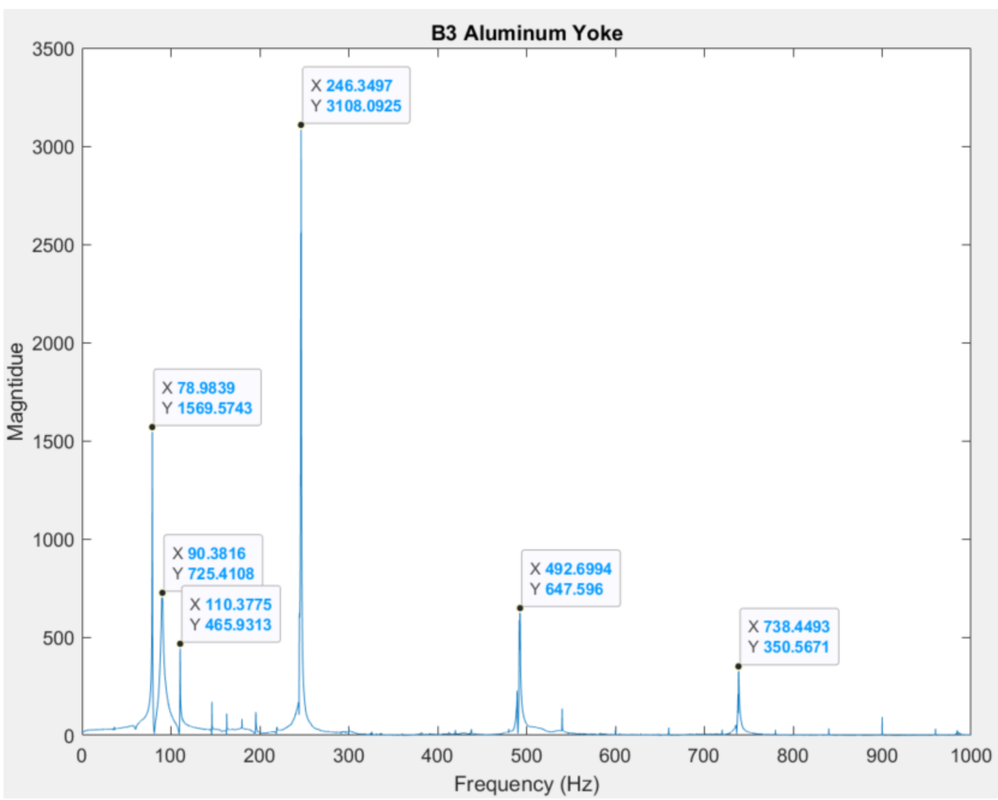


Figure 45: B3 string (aluminum yoke, no bearings).

