5. Magnetic Pickups

In a magnetic pickup (TA) the vibrating string produces an alternating magnetic field which generates a voltage in a wire winding (coil). The string in itself in its original state is not magnetized; the magnetization is derived from a permanent magnet installed at a small distance under the string. Consequently, the pickup consists of a permanent magnet and a coil plus some housing components, which keep everything in place. Sometimes additional metal parts are included to guide the magnetic field.

The magnetic pickup belongs in the category of passive magnetic transducers [3] and uses the electromagnetic conversion principle. The vibrating string changes the magnetic reluctance resistance in the permanent magnetic circuit, and due to temporary magnetic flux changes in the coil an electric voltage is induced. The magneto-electric conversion must not be confused with the electro-dynamic conversion – in the latter a voltage is induced in an electric conductor moving in a magnetic field. Examples for electro-dynamic transducers are the dynamic loudspeaker and the dynamic microphone. For both it is the coil which moves relative to the magnet. In a guitar pickup coil and magnet are fixed relative to each other. Although a minute induction voltage is generated in the moving steel string this effect is not exploited.

5.1 Single-coil pickups

Close to the bridge, the six strings of the guitar have a distance relative to each other about 1 cm. In order to generate the loudest possible signal, every string has to be subjected to a strong magnetic field. For many pickups, this is achieved by the use of six cylindrical permanent magnets positioned in parallel and having a diameter of about 5 mm and a length of about 1 cm. They are oriented all in the same way i.e. such that all north poles point in the same direction. The magnets are stuck in a **bobbin for the coil wire**. The coil is protected against damage by insulating tape or by a proper housing. Two to four screws keep the pickup at a short distance below the strings. Most electric guitars have two or three pickups; one or four pickups are more rare. A special design form is the twin-coil humbucking pickup. For these pickups two coils are positioned side by side in the same housing. This design reduces the sensitivity against external noise.

Instead of the six individual magnets, alternatively a **bar magnet** positioned below the coil may also be used. For improved field guidance six cylindrical iron slugs are inserted through the coil in this case. On their lower side, these slugs (also called pole-pieces) touch the magnet, or they are held in a metal bar which touches the magnet. Often these pole-pieces are designed as screws such that the volume of each string can individually be adjusted. Over time, different pickup designs came into existence – the most important ones are being compiled at the end of the chapter

To shield the pickup against **electrostatic interference**, metal covers are sometimes installed over the pickup coil. In practice, the **effect of this shield** is rather modest because the main interferences are not due to electrostatic but due to magnetic interference fields (such as they are e.g. generated by transformers). Against magnetic fields a pickup should not be shielded due to its working principle. The string vibrations are generating also a magnetic field and it is this field which the pickup needs to sense - a cover made out of magnetic material consequently is ruled out. Moreover, even shielding covers made of un-magnetic material (e.g. brass or nickel silver) can have undesirable effects on the magnetic field because **eddy currents** are generated within the material which themselves again generate magnetic fields. Many guitar players therefore remove the pickup covers and achieve a small change in sound: the pickup resonance emerges a bit more strongly which usually which often is perceived as sounding better

The magnetic guitar pickup has a long history. In 1831, the English physicist MICHAEL FARADAY (1791 – 1867) made the fundamental discovery that an electric current is flowing in a closed conductor loop penetrated by a magnetic field of changing strength. At the same time – but independently – the American physicist JOSEPH HENRY (1797 – 1878) arrived at similar conclusions. The quantitative correspondences between the changing magnetic flux density and the voltage induced by it are described by the **induction law** (see chapter 4.10) which is called the FARADAY-HENRY-law after their discoverers. About 100 years after its discovery this law yielded the basis for the mechano-electric transduction of the sounds of the guitar which up to that time were rather soft in nature: the electromagnetic pickup emerged. Who in fact built the very first magnetic guitar pickup cannot be established with absolute certainty. DeArmond, Rowe and Beauchamp are often mentioned, and likewise manufacturers such as Rickenbacker, Gibson, Epiphone, Gretsch. National – and Fender, of course.

Leo Fender facilitated the commercial breakthrough of the solid-body guitar. Teaming up with George Fullerton, he developed the prototype for an electric guitar of solid wood in 1949. This instrument was introduced to the marked in spring of 1950 under the name **Esquire**. In autumn of 1950, the 2-pickup **Broadcaster** followed, being renamed **Telecaster** shortly thereafter. Leo Fender's original guitar is seen as the archetype of all solid guitars, even though Lester Polfuss, better known under his pseudonym **Les Paul**, had already been working on a similar concept for more than 10 years. However, his ideas – picked up by Gibson – made it into production only by 1952.

The first Fender guitars were fitted with simple single-coil pickups - a tradition which is retained to this day. Leo Fender used an individual cylindrical magnet for each string, according to his own words this was to minimize the interaction between neighboring strings. Together with flanges pressed on to them, the 6 magnets form the coil carrier (bobbin) around which very thin enameled copper wire is wound. The magnet diameter is 3/16" (approx. 4,8 mm); the length of the magnet varied over the years (and across various Fender guitar models) from 12 to 19 mm. The magnets consist almost exclusively from Alnico-5 (also known as Alnico-V) which is a magnetic alloy developed in the 1940's. The flanges were first made of vulcanized fiber of approx. 2mm thickness; this is a high-strength, horn-like material. The color and thickness of the flanges varied over the years, and from 1980, injection-molded bobbins were also used. The diameter of the magnet wire wound around the 6 magnets is measured according to the American Wire Gauge: most pickup coils are wound with AWG #42 but in some cases the thinner AWD-#43 wire is used (see chapter 5.5.).

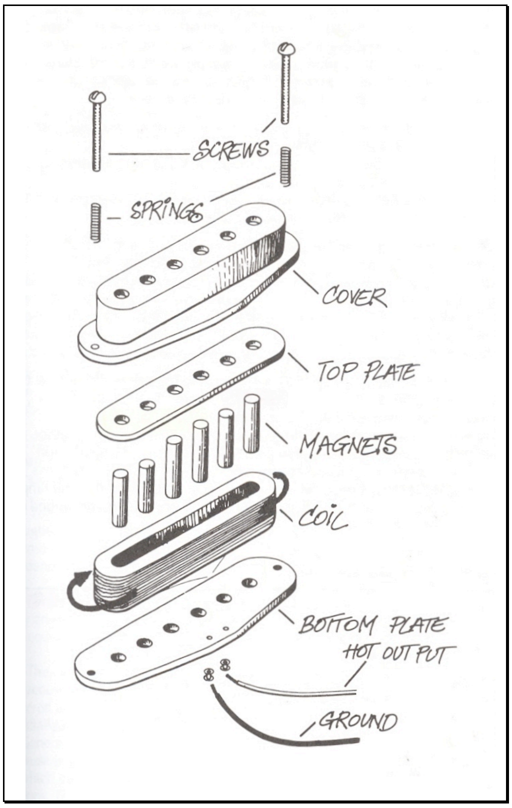


Fig. 5.1.1: Components of a Fender-Stratocaster-Pickup [Duchossoir].

Fig. 5.1.1 shows the components of a Fender single-coil pickup, in this case a Stratocaster pickup recognizable from the plastic cover. The characteristic feature is the group of 6 cylindrical magnets onto which the winding is directly placed. The two Telecaster pickups are structured in a similar way although there are some minor different details. Using the same basic construction principle, the Jazzmaster pickup was developed in 1957 - it however clearly departs from its predecessors in its dimensions. Leo Fender sought a different sound and widened the coil from 12 to 35 mm, while at the same time reducing the pickup length. "*The Jazzmaster pickup wasn't so deep, and it was wider, thinner, more spaced out. See, the more spaced out the coil is – the wider the spectrum under the string – the warmer the tone. But a broad spectrum of tone places a lot bigger demand on the amp, and the earlier tube amps we had were kind of limited in the amount of power they could handle.* [Wheeler]."

