

Improved Pickup Cover Geometry

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Background

Guitar pickups were introduced early in the 20th century. At that time, early designs were limited by material technology and lack of prior knowledge, and improvements soon came along. Noise canceling, smaller footprint, higher output are examples of these. As the device consists of electrical coils and magnets, there was a need to protect them from the environment and hide them for aesthetic reasons. So many of the new designs incorporated metal covers for that purpose.

There are problems with positioning a metal substance between the pickup and the strings. If it is magnetically susceptible, it will interfere with the magnetic field that transmits the string vibrations to the pickup. So designers avoided these, and used non-magnetic substances like brass or plastic instead. However, non-magnetic metals have another problem. When they are in an alternating magnetic field, electric fields are induced in them according to Faraday's laws of induction. If the geometry of the field and the substance are in certain configurations, an electrical current will flow in the metal. This effect manifests itself as an attenuation of signal or dulling of tone, in the case of a guitar pickup.

Pickup designers responded in several ways. One was to use plastic covers. Another was to use a non-magnetic metal that has a relatively low conductivity, thus reducing but not eliminating the effect. Yet another was to alter the cover geometry in order to mitigate the currents. The latter approach was used in the 1957 U.S. patent of J.R. Butts, number 2,892,371. Although the approach was used in a mass produced and popular pickup, it didn't find its way into other products. It is possible that the cost of punching a cutaway shape into the cover exceeded the cost of changing the base material from brass, which is cheap but very conductive, to less conductive alloys known as "nickel-silver" or "German Silver".

As the physical principles of a guitar pickup are relatively simple, also as musicians are generally not concerned with them, and as the proprietary nature of their development and sale has kept the design processes hidden, scientific studies are rare. Also, some of the original thinking behind certain features has been lost. This is unfortunate, not only because they are easier to conduct now than 50 years ago, but because today's technology and markets encompass a much wider range of design variation. Thus, it is rewarding to revisit earlier discoveries as the significance of them has often been overlooked.

Investigation

The presence of the magnetically induced currents mentioned above, known as "eddy currents", are well known. However, they are usually measured and considered in an aggregate fashion. The currents that flow in a cover are impractical to measure in a direct way, for example by applying probes and amplifying the voltage. The voltages are too small, because the ohmic resistance of the cover is very

low. Electrons flow in specific paths, so the effect of eddy currents in materials in a magnetic field depends on finding the paths that they take. They are not directly proportional to shape and size, as when a simple force is blocked by a simple obstacle. Many cover designs fall into this fallacy. For example, If it were a simple field phenomenon, the interference could be reduced in simple proportion to the area of cover material between pickup and strings. But this is not the case.

In a conductor, the flow of electrons is always in continuous paths. In other words, closed loops where the beginning meets the end. This is true, regardless of whether they are constrained by narrow limits, as in a wire, or exist in a large conductive medium in the shape of a block or sheet. Static electric charge is uniform throughout a conductor, but this is not true of currents. By finding the forces that act on the electrons to induce currents we can predict what the current paths will be, given a certain conductor shape.

Electric currents always follow the path of least resistance. By measuring the current in many specific conductor shapes, we can find the ones that have the least resistance. Putting these two facts together, we can deduce what the current paths must be in a sheet or block conductor. Finally, we can then control the currents by introducing insulating gaps in the sheet.

Investigation Phase

To find the current paths, a number of different conductive loops are placed between a magnetic test generator, and the pickup. By considering the geometry of the loops and measuring the electrical response, we can draw probable conclusions about the current paths. These conclusions are tested with prototypes covers to confirm them.

In a bulk conductor sheet such as a solid pickup cover, electrons are free to move in 2 dimensions but are constrained in the 3rd dimension. According to Faraday's law, the electrons are subject to a force at right angles to the direction of the changing magnetic field. The constraints limit the movement of the electrons to 2 dimensions, so the current will follow a vector that is roughly at right angles to the component of the movement of the magnetic field in the plane of the cover.

This perpendicular direction of the electron flow is exploited by the pickup coil, as the magnetic field change is both radial (co-planar with the pickup face) and perpendicular (vertical with respect to the pickup face). Coil geometry is designed and evolved to maximize the efficiency of this arrangement.

A rarely understood consequence of this, however, is that the currents in the cover material obey the same laws. Thus the major flow of eddy currents parallels the geometry and direction of the current in the coils. This makes the design of covers very simple, with respect to eddy currents, because it is very easy to predict where they flow, using these principles.

It only remains to demonstrate the reliability of the theory. This has been accomplished in the following experiments.

Theory

A collapsing magnetic field, shown in the diagram below as inward pointing arrows, represents the change in magnetic field produced by a vertical movement of the string. It also has a vertical component, which is not shown for simplicity.

The resulting electron flow is shown also, in A) and B).

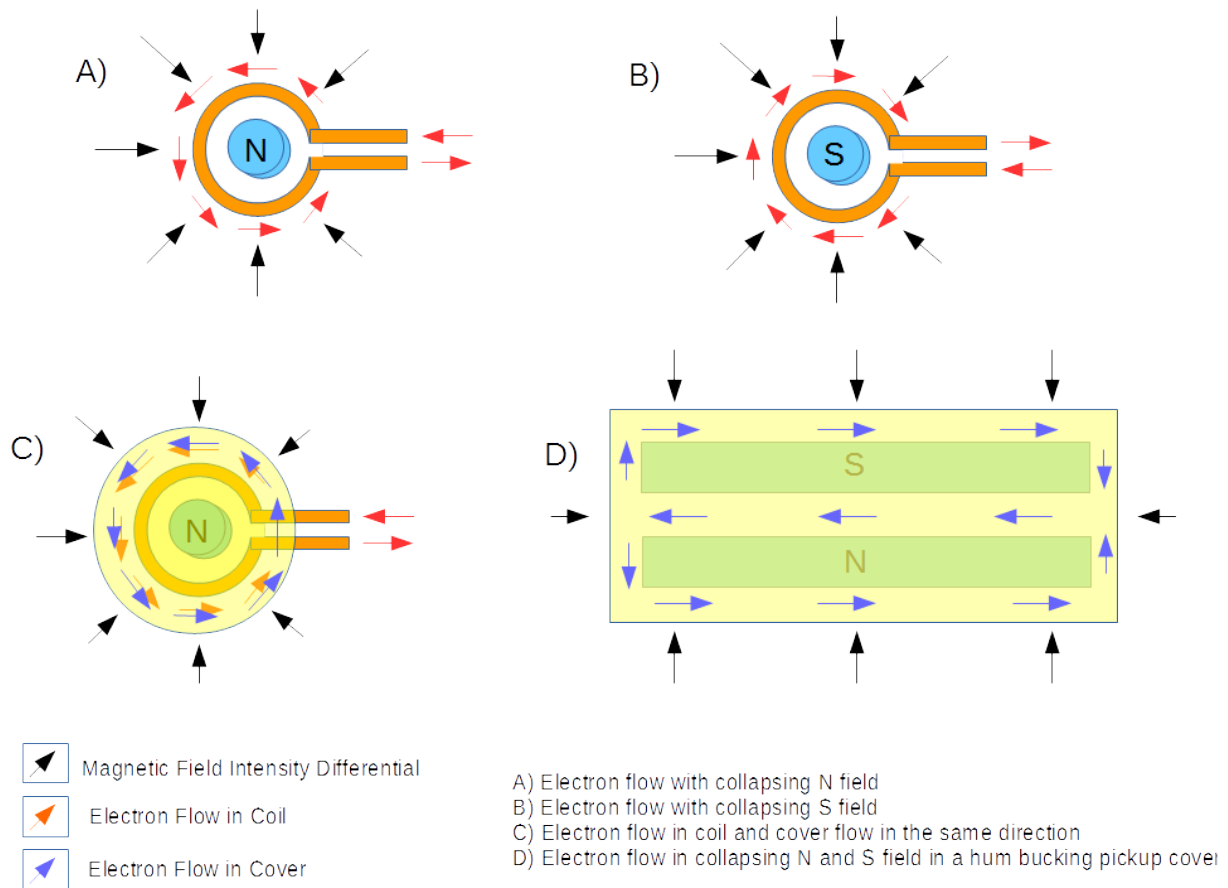


Illustration 1: Electron Displacement

As you can see, the electron flow is dependent on the polarity of the magnet, so that the current flows in different directions in A) and B) because the magnet polarity is N and S, respectively. When a cover (represented by the yellow circle) is placed over the coil in C), electrons flow in the same direction in both the cover and coil as represented by the blue and red arrows. This happens because they are both in the same magnetic field.