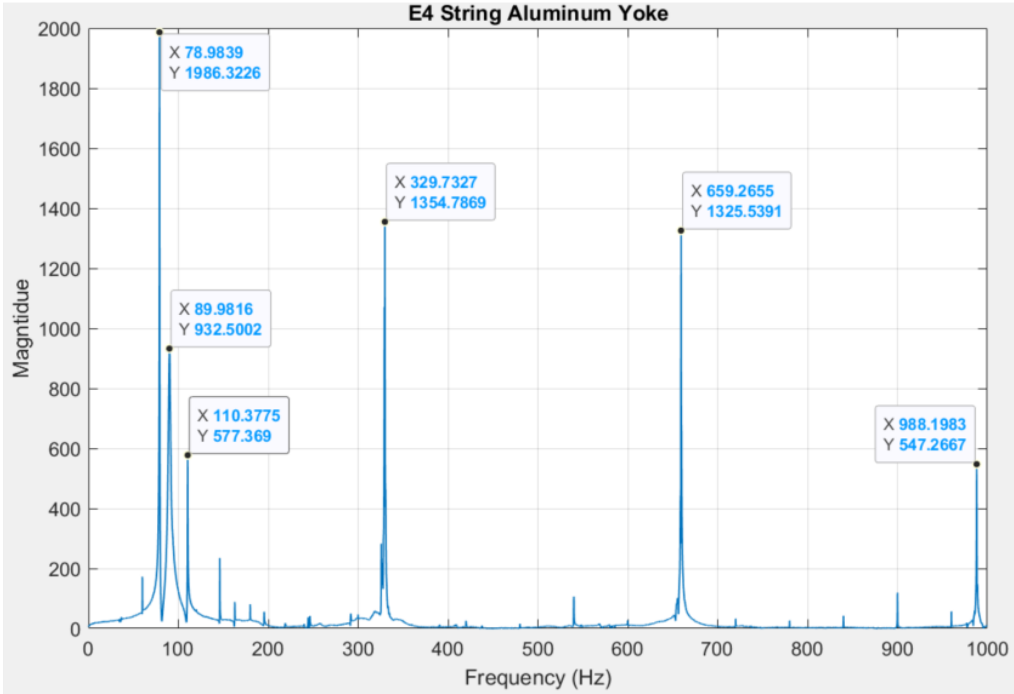


Figure 46: E4 string (aluminum yoke, no bearings).

Different low frequency artifacts were present in the samples from the PLA yoke, shown in Figures 47-52. They were less consistent and less pronounced than the artifacts from the aluminum yoke. Common artifact frequencies were ~50-60 Hz, 80.38 Hz, 90.78 Hz, and 106.6 Hz Hz. Similarly to the aluminum yoke, an exception can be seen with the E2 string, the 80.38 Hz artifact was absorbed by the fundamental note at 81.18 Hz (theoretically 82.6 Hz). There was an additional band between 50 and 90 Hz. Overall, the amplitude of the low frequency artifacts on the PLA yoke were less prevalent than those from the aluminum yoke.

PLA Yoke (no bearings) Spectra

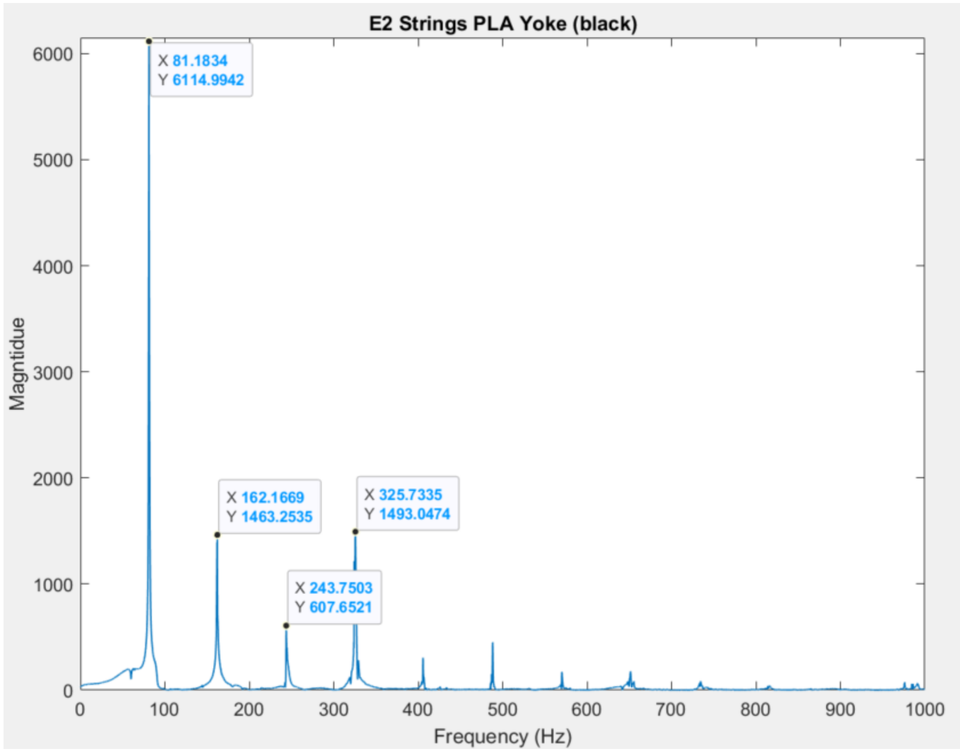


Figure 47: E2 strings (PLA yoke, no bearings).