From the point of view of today's systems theory, Leo Fenders above explanation is not comprehensible. One could surmise that the thinking then was to sample a longer part of the string vibration via a wider coil, i.e. longer magnetic window (the magnetic aperture) was desired. However, as will be shown by the analysis in Chapter 5.4.4, the length of the aperture is in practice only dependent on the diameter of the magnet irrespective of the coil. Fender's referring to *spectrum* also remains unclear: surmising that he desired a larger window-length, one would expect a *narrower* bandwidth since time and frequency have a reciprocal relationship. Conversely, Leo Fender talks about a *wider* spectrum to which he attributes a *warmer* sound. Again, this does not fit: warmer sounds result from attenuating the treble, i.e. are connected to reduced bandwidth. Bandwidth reduction, however, cannot be what Fender meant, either, because his statement that a broadband signal challenges the amplifier more is correct. It seems wise not to expect a lot of theory behind the first pickups: the systems theory was still the new kid on the block in those days, and the development objectives were not governed by science but by an empirical approach and sales reports.

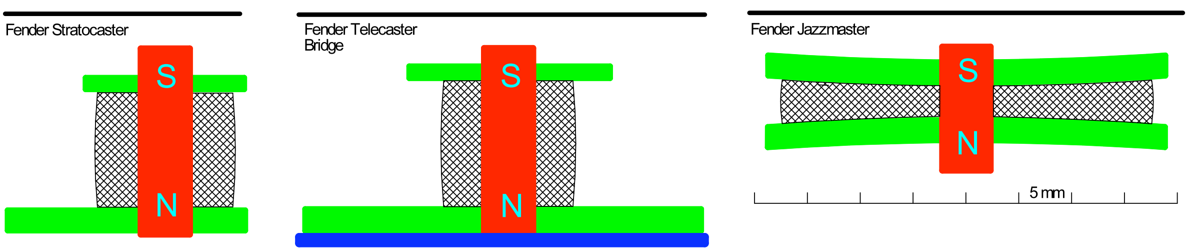


Fig. 5.1.2: Cross-sections of Fender pickups: Stratocaster, Telecaster (Bridge), Jazzmaster.

In **Fig. 5.1.2** shows cross-sections of Fender pickups. The heavy line at the upper border marks the position of the string while the cross-section of the coil is represented by the crosshatched area. Length and protrusion of the magnets changed several times for the Stratocaster and Telecaster – only the Jazzmaster-pickup with its relatively short lifespan retained its geometry.

The magnets of the first pickups were mounted flush with the upper flange (the one closer tot he strings), but as early as approx. 1954 **staggered pole-pieces** were introduced i.e. the magnets were protruding unevenly from the upper flange. This allows for compensating for different loudness of the individual strings – but NOT by the musician! Recommendations to shift the magnets with light hammer strokes such that all strings have equal loudness may meet with a rather unexpected success. If in this process the coil wire directly sitting on the magnet is torn, indeed the loudness of all strings will be equal: it will be equally at 0! The philosophy behind the staggering is unclear: the first "staggered" pickups had the D-Magnet protruding the most, then this changed and the G-magnet was closest to the strings. Later, pickups with magnets of equal length and protrusion were built (**level pole-pieces**), and then again the D-magnet is most prominent "to eliminate the *chorusy warble*". A result of the staggering is the overall lower loudness of the guitar because the coil needs to move away from the string (5.4.5). There might be some reasoning in the fact that the G-string may be wound or plain, but the multitude of pickups offered today proves that staggering is not a mandatory requirement.

The material for the magnets of early Fender pickups was **Alnico-V**, an alloy from aluminum, nickel, cobalt and iron. Although literature for magnets lists exact percentages of the alloy components, considerable **variations** in the actual magnet data should be expected. The shape of the hysteresis does not only depend on chemical composition but also very much on the manufacturing process (4.4.1). Furthermore, it should be considered that due to the war effort cobalt became scarce. Today nobody can remember exactly what was actually sold ... and what was in fact used. Seth Lover, the man who developed the Gibson Humbucker, notes: "*We also used Alnico II and III, and the reason is, that you couldn't always buy Alnico V, but whatever was available we would buy as they were all good magnets*". And even if the same magnet material is used in pickups: in modern times the data of simple cylindrical magnets vary by ±10% – the likelihood is small that back in the good old vintage days this situation would have been any better.

Finally we need to consider the magnet-parameter which no data sheet presents with much precision: the **reversible permeability** of the magnet. This quantity describes how many times the alternating flow conductivity in the magnet is higher that that in air. Typical values range from 3 to 6; it is almost impossible to give exact data since the inhomogeneous (location-dependent) magnetic flux-density leads to a total value which is application dependent. The reversible permeability μ_{rev} determines by how much the magnet increases the inductivity of the coil. However, μ_{rev} may not be applied directly; rather, a corrected, smaller values need to be used because the major part of the field travels through air. Replacing the magnets in a pickup may have several consequences: the string magnetization can change which results in different loudness. Changes in the field geometry could change the length of the aperture, although the connected change in treble reproduction will be mostly minor. Changes in the reversible permeability moves the pickup resonance which determines the sound, and changes of the eddy currents generated in the magnet change how much the resonance is pronounced (i.e. the emphasis or Q-factor).

Since the construction principle of the first Fender pickups was as simple as it was efficient it is still used today. Criticism was voiced only regarding two disadvantages: the sensitivity to hum (chapter 5.2, 5.7), and the missing control over individual string loudness. Though *staggered magnets* offered a kind of loudness balancing, adjustment by the musician was not possible. Pickups with adjustable magnets provided a remedy. In old **Schaller** pickups, the magnets are stuck in thin tubes which carry a screw thread on their outer surface (headless screw, grub screw). Turning these magnets will shift them axially. This trick with the grub-screw design was necessary because almost all magnetic materials (except CuNiFe) are so hard and brittle that no thread can be cut into them. Old **DeArmond** pickups as they are found in early Gretsch guitars have 6 adjusting screws which allow for axial movement of the magnets.

Gibson designer **Walter Fuller** chose a different approach to individual string-loudness control when he developed the **P-90**: this single-coil pickup utilized from 1946 featured two bar magnets below the coil. 6 ferromagnetic screws supply the magnetic flow to the strings (**Fig. 5.1.3**). Occasionally, these screws are called *nickel* screws but this does not indicate that they are (or were) made from solid nickel. It is well possible that they are regular steel screws with a nickel (or chrome) plating. The DiMarzio **SDS-1** and the **Fender**-**Mexico** pickups share their construction with the P-90. The common characteristic are the field-guiding pole-pieces which bridge the (re. Fig. 5.1.2) larger distance between magnet and string. The high permeability of these pole-pieces focuses the magnetic flow through the coil, however at the same time a new material is added into the magnetic circuit on top of magnet and air. The magnetic conductance of air is very small and frequency-independent. Steel (as well as nickel) conducts the magnetic flow much better than air - but only at low frequencies. For higher frequencies, which for pickups already include the kilohertz-range, **eddy currents** appear which lead to an additional attenuation (chapter. 5.9). In comparison to a Fender pickup with cylindrical magnets, a Fender pickup with bar magnets generates somewhat less treble due to the eddy currents.