This situation models the movement of electrons in a single coil pickup, except that the overall shape is rectangular rather than round.

A humbucking pickup combines two coils and magnets of opposite polarity, so that in effect the devices A) and B) are placed adjacent to one another under a single cover, as shown in D). In that case, the eddy currents form two paths which meet in the middle. Also, the currents at the outer boundary are in opposite directions, and perfectly cancel. Hence there is no current flow there.

Thus, for the eddy currents in a single coil to be reduced, the cover sheet must have an insulating gap somewhere between the center and the periphery, to interrupt these large scale current loops. For a humbucking pickup, the cover sheet must have an insulating gap that blocks both of the current loops that are formed by the two opposite magnetic fields.

This was the method used by Ray Butts in his 1957 patent:

Observe how the poles screws are exposed and the cover material has a gap in the middle section, visible in Fig. 1 and Fig. 6.

This is specifically designed to block eddy currents.

Because it is in the middle section, it simultaneously blocks the currents from both coils.

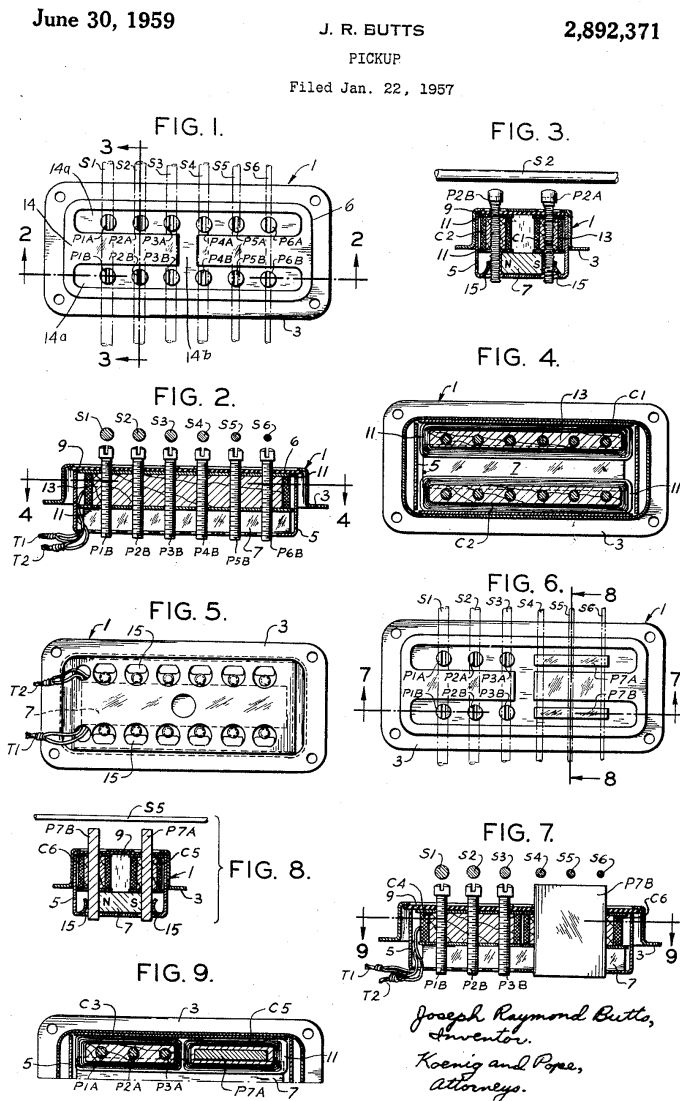


Illustration 2: Patent 2,892,371

Method

A specially constructed test coil is placed in front of the pickup, where the strings would be positioned. It is driven with a constant current sine wave, swept across the audio range. The signal from the pickup is buffered by a high impedance amplifier, and then integrated to compensate for the differential +6dB/octave slope imposed by Faraday's law. The result is a frequency vs. amplitude graph of the pickup's response in the audio range.

An assortment of copper wire loops were built, with different dimensions:

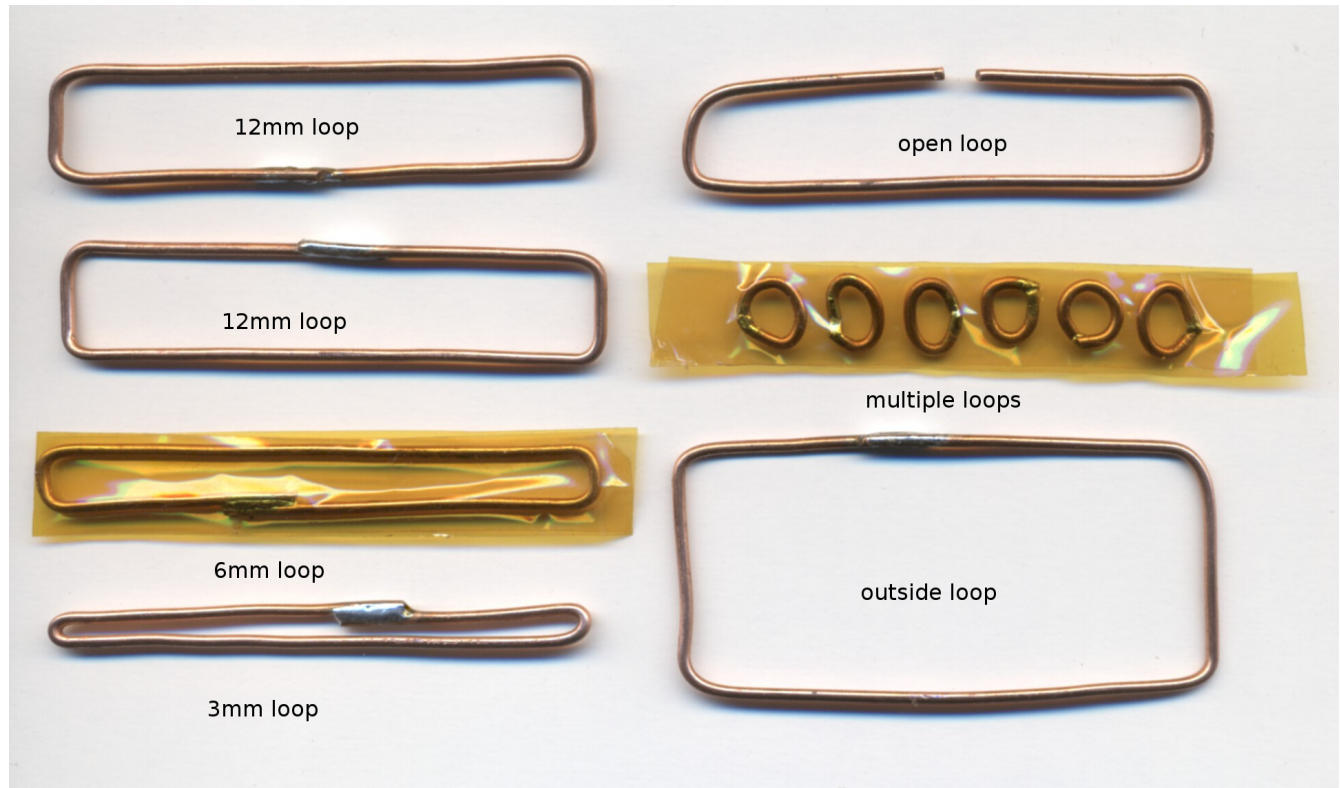


Illustration 3: Copper Test Loops

These loops were placed between an uncovered pickup and the test coil, such that the currents in the coil can be deduced from the measured losses, obtained from a test plot. By comparing different loop positions and shapes, favourable paths for induced currents can be found by identifying the configurations that produce the highest losses.