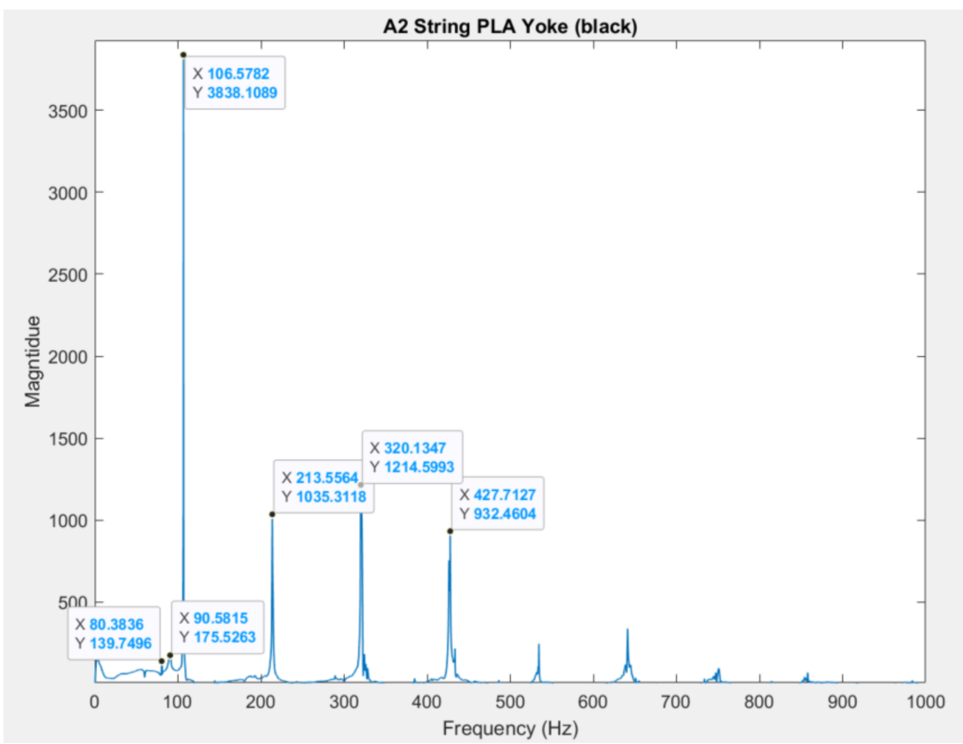


Figure 48: A2 string (PLA yoke, no bearings).

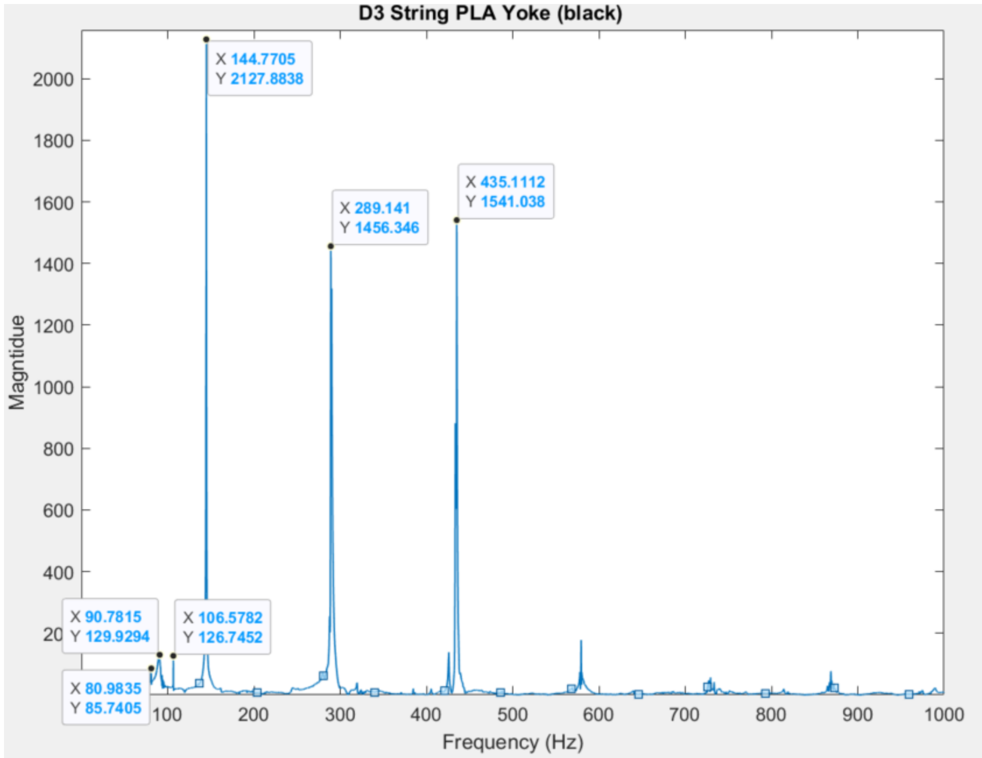


Figure 49: D3 string (PLA yoke, no bearings).