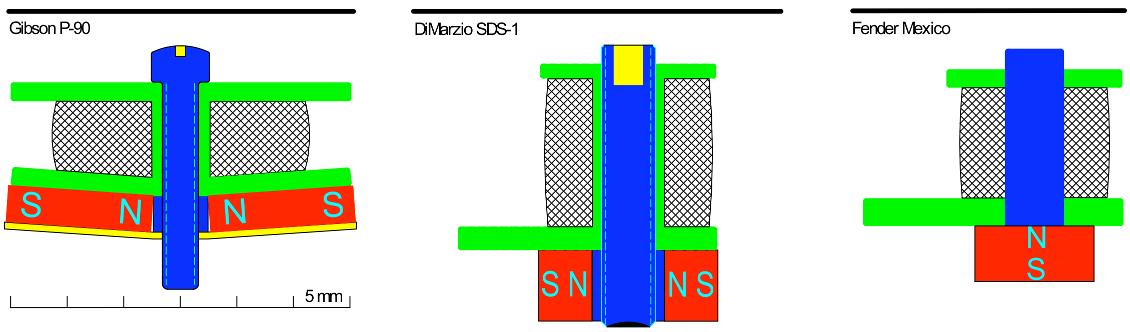


Fig. 5.1.3: Single-coil-pickups: Gibson P-90 (left), DiMarzio SDS-1 (middle), Fender Mexico (right).

Besides magnet and string, the coil **winding** is the third component in the signal generation. The first electric guitars were connected to the simplest tube amplifiers having a low input sensitivity. Consequently, the pickup had to deliver as strong a voltage as possible which necessitated a high number of winding turns: typically 5000 - 10000 turns. Exact figure quotes regarding pickup coils come with self-proclaimed guitar gurus just like year dates come with Nostradamus. The first Stratocaster pickups had approx. 8350 turns. Or so one reads. Or knows. Thus a tad more than the Texas-Special neck pickup. That one had "only" 8200 turns. As one extends the search, tolerance specifications pop up: the magic number of 8350 turns emerges as the *mean value* between 8000 and 8700 turns [Duchossoir] which evidently represents the range of variation as it occurred back in the day. For years, pickups were wound without the use of a counter, just according to "feel" until the bobbin was full. Or belt-drive counters were used, in the hope that the inherent slippage wouldn't be too great. How else could it be explained that Duchossoir specifies 7,5 kΩ for early Telecaster bridge pickups, while Day/Rebellius report up to 11 kΩ. No sooner than 1960 does Fender introduce precise automatic winders - and still they continued to experiment with winding numbers.

Duchossoir writes in the Stratocaster booklet that the finished coils were merely monitored by measuring the coil resistance with an **Ohm-meter** having a tolerance of as high as ±20%! Considering - on top of this - that the wire resistance per length is also subject to production tolerances, it is easy to imagine enormous variations in the winding numbers. Very generally the following holds: if for a specific pickup the number of coil turns is increased, an increase in resistance and inductivity follows. The resonance frequency drops, and the pickup gets louder. However, the resistance itself has little bearing on the transmission characteristic – the dampening effect it has remains small compared to that of other components in the circuit. If geometry and wire diameter are indeed known, it is possible to draw conclusions about the winding number from the resistance. Only given these boundary conditions there is validity in the rule: higher resistance = louder reproduction.

Next to single-coil pickups without any field-directing pole-pieces (e.g. the Stratocaster) and pickups comprising pole-pieces between magnet and string (e.g. the P-90), there is a third significant group which features guidance of the *return of magnetic flux* via pole-pieces. **Fig. 5.1.4** explains the principle based on the Fender Telecaster bridge pickup. Here, a metal plate positioned underneath the coil is - according to advertisements - supposed to shield, and to "reflect" the magnetic field. Duchossoir describes the material of this approx. 1,2 mm strong metal sheet as "tin" although this should not translate into actual sheet tin. "Tin" can also stand for tin-plated steel which is more likely to have been used since solid tin is not magnetic. Fender brochures refer to a *zinc shielding plate*, i.e. a galvanization. That's also fine. From 1951 a copper-plated steel sheet is used which is dropped in 1981 without any replacement. Presumably people at Fender realized, too, that the strengthening of the magnetic field towards the strings is so insignificant that the plate may as well be dropped. Another possible reason may have been movements of the plate which could lead to microphonic noise and feedback. Measurements do not confirm any magnetic shielding effect: the presence of the plate creates merely a difference of 0,1 dB in the interference in the parallel field. The signal level is increased by the plate by only 0,6 dB which is too little to be noticed much. Similar results occur for the resonance frequency (3% change) and the eddy current dampening (approx. 1 dB difference).

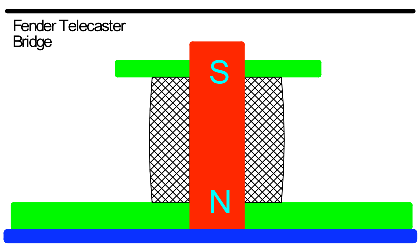


Fig. 5.1.4: Telecaster pickup with metal plate under the lower flange. The plate increases the sensitivity by 0,6 dB and reduces the resonance emphasis by approx. 1 dB; the resonance frequency drops by 3 % (due to an increase in inductivity by 6%)

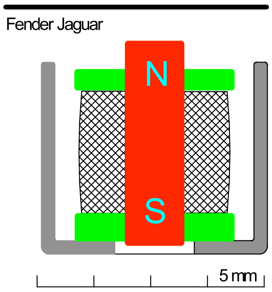
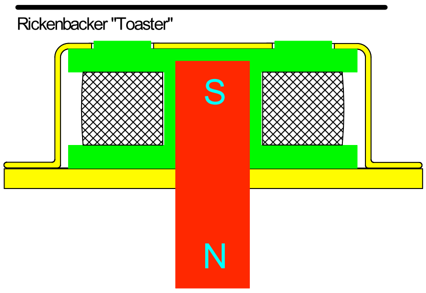


Fig. 5.1.5: Pickup with field guide sheet: Fender Jaguar.

Thoroughly continuing to think along the lines of the idea behind the Telecaster metal plate brings us very quickly to the variant Leo Fender implemented in the **Jaguar**. Here, a yoke sheet is bent around the coil winding in the shape of a "u" and the toothed upper rim focuses the field towards the strings. It didn't help much, though. At the time Fender's most expensive guitar, the Jaguar was not a commercial success. Incidentally, the pickup shielding was quite efficient, but other features of the guitar (e.g. the bridge) mercilessly bombed on the market.

Since pickup coils are comprised of extremely thin wire, they should be protected against damage by a **housing**. For the Telecaster's bridge pickup, this was accomplished by winding a thick thread over the copper winding. Simple and effective. Mechanical – not magnetic. Indeed, a magnetic field cannot be changed by a thread – but it may easily be by a metal housing (**Fig. 5.1.6**) as found with the Telecaster neck pickup (eddy currents, chapter 5.9.2.2). A motivation behind the metal housing was – on top of the physical protection – presumably the desire to shield the pickup. Mind you: no remedy can be achieved via this approach against *magnetic* interference; for that, the principle of construction would need to change (chapter 5.2, 5.3)..



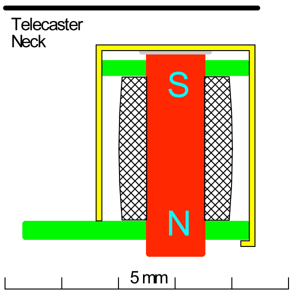


Fig 5.1.6:
Single-coil pickup with protective metal casing. To avoid losses due to eddy current, the housing needs to be made of nickel silver.

A pickup installed in Gretsch guitars merits particular consideration: the "HiLoTron" (**Fig. 5.1.7**). In order to pickup as many harmonics as possible, the magnet was installed with horizontal orientation. This reasoning is elusive from a systems theory point-of-view, but apparently only the resulting sound counted for the developer – which in itself is highly purposeful, and the justification in the associated patent (chapter 5.10.5) does not really need to be correct now, does it!? The horizontally oriented magnet is also found in the Attila-Zoller-Pickup (US-Patent No. 3588311) – and to go with it again a rather unconventional reasoning in the corresponding patent. The US patent examiner was apparently not phased by that ...