Once the fundamental eddy current paths are found, brass covers of different designs were constructed and placed on the pickup coil assembly for testing. The results of these tests are exactly consistent with the copper loop experiments, showing conclusively that the major eddy paths follow the usual coil geometry by forming paths around the magnet or magnetized pole pieces of the pickup.

First the effect of cover height and the possible interference of the cover with the test coil were investigated. This was performed by separating a single coil pickup from the test coil by 1 cm. Then the test loop was placed in different positions and the losses measured.



Illustration 4: Loop at bottom of coil



Illustration 5: Loop adjacent to exciter coil



Illustration 6: Loop at top of coil

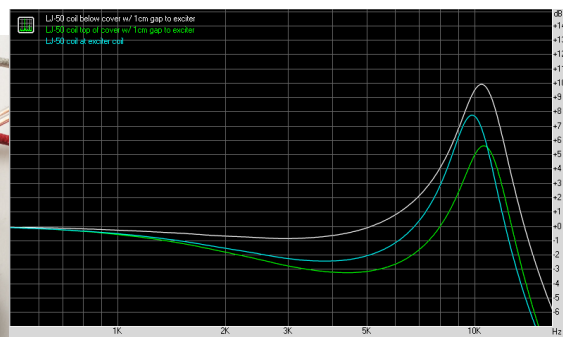


Illustration 7: exciter coil effect test

It is evident that the test loop (which creates large eddy losses) has some effect on the test coil, as shown when the loop is adjacent to the test coil, and the relative loss is about 2dB. The loop has minimum effect when it is positioned at the bottom of the coil, as in Illustration 4. The maximum effect is seen when the loop is at the top of the coil, as in Illustration 6. This shows that the eddy effects are greatest at the top surface of the pickup cover, and that pickup materials have diminishing effects as the distance from the top increases.

It also strongly indicates that components such as the pickup baseplate will have minimal eddy current losses compared with the cover and magnetic poles that are nearer to the top.

Having shown that the loop losses do not interfere very much with the exciter coil, we then measured the losses with the loop in several positions, shown in Illustration 8. It is obvious that the losses diminish in exact proportion to the distance from the top.

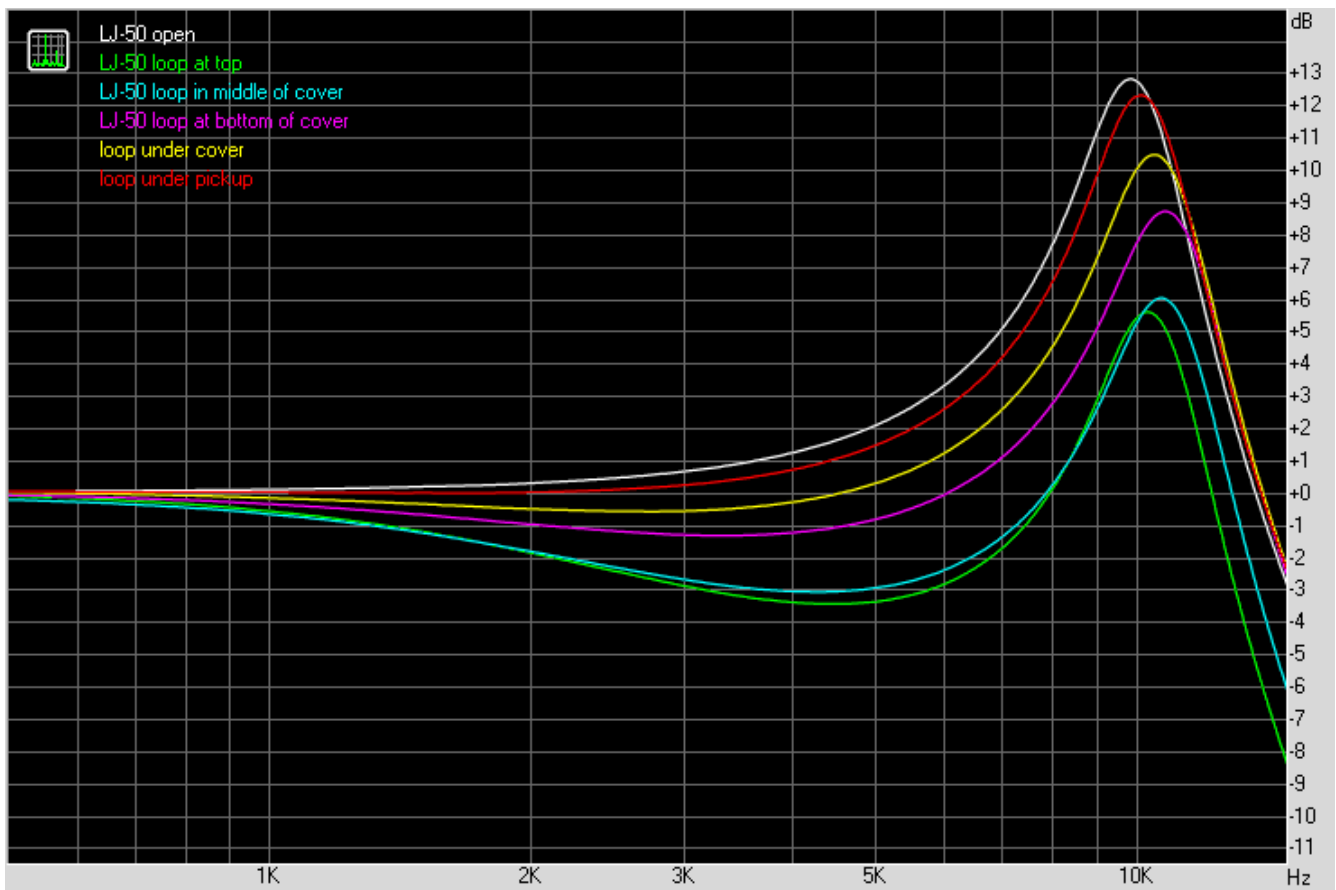


Illustration 8: Losses vs. Loop Vertical Position

The significance of this part of the investigation is that it proves that we can concentrate on the losses induced on the front surface of the pickup, and not worry too much about losses behind the coils, in the baseplate and other supporting components.

The next step is to firmly establish the geometry of the currents at the cover surface. This was achieved by comparing test loop configurations with loss measurements. These strongly confirm the theoretical current flows in Illustration 1.

For this, the loops are placed over the pickup (the poles must be insulated with Kapton tape), and the exciter coil place in position over it:

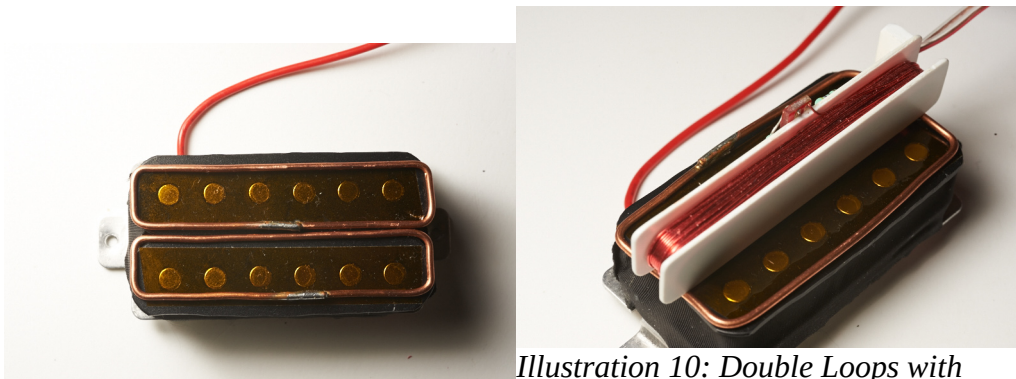


Illustration 9: Double loops

Illustration 10: Double Loops with Exciter Coil

The configurations of Illustrations 9 and 10 show the following plots:

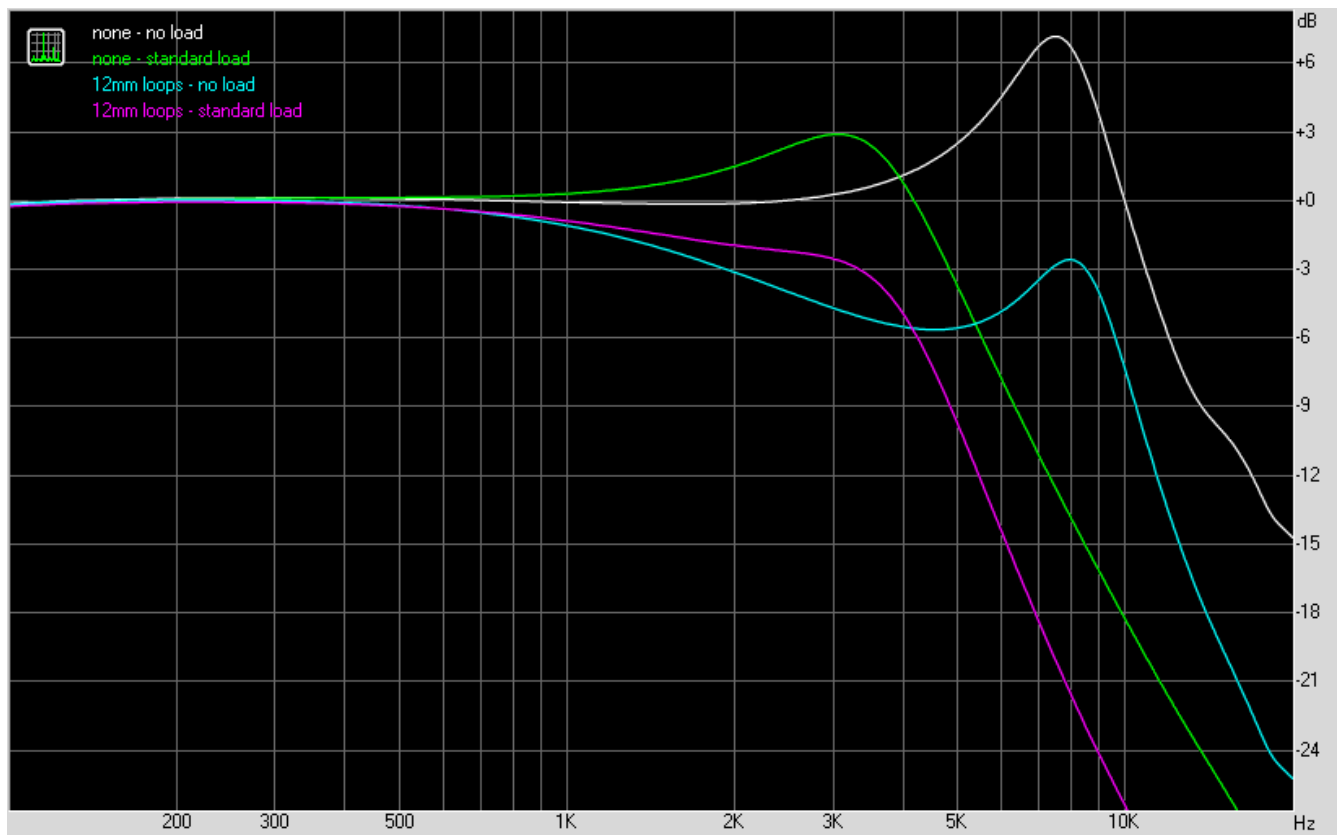


Illustration 11: Double 12mm Loop Load Effects

In Illustration 11, the pickup response is shown with and without the loops in place, and with and without a simulated guitar electronic load of 200k resistance and 470pF capacitance. The 12mm loops show a dramatic loss in both the loaded and unloaded plots. There is a 6dB loss when loaded, and a 10dB loss when not loaded. Although the 14 gauge copper wires are thicker and more conductive than a formed sheet metal cover, they demonstrate the effect of a solid brass cover which has a slightly lower conductivity.

Actual solid cover vs. no cover measurements differed by about 3dB for a loaded, and 8dB for an unloaded pickup, which can be observed in several of the following charts.

To ensure that the theory accounted correctly for other possible current paths, a variety of other loop configurations were tested. Loop width was tested with a series of 3mm, 6mm, and 12mm wide loops. Individual pole currents vs. compound pole currents were tested with a multiple set of 6 individual loops. The necessity of continuous circuit was tested with an opened vs. a closed loop. The differential current around the perimeter of both coils, was tested with a single 30mm x 70mm “outside” loop.

All of these tests supported the basis of the predicted current paths in a sheet conductor cover as shown in Illustration 1.

In the interests of brevity, I will show them and for the most part allow the reader to examine the plots to see how the tests resulted. I will summarize at the end.