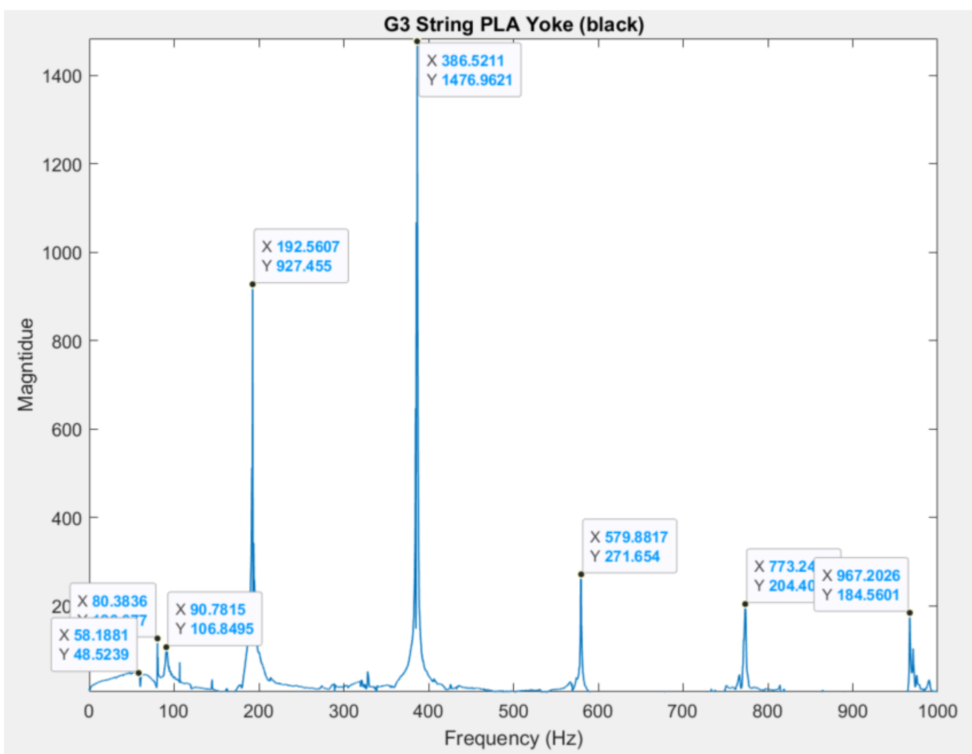


Figure 50: G3 string (aluminum yoke, no bearings).