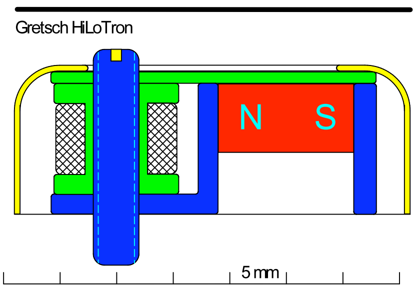


Fig.. 5.1.7: Gretsch HiLoTron (see also US-Patent No. 2683388).

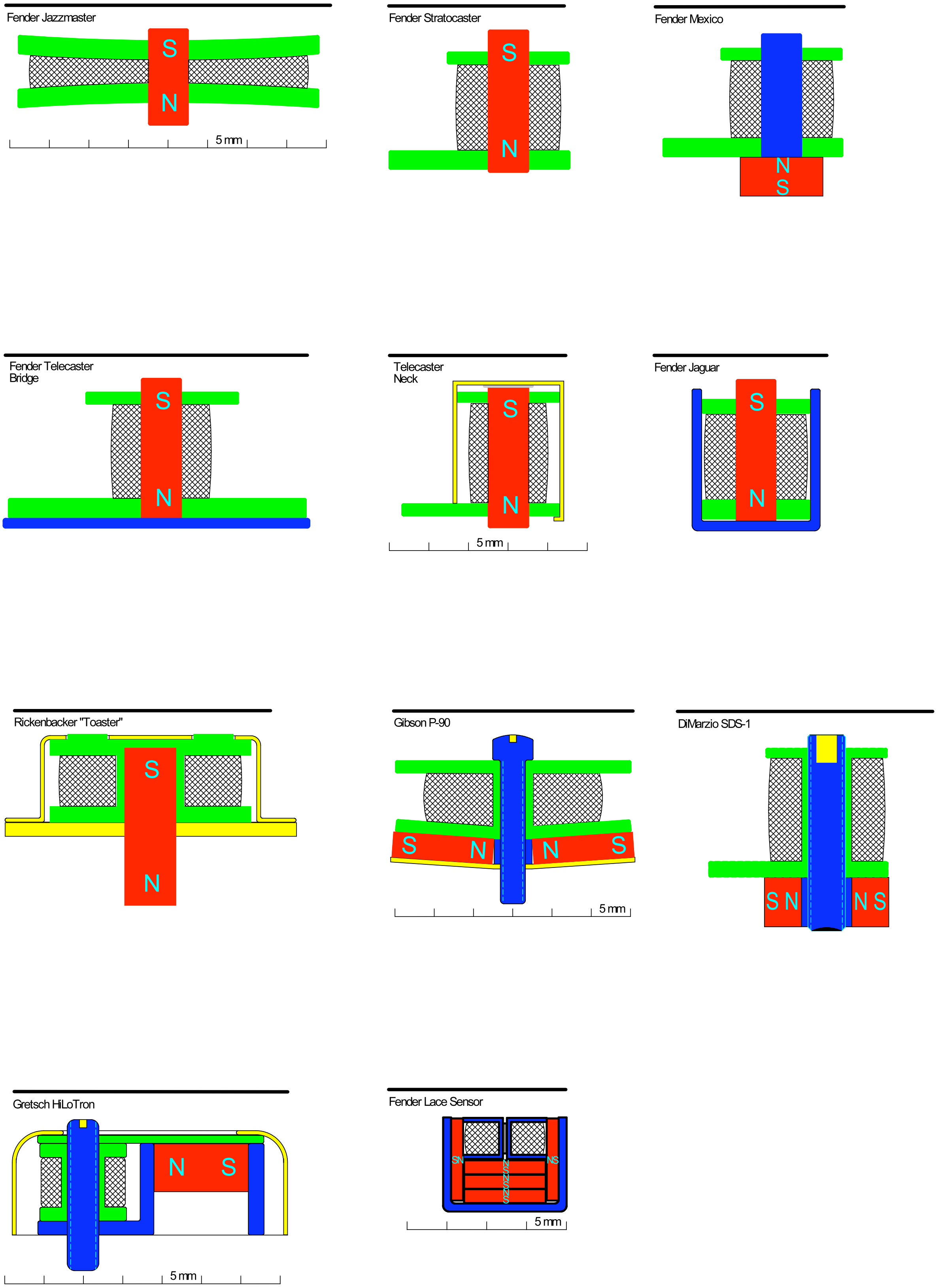


Fig. 5.1.8: Comparison of single-coil pickups

5.2 Humbuckers

The interference occurring with single-coil pickups motivated the development of the Humbucker. Single-coil pickups do not only pickup the vibration of the strings and generate a corresponding electric voltage, but they are also sensitive to magnetic fields as they are radiated by transformers, fluorescent lamps, or mains cables. Instead of having one coil, the "Hum-Bucker" consists of **two coils** connected to form a dipole and wired such that they are out of phase. The magnetic field generated by external interference sources induces in each coil the same voltage. Because of the **anti-phase connection** of the two coils the voltages cancel each other out. If the field generated by the permanent magnet would also flow through both coils with the same polarity, the signals generated by the vibrating string also be cancelled – this of course must not happen. For this reason the permanent field flows through the two coils in an anti-parallel manner such that the voltages induced by the vibrating strings are out of phase. Because the coils are connected out of phase, the voltages are turned twice by 180° i.e. they are again in phase (180° +180° = 360° corresp. to 0°). With this arrangement the signal-to-noise ratio can be improved somewhat compared to single-coil pickups (chapter 5.7).

As early as the 1930s designers sought to develop a marketable pickup based on compensation principles which were generally already known. **Seth Lover**, technician with the guitar manufacturer **Gibson**, achieved the commercial break-through. He is the designer of the Gibson Humbucker, but he's not the inventor of the humbucking principle as he himself noted: "People had been working on double coil pickups since the 1930s [13]". Lover's patent application from 1955 cites a further seven earlier patents for pickups considered in the procedure which also already had been referring to the compensatory principle. Lover was thus not the first but he succeeded together with Gibson in creating a commercially highly successful, even "mythical", pickup which in this respect far surpassed e.g. the **Gretsch** humbucker appearing almost at the same time (FilterTron pickup developed by Ray Butts).

Gibson applied for a patent for their humbucker in 1955. The patent was granted in 1959, however already in 1957 Gibson guitars fitted with humbuckers appeared on the market. Up to the granting of the patent the pickups sported the sticker "Patent Applied For". This led to the abbreviation **PAF**-pickup. In 1962 the PAF sticker was changed: instead of "Patent Applied For" now the patent number 2.737.842 could be read. The correct number of the "Humbucking"-patent from 1959 was however 2.896.491. Allegedly, the misleading number was deliberately printed on the sticker to fool competitors. Or so says Seth Lover.