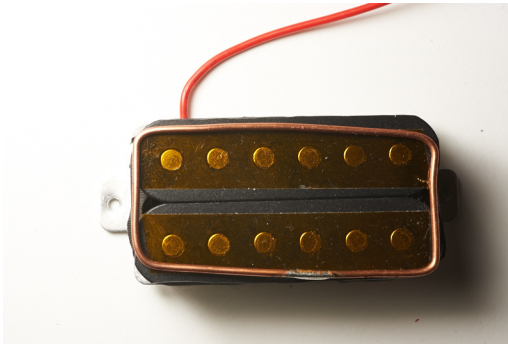


Illustration 12: Outer Loop

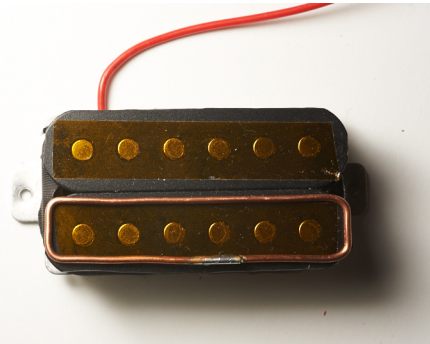


Illustration 13: 12mm Loop

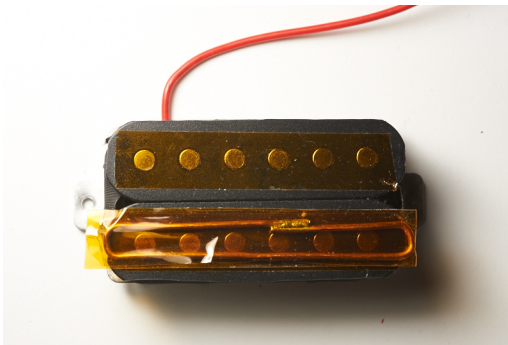


Illustration 14: 6mm Loop

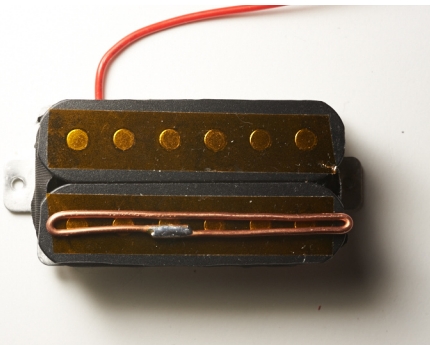


Illustration 15: 3mm Loop

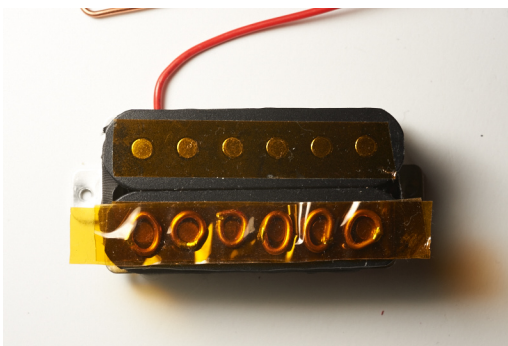


Illustration 16: Multiple Loops on Poles

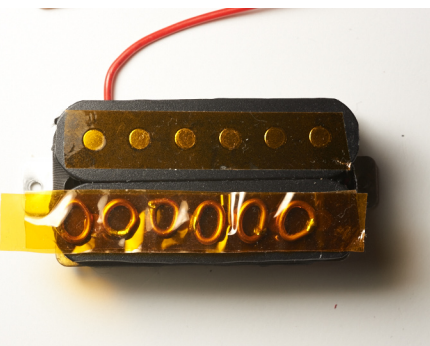


Illustration 17: Multiple Loops on Poles - offset 1/2 pole distance

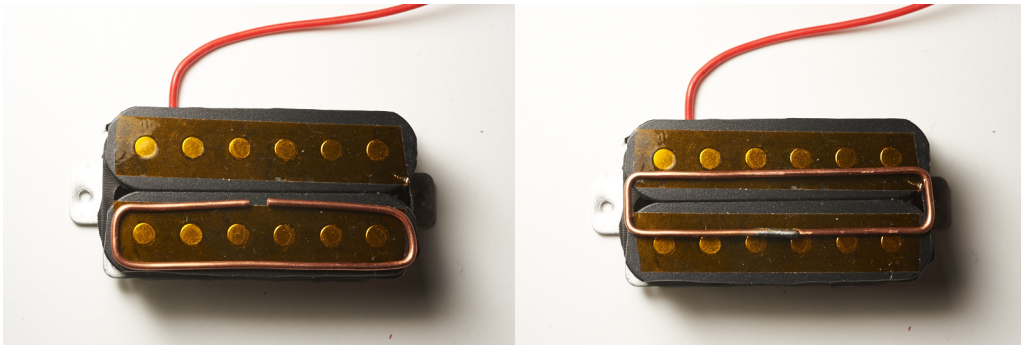


Illustration 18: 12mm Loop with insulating gap

Illustration 19: 12mm Loop centered on pickup

The effect of the outer loop in Illustration 12 was minimal, introducing only fraction of a decibel losses. The same can be said of a centered loop, as in Illustration 19.

Loop width as shown in Illustrations 13,14,15 has a proportional effect. The smaller the loop, the fewer losses, and therefore the less eddy current is found closer to the poles. The greatest currents were seen with the 12mm loop:

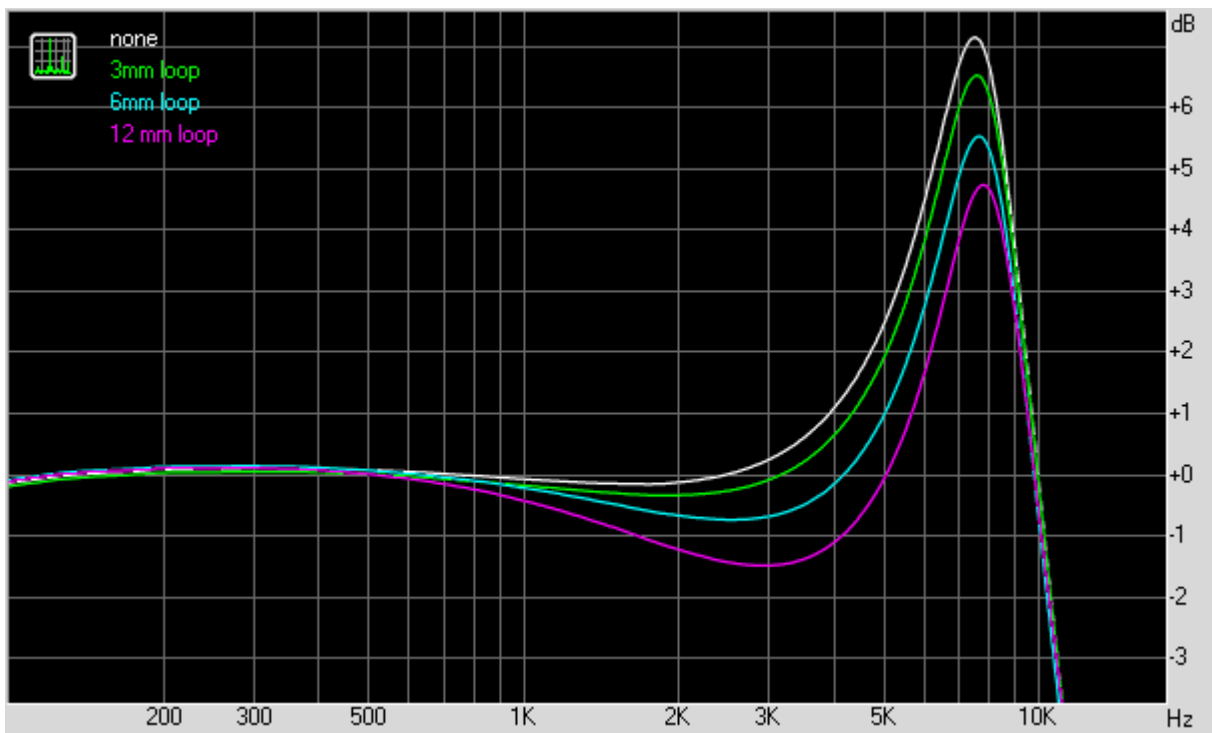


Illustration 20: Loop Width Effect

Currents local to the poles are explored with the multiple loops in Illustrations 16 and 17:

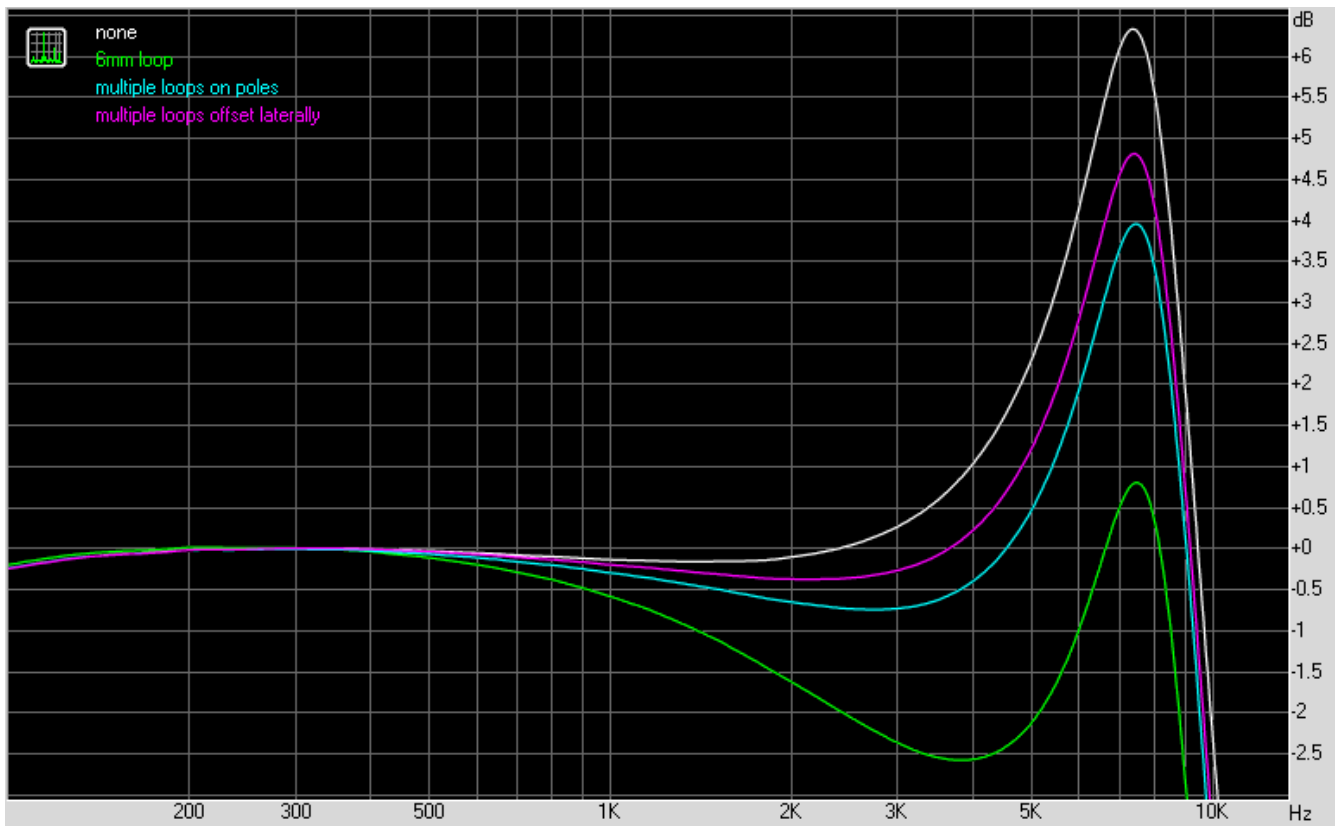


Illustration 21: Multiple Loops vs. Single 6mm Loop

As the multiple loop assembly uses approximately 6mm loops, a comparison to a single 6mm loop (Illustration 16) shows that a major circuit around all the poles is much more significant than the smaller eddies around the poles. By offsetting them by $\frac{1}{2}$ pole spacing, it is shown that the effect is indeed centered on the poles, and is definitely dependent on position.