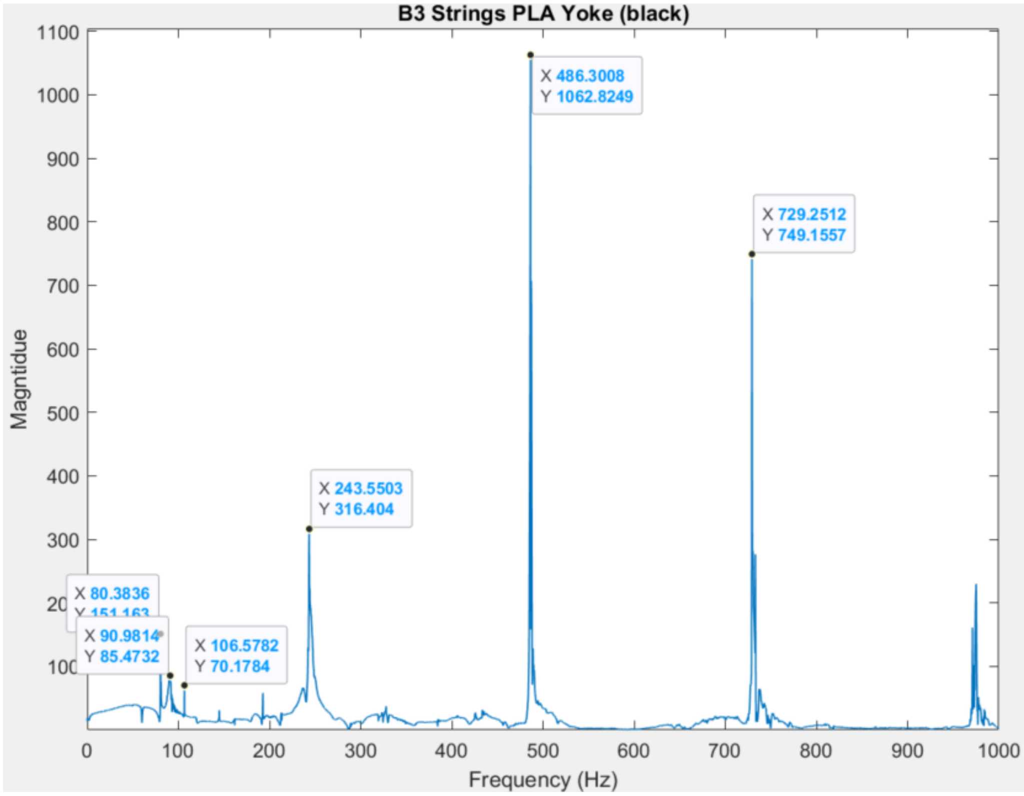


Figure 51: B3 strings (PLA yoke, no bearings).

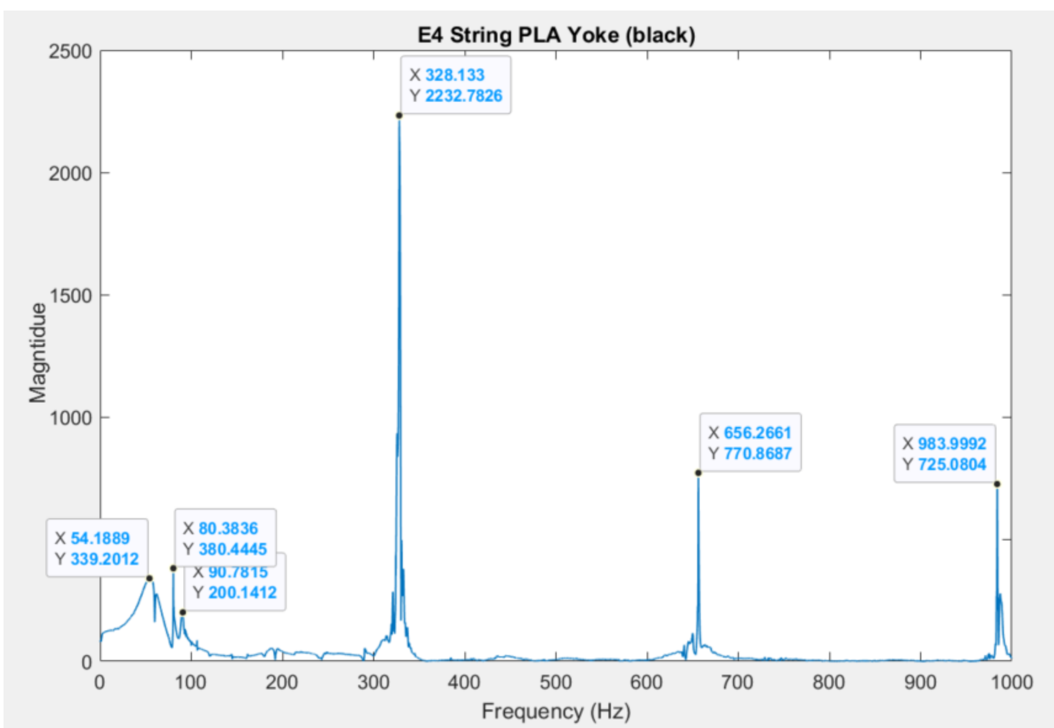


Figure 52: E4 string (PLA yoke, no bearings).

Since the low frequency artifacts were not measured in the noise sample, we draw the conclusion that they result from the action of the pickup as a bridge piece, and are for a large part determined by the design of the yoke. Presently it is not determined whether they are generated by the yoke and bobbin itself, the portion of the string between the bridge and tailpiece, the attractive force of the strong NdFeB magnets, or a combination of these mechanisms. Determining the precise mechanism for these artifacts, and how to prevent or alter them, could be the subject of further investigation. Note that these low frequency artifacts will not be audible when played through typical laptop speakers.

Recommendations for Future Work

Further Signal Analysis

Not yet completed is analyzing the acoustic response of the strings. In particular, it would be insightful to compare the frequency spectra of the acoustic response to the electric signal across different yokes types. If the low-frequency artifacts were also present in the acoustic response, it would further confirm that the yoke is responsible for the artifacts. Other inquiries include comparison between the pickup with bearings and the pickup without bearings, a comparison to a conventional pickup, and comparison to the control test where the yoke was removed from the pickup. At present, recordings of these different tests have been sampled and are in the repository, but have yet to be investigated. Lastly, a topic of investigation is how the frequency response changes over the course of the strings' decaying oscillations (if at all).