The humbucker uses two coils instead of one with the objective that hum voltages are superimposed out of phase and thus cancelled while the voltages derived from the moving string are added in phase and thus amplified. Single-coil and humbucking pickups differ not only in the interference voltages they pickup. Their different construction results also in different transfer functions in i.e. a different sound. Musicians often express the opinion that single-coils are softer but have more treble while humbuckers are louder but sound darker. This may have been a reasonable assessment correct statement regarding the early guitars of Fender and Gibson, however this prejudice is not suitable as dogma. The pickups of a Fender Telecaster and those of a Les Paul differ not only in the number of the coils but also in the pickup's inductivity, resonance frequency, and resonance dampening. The following sections explain how the pickup parameters influence the magneto-electric transmission, and how this determines the sound

 Translation into English by Tilmann Zwicker

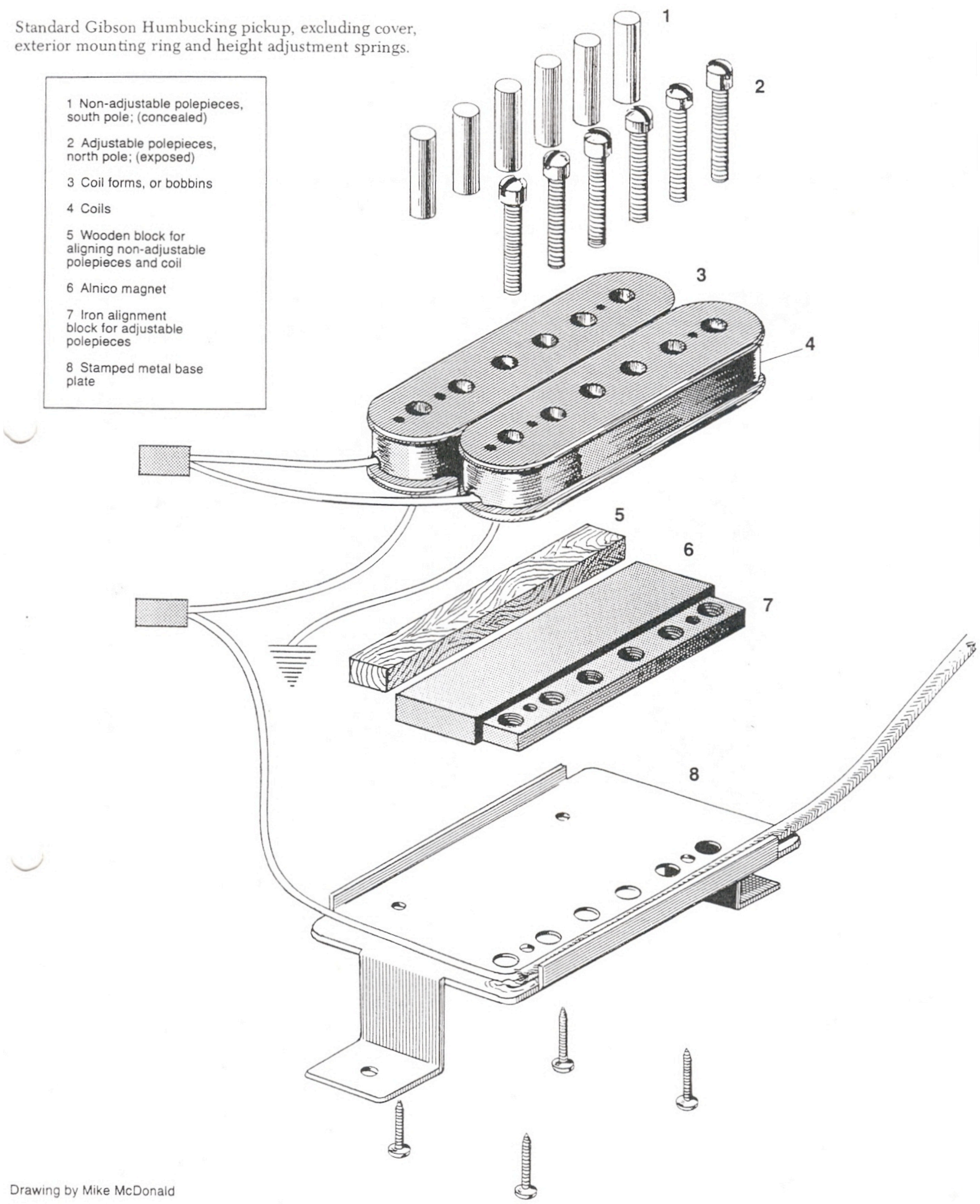


Fig. 5.2.1: Gibson-Humbucker [drawing: Mike McDonald].

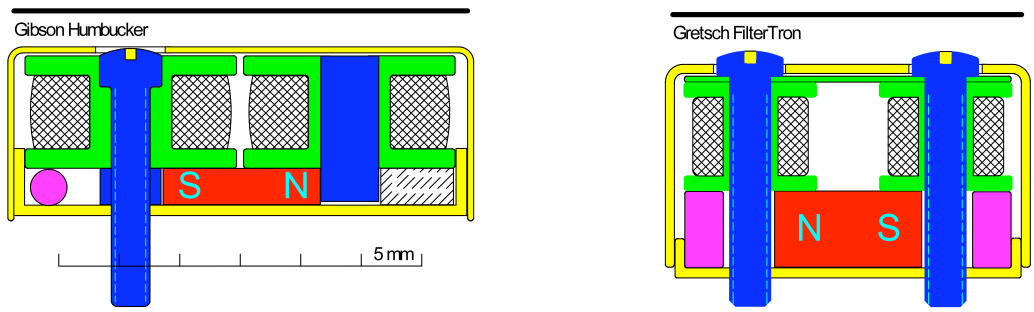


Fig. 5.2.2: Cross section of Humbucker. Gibson Type 490 (left), Gretsch FilterTron (right).

Fig. 5.2.1 shows the construction of a Gibson-Humbucker. Mounted on a base-plate (8) we find a wooden strip (5) serving as spacer, an alnico bar-magnet (6), and a metal block (7) with multiple bores. Placed above this are the two bobbins (3) with their coil windings, fixed with two screws. One of the bobbins carries 6 cylindrical metal pins (1) which are often called slugs, the other 6 metal screws (2). The cross-section shown in **Fig. 5.2.2** describes the magnetic flux: the bar-shaped permanent magnet is polarized horizontally and causes a circular flux flowing – from the north pole – through the pin (slug) and returning through string, screw and metal block to the south pole. Only a small part of the overall magnetic flux runs through the string while most of it circles back through air as flux leakage. In Gibson's patent publication two similar coils with pins are shown. The production version included the two different coils, with the second one carrying the screws for adjusting the volume of individual strings. The FilterTron pickup installed in Gretsch guitars uses a similar construction principle. With its two rows of screws it achieves full mirror symmetry and thus a better hum suppression. Both humbuckers shown in Fig. 5.2.2 are sealed with a metal cover.

In the Gibson Humbucker, an **alnico magnet** generates the permanent field. Without it the pickup would not work. However, the influence of the specific magnetic material must not be overestimated: the alternating magnetic field (which exclusively induces the voltage in the coils) oscillates predominantly in the vicinity of the string; only a very small part reaches the magnet (chapter 5.4.3). We have a similar situation for the magnetic field generated by a current flowing in the coil and determining the inductivity: measuring the pickup resonance with and without magnet show merely a 3% difference in the inductivity (chapter 5.9.2.6) which is negligible compared to other parameter variations. Whether a strong or a weak magnet is incorporated will have slight effects on the sound, but a significant change is to be expected only in the loudness. Regarding the question which magnetic material was (or is) in fact used one finds comprehensive answers in literature. Not to mention the Internet! "You have many more hits than there are magnetic materials!" BINGO!

"Up to 1950, there was no commitment to a specific alnico material at Gibson, and Alnico 2, 4, 5, and 8 were installed depending on availability and presumably also on most favorable purchase cost. From 1950 (...) Alnico 5 prevailed as predominantly used magnet material. Which however does not mean that it stayed that way. Even towards the end of the 1950's humbucker specimen with by all appearances other Alnico magnets do surface [Day et al.]". "The magnets in Burst-PAFs were made of **Alnico II and IV** [VG Magazine]". "This pickup (SH-55) was re-introduced by Seymour Duncan using the specifications of PAF-inventor Seth Lover to 100%: **Alnico-2** magnets" [Musik Produktiv catalogue]. "The SH-55 is really faithful to the original, it will have my stamp of approval on it [Seth Lover in VG Magazine]". We also used **Alnico II and III**, and the reason is, that you couldn't always buy **Alnico V**, but whatever was available we would buy as they were all good magnets [the same Seth Lover in the book *The Gibson*]".