Covers

Four identical chrome plated brass covers were obtained, and three of them were modified to produce prototype cover geometries. This ensured that any differences could only be attributed to shape.

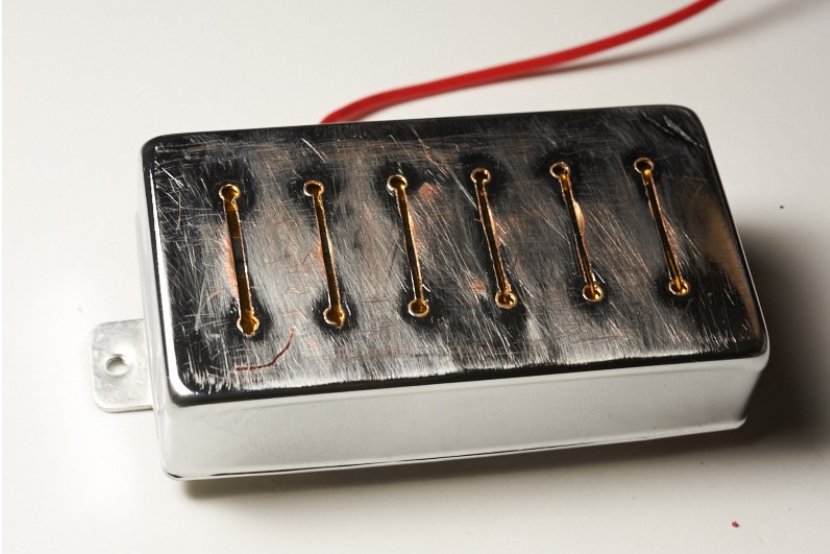


Illustration 22: Half Slot Cover



Illustration 23: Full Slot Cover

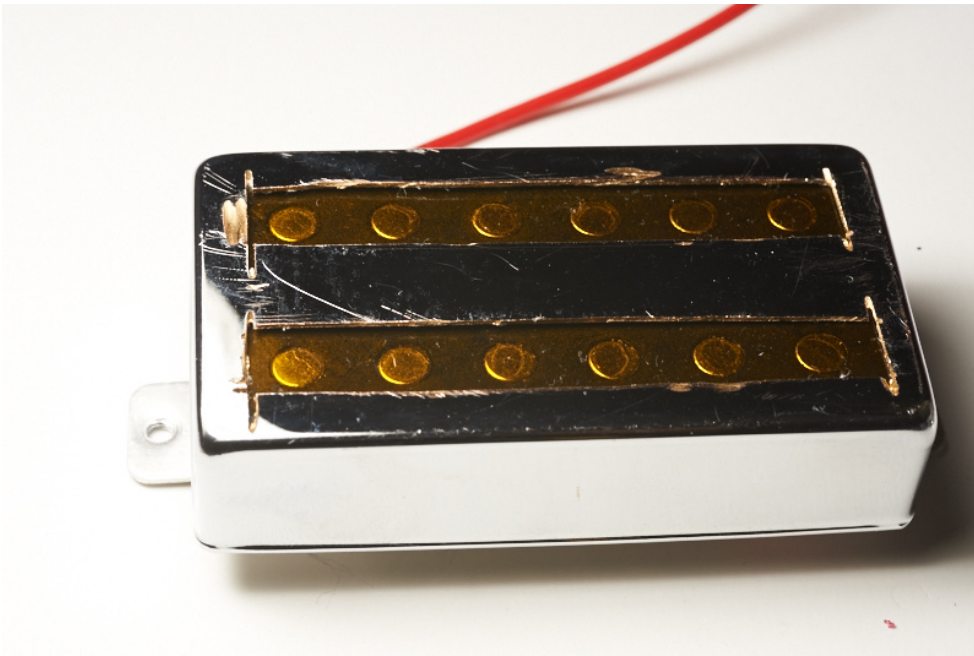


Illustration 24: "toaster" cover - non gapped center section

The “toaster” cover emulates a Butts type cover without the insulating gap in the middle section. As such, the losses are almost as bad as a solid cover. Yet, it is actually used by a fairly well known guitar company in several models. In that pickup type, the cutouts are only an alternative to through holes for the double set of pole screws that protrude above the pickup top. Clearly, it is only for cosmetic value, or to convince people that the poles can magnetically “see through” the spaces. But it is a design failure. It can only work when nickel-silver is used as a material, in which case a solid cover is almost as good.

Here is how it compares. It is barely different than a solid cover:

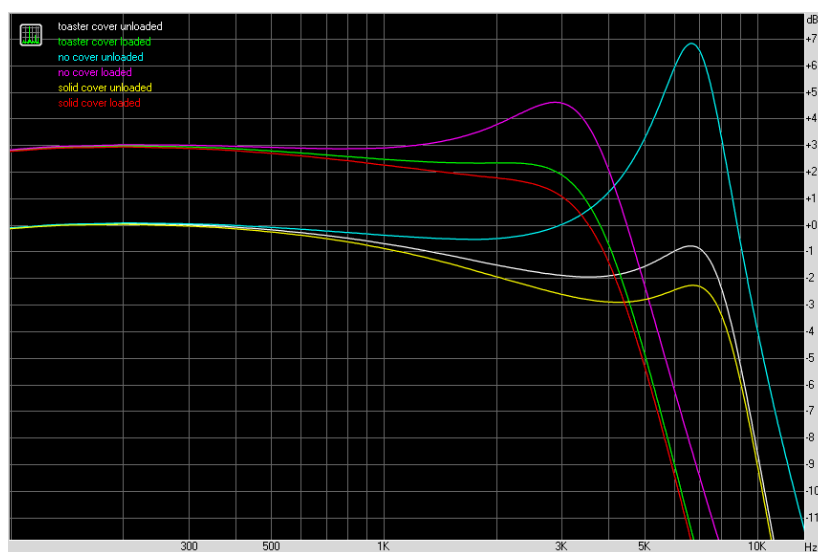


Illustration 25: Toaster cover performance

The full slot cover in Illustration 23 embodies insulating gaps to interrupt both the major current flows, and the localized flows around the gaps. It does this by gapping both sides, and across, the poles. It yields the highest performance, as shown here:

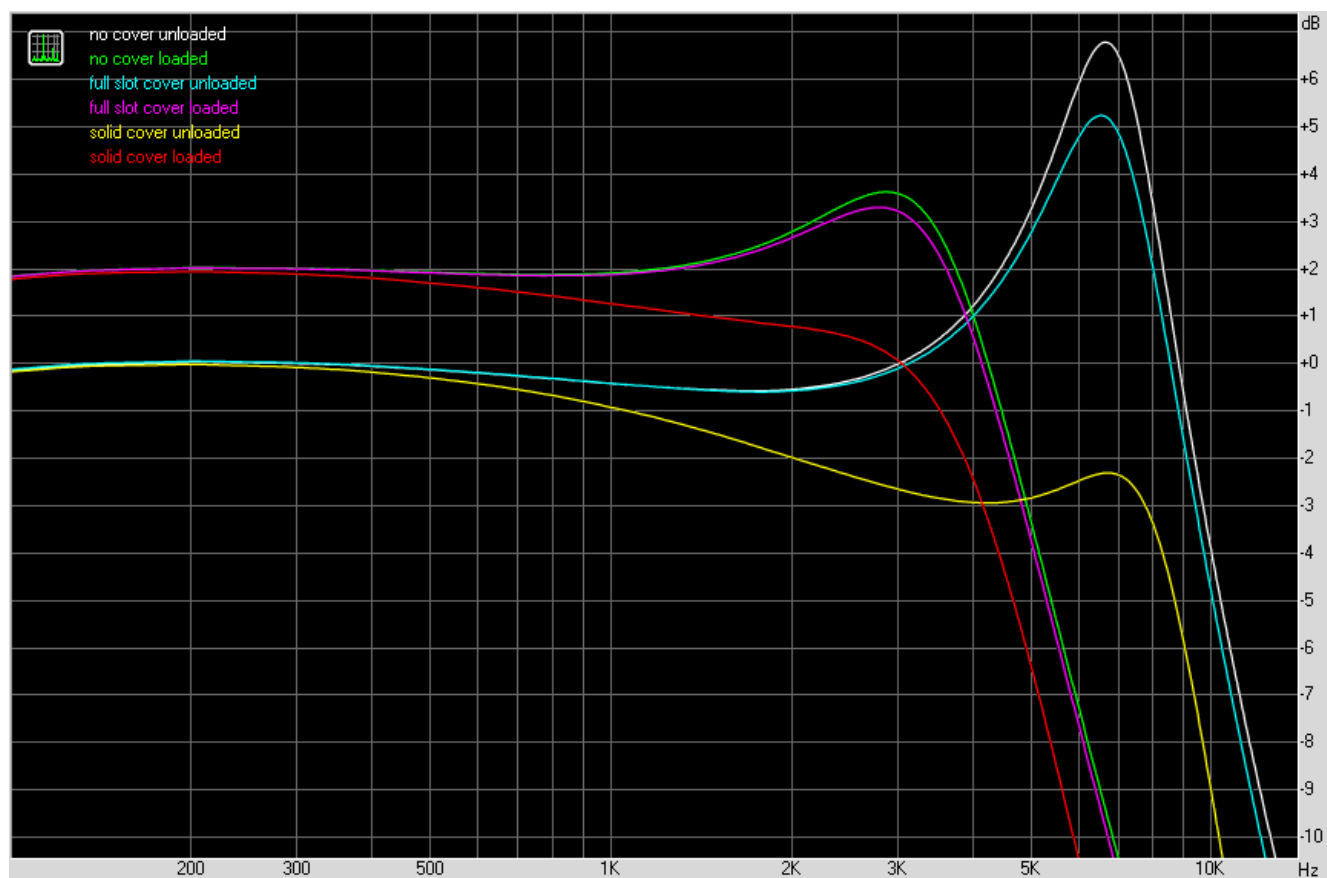


Illustration 26: Full Slot Cover performance

The magenta and green line in Illustration 26 differ by at most about 0.5dB, which is considered completely inaudible under all but extremely unusual circumstances. It is a close approximation to how the tone would vary in an actual guitar circuit. If the cover were made of nickel-silver instead of brass, the difference would narrow to an extent that would make it difficult to even measure. Thus, such a cover could be used in the absolute confidence that it would have no audible effect on the tone of the pickup.

The Half Slot Cover in Illustration 22 performs surprisingly well. It seems counter intuitive that there is so much solid area in the outside region adjacent to the poles, and yet it has little effect. This really happens because the major current flow around the periphery of the poles has been blocked on one side by the series of slots. These need only extend to the pole centers for this design variant to work. It does not perform quite as well as the full slot version because the minor eddy currents have larger regions in which to develop.

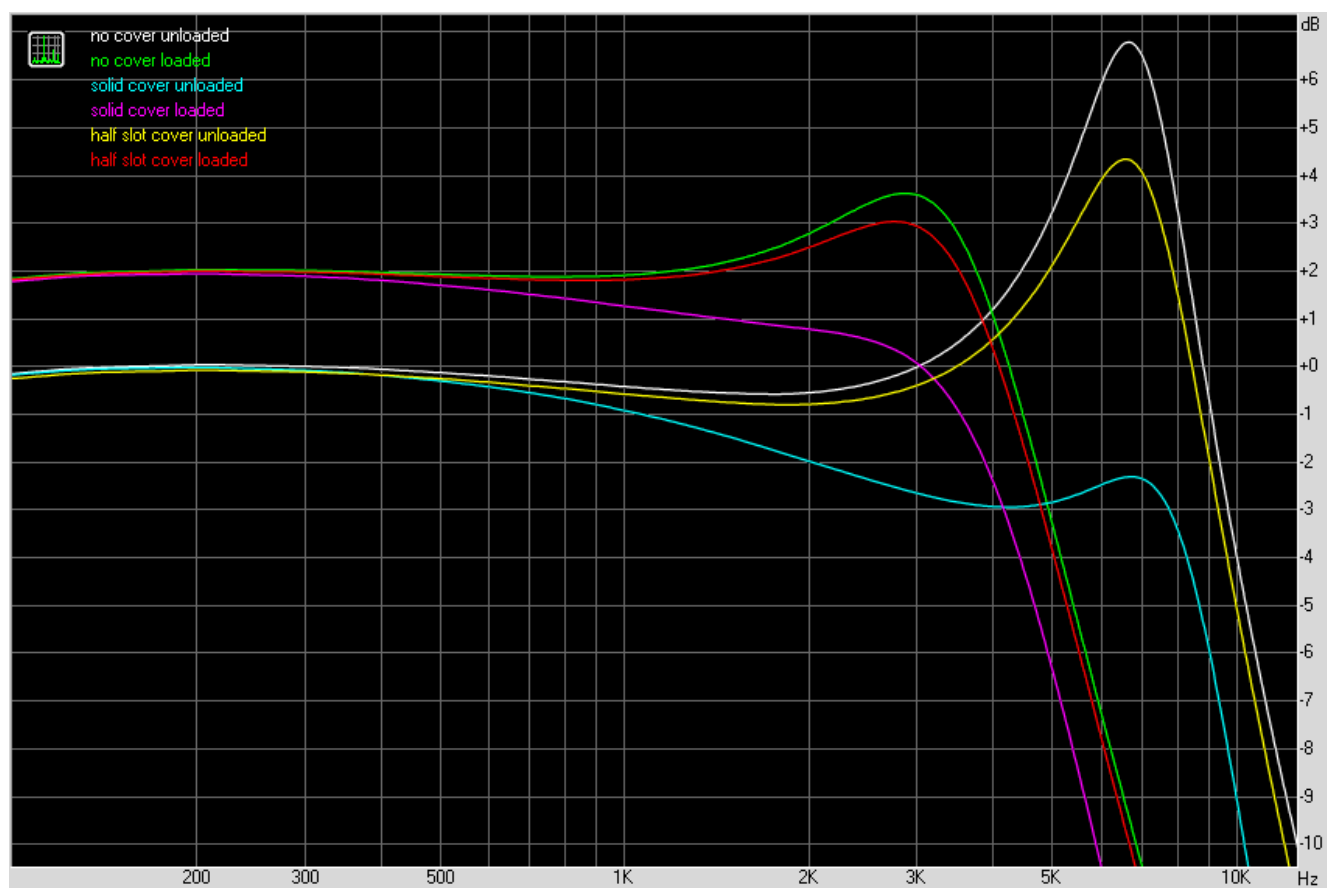


Illustration 27: Half Slot Cover performance

Amazingly, the loaded loss is about 0.7dB, which is on the extreme threshold of audibility.

Because these innovations can be applied to any kind of cover material, there are two main application areas in which they may be useful. First, it allows the use of brass, which is a cheap and readily available metal with which to build covers. In that case, there are only minor losses, the elimination of which will simply improve the treble tone of the pickup. Alternatively, when using nickel-silver, it could guarantee complete sonic transparency to players who value that quality very highly, yet do not wish to sacrifice the protection and better appearance that metallic covers provide.