All tests of this pickup were performed with the test rig on its four legs, making the bottom of the pickup parallel to the ground. This, of course, is not the orientation of a pickup when it is being played by a musician. We recommend that the next group rotate the test rig 90° so that the pickup is perpendicular to the ground, and identify the effect this has on the sound and its orientation due to gravity.

Optimizing Tailpiece Design

The tailpiece that was machined for this project was intentionally designed to be simple, quick, and dirty to get the job done and focus attention on the pickup. That being said, it could certainly use some optimization as exemplified in Figure 53.

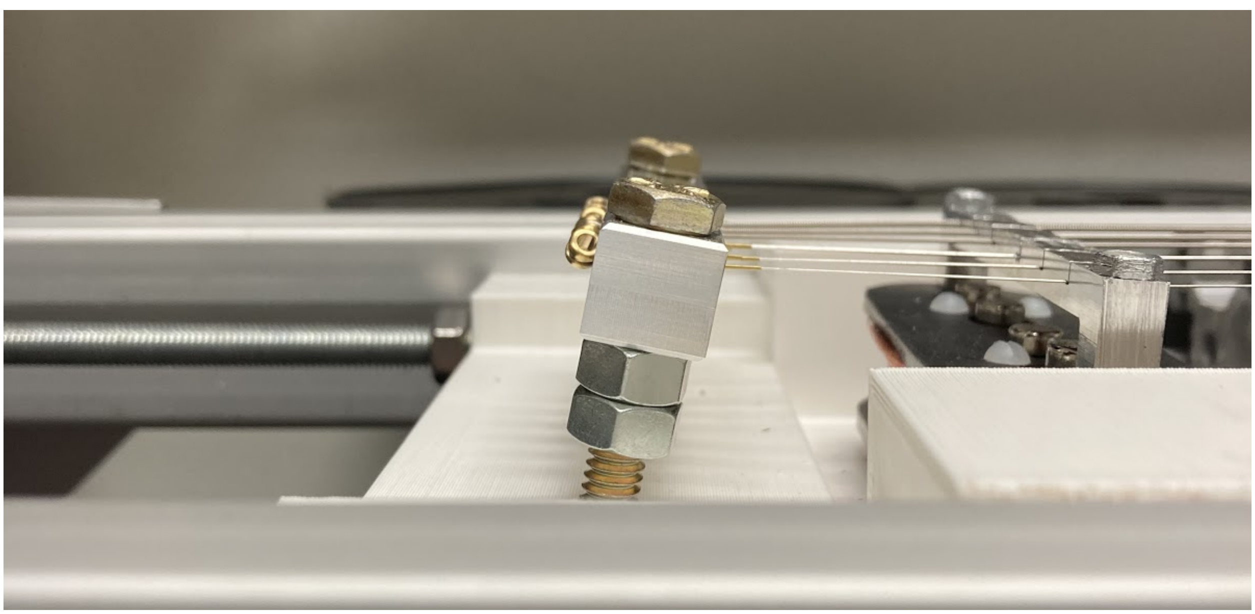


Figure 53: Tailpiece bending as a result of testing.

The string tension was far too great for the tailpiece bridge block, and as it pulled on the tailpiece and bolts, the threaded inserts dug into the PLA block. This made tuning the rig very difficult as the tailpiece would creep closer towards the headstock everytime the strings were tightened. Perhaps a tailpiece that was flush with its bridge block or manufacturing the bridge block out of a harder material would help curb this issue and allow testing to be more efficient and accurate.

Another potential adjustment to the test rig would be mounting a fretboard to it to analyze how fretted notes sound compared to the open strings. The effect of the force down on the string on the pickup yoke may be of interest.

Perhaps more of a note than a recommendation, the G string groove in the aluminum yoke machined with the wire EDM came out too small to fit the string and had to be enlarged using an abrasive string. This fixed the groove to fit the string properly, but the alteration appeared to have an effect on the tone when the G string was plucked during testing. The surface roughness inside that groove was likely astronomical. A small change to the ESPRIT file for that toolpath would likely fix that problem.

Moving the Magnets

In the 1959 patent, Les Paul states that a system which moves the magnets relative to the coil, as opposed to the coil relative to stationary magnets, would still be within the scope of the patent. Such a mechanism could be the subject of future investigation.