So there we have it: most probably anything that couldn't climb a tree fast enough was installed by Gibson in their pickups. Add two coils with 4500 turns each ... or more .... or less. Then: slap on the cover and – most importantly from today's point of view – stick that PAF-sticker to the bottom. Done. Today it'll cost ya $3000.- per piece. That's per piece pickup, not per piece guitar! Occasionally that could rise to $10000.-. Trend: upwards. But then ... Rembrandt's legacy is not evaluated based on the cost of paint and canvas he incurred back then, either.

The screws and pins (i.e the pole-pieces) focus the field and sample the vibrations of each string in two sectors which are separated by about 19 mm. In particular for the bass-strings of the guitar a loss in brilliance results, which however is not generally undesired in particular for distorted sound (chapter 5.10.5). To counter the treble loss – which is due to interference effects – the distance between the poles needs to be reduced to a few millimeters. At the same times, this allows for mounting the humbucker (now reduced in size) into a housing foreseen for single-coil pickups – it will now fit into the single-coil-routing in the guitar body. **Fig. 5.2.3** shows an in-scale comparison between a Gibson Humbucker (here a special version with 3 magnets) and a DiMarzio-Humbucker. The latter employs 2 1,6-mm-strong iron blades of 6 cm length, which run at a distance of 7,5 mm across the strings. Instead of screws and pins, narrow blade-shaped pole-pieces were used very early on by Willi Lorenz Stich, alias Bela Lorentowsky, alias Billy Lorento, alias **Bill Lawrence**, they later show up in Joe-Barden-pickups, and by now they are also offered by Seymour Duncan and DiMarzio – an the are rejected rigorously by many guitarists just because of their look.

Fig. 5.2.3: Gibson 'Super'-Humbucker [acc. to Lemme] with 3 magnets, und DiMarzio-Humbucker with two metal blades. The Super-Humbucker installed in the L6-S had coaxial coils, however [Billlawrence.com].

Different construction of the two coils **(Fig. 5.2.4)** influences in particular inductivity and Q-factor. Humbuckers with identically constructed coils target a broad-band cancellation of the interference. Differences in shape and/or material of pole-pieces, wire diameter and/or number of turns allow for limiting the cancellation to specific frequency ranges (usually the lower frequencies), and for modification of the transfer function in the remaining frequency range. The typical humbucker interference notch (chapter 2.8.3) can be shifted or reduced in this manner. The exact calculation of the transfer behavior gets complicated since the coils are magnetically (and in some cases to a non-negligible degree even capacitively) coupled. This coupling needs to be considered also if only one of the coils of a humbucker is connected (**humbucker in single-coil mode**, split operation). The magnetic poles (or the pole-pieces) of the unused coil still generate an alternating magnetic field which partially flows through the used coil and induces a voltage there.

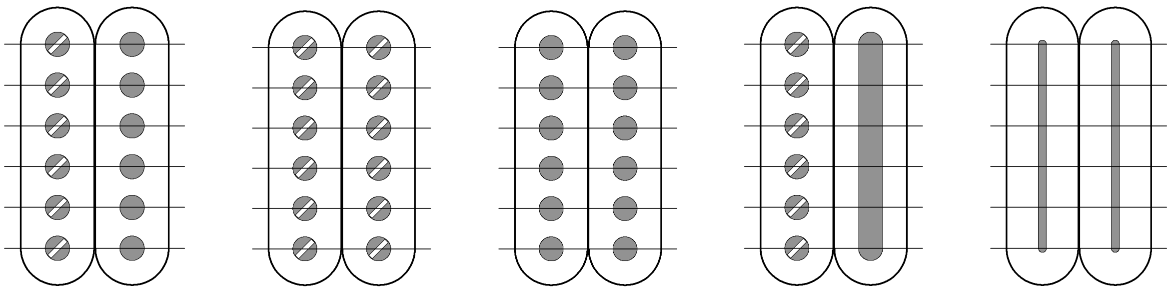


Fig. 5.2.4: Various humbucker construction types.

5.3 Hum-compensated Single-coil Pickups

Magnetic pickups convert alternating magnetic fields into electrical alternating fields. If these fields are generated by a transformer, an electric motor, a monitor working based on magnetic deflection, or similar source of magnetic fields, the conversion happens nonetheless – how should a pickup know that these are unwanted signals? A possibility to attenuate such interference was discussed in chapter 5.2 – another approach is taken by so-called **stacked single-coils** also known as stacked humbuckers or co-axial humbuckers. Viewed from the direction of the strings, such a pickup looks like a normal single-coil. However, in its interior *two* coils are at work, and the designation single-coil is therefore not entirely correct. Or maybe it is, after all, because only one coil senses the vibration of the strings; the other coil compensates the hum voltage. Thus: humbucker – but a special one, specifically a co-axial one.

Co-axial indicates that both coils are wound around the same axis; they do not, however, lie in the same plane (as they could if they had different diameters of the winding). Rather, two similar coils are 'stacked" on top of each other: one closer to the strings, one further away. As we will see in chapter 5.4.3, the *alternating* magnetic flux circulates only close to the strings, i.e. it does not penetrate the whole magnet with the same strength. For this reason, only the coil windings positioned close to the string receive a significant part of the alternating flux. the **interference field** of an external interference source creates an entirely different situation: its virtually parallel field lines penetrate the whole of the winding and therefore induce approximately the same voltage in every turn irrespective of the distance to the string♣. Dividing the coil into one half closer to the strings and a second half facing away from the strings, and at the same time connecting the two partial coils out-of-phase, will result in a compensation of the interference voltage while the useful signal is attenuated only a little.

Compared to the uncompensated single-coil pickup, the co-axial humbucker shows several differences: there is no hum but more space is required plus the sound is different. The space requirement it rarely problematic but the altered transmission characteristic continues to be fodder for extensive discussions. In order to clarify the context, it is helpful to separate the pickups into two groups: there are those with elongated, slim coil shapes (such as e.g. the Stratocaster pickup), and those with wide, flat coils (e.g. the P-90, **Fig. 5.3.1**).

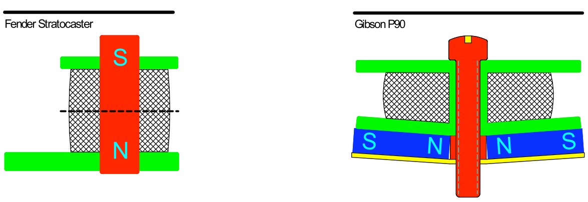


Fig. 5.3.1: different winding-shapes in single-coil pickup

Let us assume that the winding of the Stratocaster pickup shown in Fig. 5.3.1 would be divided at half its height such that two coils result. The induced voltages are, however, not divided in a 50:50-ratio, but – due to the location-dependent alternating flux-density – by 75:25. The upper winding (closer to the strings) receives a voltage which is 3 times that of the lower winding. Connecting both halves of the winding out-of-phase to compensate the hum decreases the string-induced voltage by half. The pickup is softer in loudness than an uncompensated single-coil would be.