The slotted designs lend themselves to aesthetic variation, such as silhouetted slot artwork, integration with pole screws, and coloured or textured insulation layers behind the slots (gold foil, for example).

The same principle can be applied to single coil pickup covers. However, care must be exercised as the outer frame currents do not cancel as in the case of a humbucker. Thus, it is important to make a fully insulating gap, not only on the top surface, but also all the way around. This is problematic when the baseplate is metallic. However, the Telecaster neck pickup base is non-metallic, so it is possible to gap it completely. The single tab can still be used to ground the shield without creating any eddy losses. As with the humbucker, all metal parts including magnets must be insulated from the cover with tape.

Tele neck cover mod
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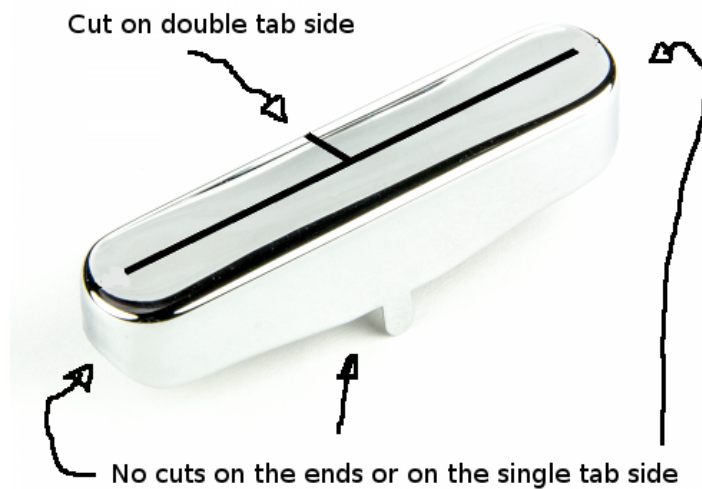


Illustration 28: Tele Neck modification - bridge side

Tele Neck cover mod
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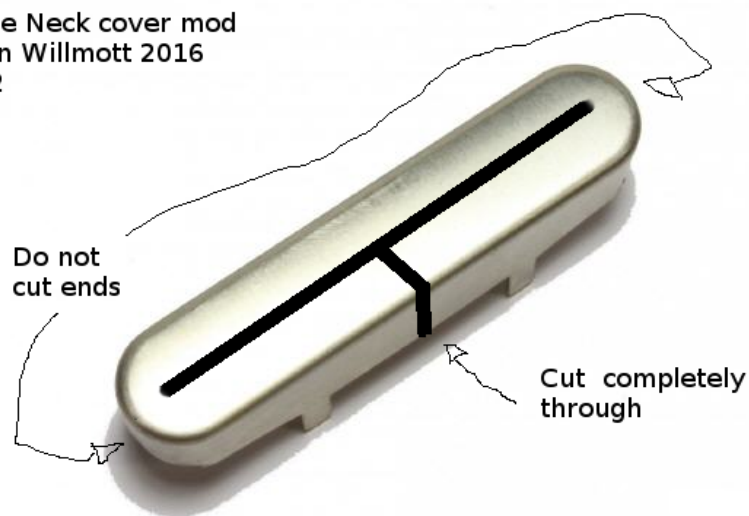
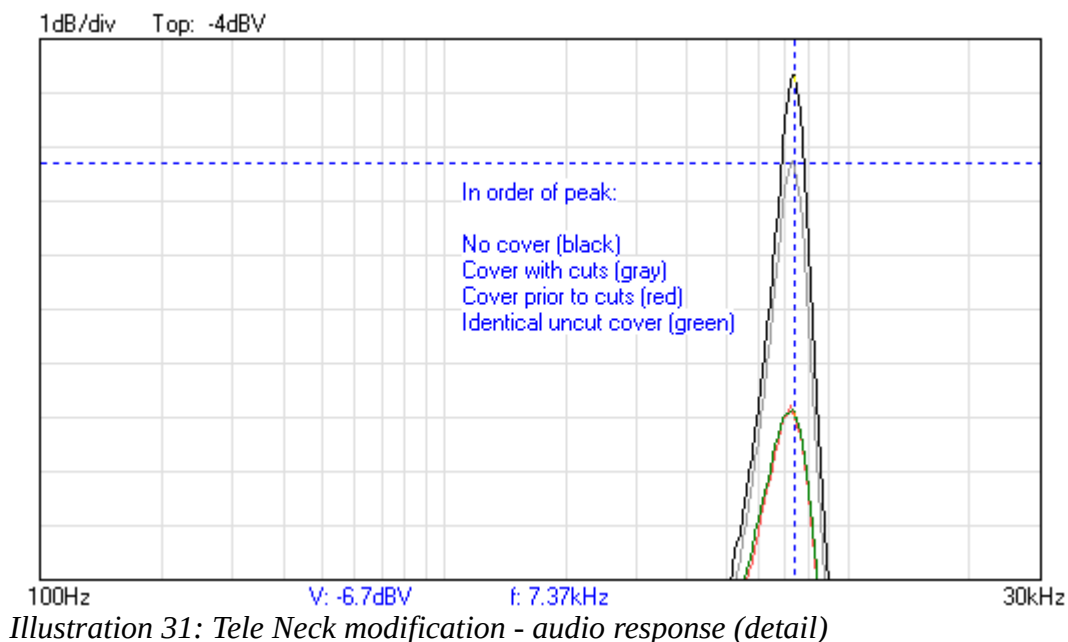
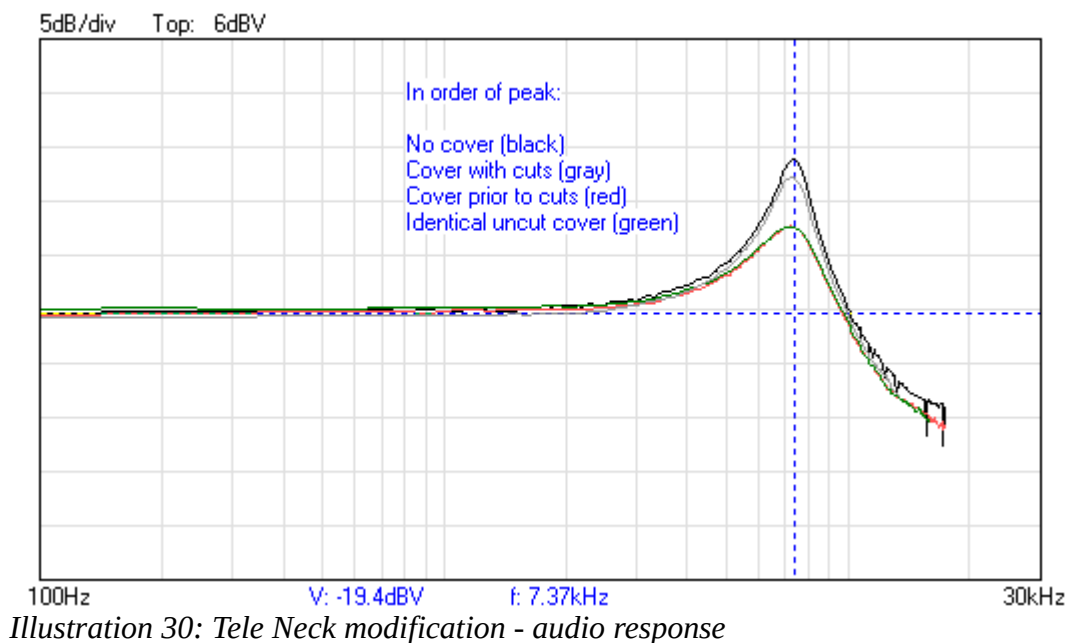


Illustration 29: Tele Neck modification - neck side

The tests reveal that with this modification, the eddy current losses in the pickup are reduced to a small fraction of what they are with the solid cover in place. In the case of a brass cover, this means that the tone will improve audibly. In the case of a superior nickel-silver cover, it can be said that there can be no significant difference between the pickup with the cover on or with the cover off.



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Special thanks to Andrew Flanders for performing the Telecaster Neck pickup testing.