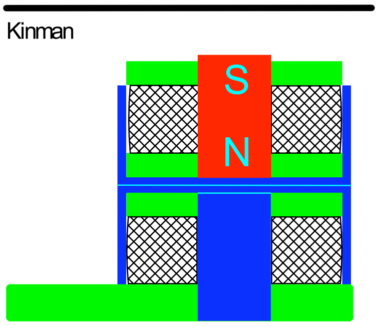
♣ the voltage induced into the winding depends dB/dt and on the area of the winding

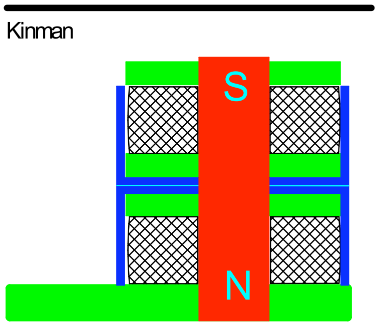
Not only the loudness changes but also the sound-spectrum. This is because the phase-switch reduces the inductivity of the pickup. The **inductivity** is the quotient of coil flux and current [e.g. 18]. If the two anti-phase-connected halves of the coil were in the same place – this only works as a though-experiment – then the excitation current flowing through both coils would generate no magnetic field at all and the inductivity of this 'bifilar'-wound coil would be zero. In reality the two halves of the coil are at different locations and the magnetic flux (generated by the excitation current) in one coil would not fully compensate the flux in the other. The inductivity therefore is not zero but smaller than for an in-phase connection. Smaller inductivity implies a higher resonance frequency (chapter 5.9), and consequently the conclusion is: due to the phase reversal, the pickup sound softer and with more emphasis on treble. Whether this is perceived as advantage or disadvantage is a matter of individual assessment. However, often a direct comparison with the uncompensated original pickup is done, and the scathing verdict is: the hum-compensation kills the sound.

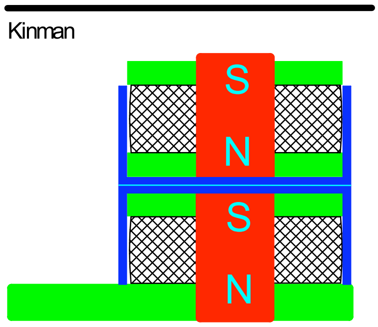
So far our considerations showed two effects of the phase reversal: weaker output voltage and smaller inductivity. Simple corrective measures for this are: increased number of turns and improved decoupling of the two halves of the coil. The coupling of the coils is determined by the distance in space of the coils, and the **permeability** of the coil core. Soft iron pole-pieces passing through the coils are rather disadvantageous in this respect, while the relatively small permeability of customary pickup magnets on the other hand diminishes the coupling of the two coil fields and reduces the disadvantages of the phase reversal. An even better decoupling is achieved by a metal plate with high permeability separating – as flux-guiding yoke – the two coil halves. Optionally, this plate can be bent to a u-shape. With magnetic decoupling and an increased number of turns, co-axial humbuckers achieve a similar transmission characteristic as single-coils. Complete identity is however impossible: the spatial distribution of the magnetic flux (inc. all skin-effects) is different, and due to the higher number of turns (plus 50% or more) the dc resistance changes. The latter does not only have an effect at 0 Hz, but may influence the resonance emphasis (chapter 5.9).

For pickups constructed like the **P-90** (Fig. 5.3.1) the division of the coil as just shown is not purposeful: the coil is more shallow than the one in the Stratocaster pickup and therefore both halves of a divided coil would be close to the strings, i.e. in the alternating magnetic field. Furthermore 6 screws (pole-pieces) would make for a relatively strong coupling of all windings. Possibly for this reason, Gibson did not divide up the coil present in the **P-100** but installed a second coil below the magnets which now serve as a magnetic shield as well. A series connection of the coils would have doubled the already rather high inductance (approx. 7 H) and reduced the resonance frequency by 30%; apparently this was not desirable. For the P-100 the coils are therefore not connected in series but in parallel (and anti-phase). Of course, this has consequences as well: the resonance frequency is now higher compared to the P-90. Obviously the musicians were not excited – production has since ceased.

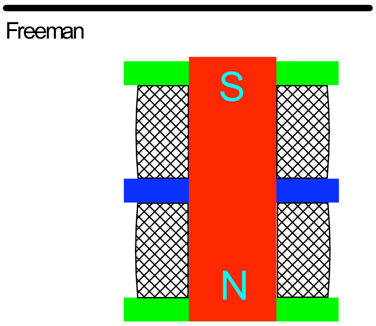
Fig. 5.3.2 shows cross-sections of well-known co-axial humbuckers. Almost all have received patent protection. US patent protection, that is. The question regarding the necessary individual inventive step would probably only have come up in pedantic old Europe.



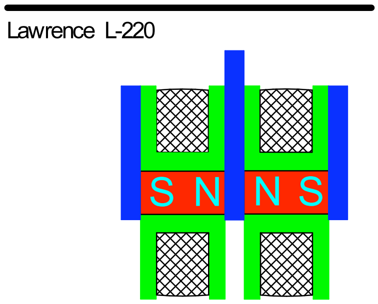




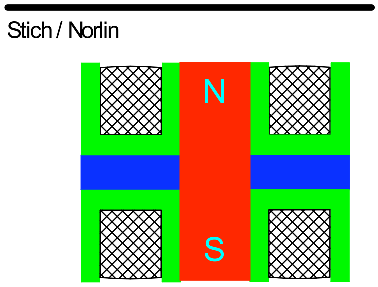
Kinman, 15.03.1996, US-Pat. Nr. 5668520, 5834999, 6103966.



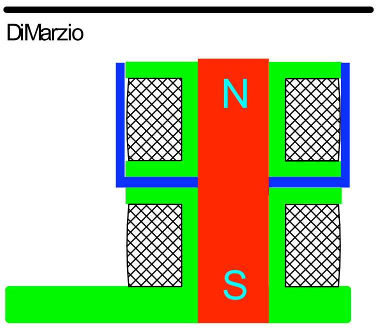
Freeman, 21.12.1970,
US-Pat. Nr. 3657461



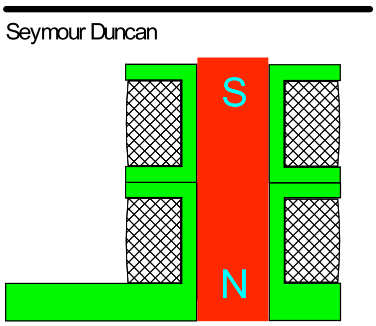
Bill Lawrence L-220. The axis of the coils run horizontally (Stich).



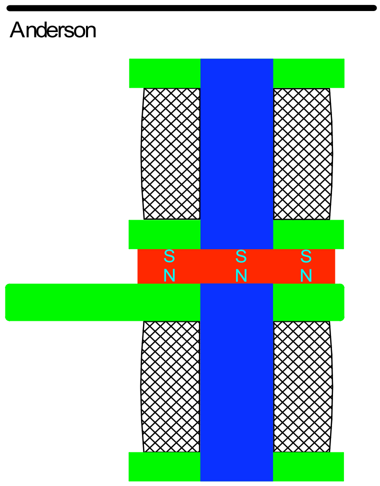
Stich, 05.08.1974, US-P. 3902394, horizontal axis of the coils.



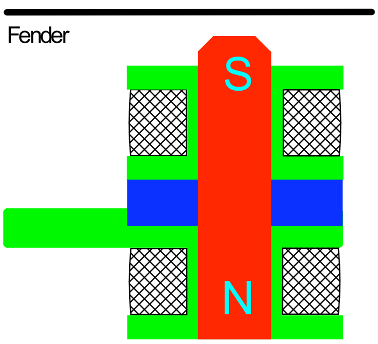
DiMarzio, 06.08.1982,
US-Pat. Nr. 4442749.



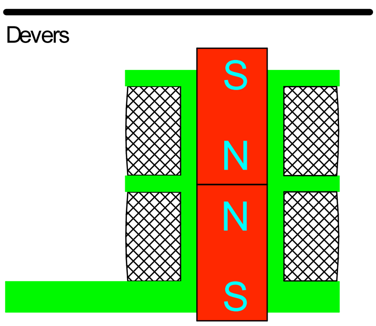
Seymour Duncan, 15.08.1983,
US-Pat. Nr. 4524667.



Anderson, 14.01.1991,
US-Pat. Nr. 5168117.



Fender, 28.01.1998,
US-Pat. Nr. 6291758



Devers, 17.05.1999,
US-Pat. Nr. 6846981

Fig. 5.3.2: Various co-axial humbuckers; dates given are those of the patent filing

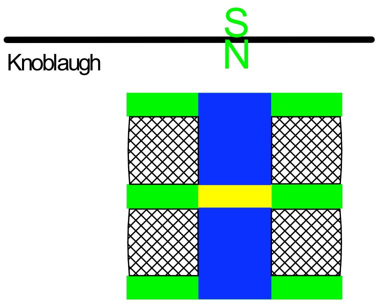


Fig. 5.3.3: One of the first co-axial humbuckers, US-Pat. 2119584. Both coils contain a core of layered transformer laminates; the cores are separated by a nonmagnetic spacer. Prior to use first a direct current had to be fed to the upper coil to magnetize the strings. Day of filing for the patent: 9.12.1935.

Fig. 5.3.3 shows that Gibson is not the inventor♣ of the humbucking principle: even before the famed PAF, there was the trendsetting idea to interconnect two coils in anti-phase. Seth Lover, designer of Gibson's humbucker, was himself informed about competing pickup developments: *"People had been working on double coil pickups since the 1930s [13]"*. As early as 1935, Arnold **Lesti** filed an application for a pickup with tow side-by-side coils (US-Patent 2026841 = Re.20070) and describes the principle of interference: *"And since these coils are wound in opposite directions, the interfering stray currents are neutralized"*. On tp of that, it would be possible to imply that Gerald **Tuininga** attempted - in his patent application filed in 1929 and leading up to US patent 1838886 – to compensate interference with the use of two coils: "*The advantage of using this style of transmitter is that no other electric current caused by foreign sound or vibration can in any way enter into the circuit"*.

In 1929, descriptions of patent applications as this one comprised only little more that one page in letter format, so we should not be too small-minded and start splitting coil wire ... *er*: hairs. Still, the circuit included in the patent description seems incorrectly drawn. If both coils indeed had the same direction of their winding the wanted signals would cancel each other out while the interference would double. Inverting one of the coils – which would have been the only way back then it would have worked in the breadboard setup – one obtains a fully functioning humbucker. Mind you, it would still needed firing up an electromagnet via a battery. That we are not burdened by such cumbersome procedures anymore today – that we owe to inventors such as **Seth Lover** (patent application in 1955). Or **Leo Fender**, who filed an application for his humbucker in 1956. Or **Ray Butts**, who filed the one for his Gretsch-Humbucker in 1957. Or **Oskar Vierling**, who as early as 1927 published the basic principle of the electromagnetic string pickup with the German patent office in Berlin.

Whether – as Day et al. surmise – **Bill Lawrence** put together already in 1948 the "probably world's first humbucker" is questionable. It would be possible: Lawrence was born 1931. On the other hand, he himself dates the beginning of his entrepreneurial activities to 1965: "Electrosounds in Munich, Germany". Back then Bill Lawrence was still called Willi Lorenz Stich, and one of his partners was Jzchak Wajcman. It was the same Jzchak who would later push Lawrence into a $ 1.156.250,00 bankruptcy [Guitar Player, September 1979, cited in billlawrence.com]. Incidentally, the St. Lorenz, alias Laurenz, alias Laurentius, alias Lawrence was "burned to death on an gridiron". You lucked out, Bill! (using this expression since B.L. later lived in the US .... for you British readers this would have to read: "You had a lucky escape, William!").

♣ In their advertisements for strings, Gibson indeed merely claim to be the "inventor of the Humbucker" ... and not the "inventor of the humbucking principle"

5.4 The magnetic field of the pickup

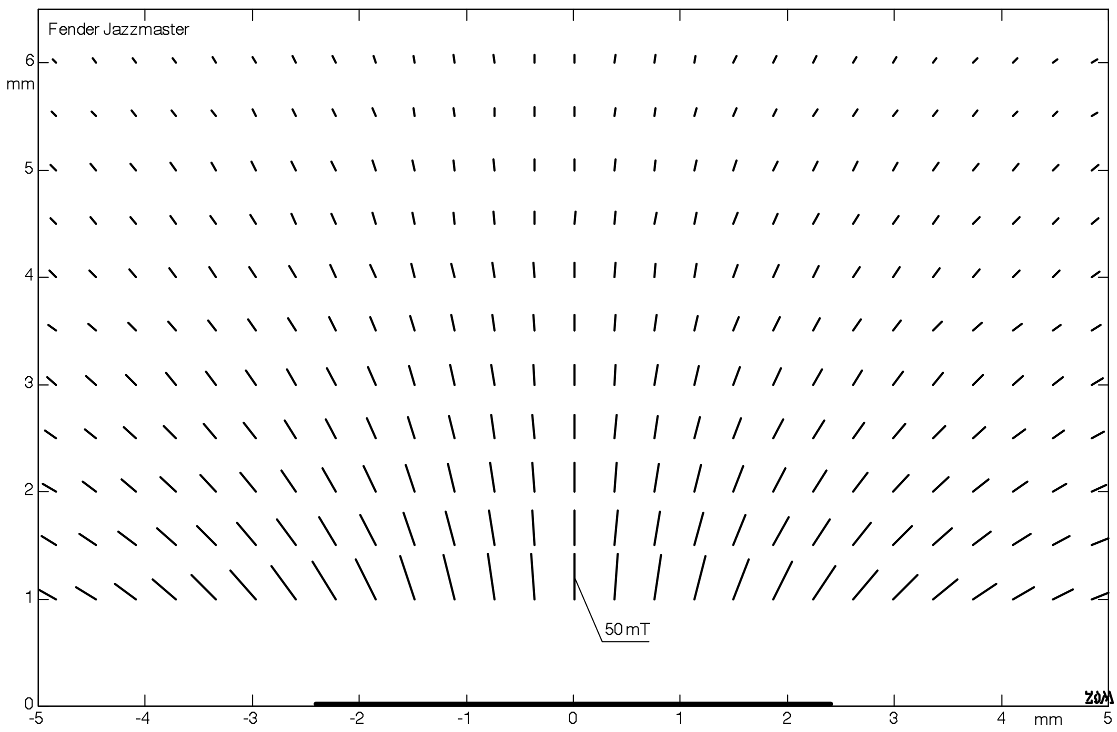
5.4.1 Static magnetic field without string

The vibrating string causes a change in the magnetic flux; this change induces an electric voltage in the pickup coil. The terminology of systems theory describes change as a dynamic (i.e. time-dependent) process superimposed onto a static magnetic field. The alternating flux is rather small and reaches merely about 1% of the static part of the field even for strong excitation of the string.

The source of the magnetic field is a permanent magnet installed under the string in the pickup housing. For a typical Fender pickup (for example the one in the Stratocaster) the end surface of the axially magnetized cylindrical magnet is positioned a few millimeters from the strings. For the Gibson P-90 a bar magnet is mounted underneath the pickup coil; for better field focus ferromagnetic screws penetrate the coil surface and guide the magnetic flux to the string. It is of interest to measure the strength of the static magnetic field since the efficiency of the mechano-electric transduction depends on it: without magnetic field there is no induced voltage i.e. the stronger the magnetic field the louder the pickup, although the correspondences are not quite that simple, after all. Besides the absolute strength of the magnetic field, its distribution in space is of importance as well. Moreover the static magnetic field exerts attraction forces towards the string which influence the vibration behavior − for this reason particularly strong magnets are not generally desirable.

To measure the static magnetic field, a Hall probe (after Edwin Hall) is suitable. This is a small semiconductor plate in which an electric voltage dependent on the magnetic field is generated. The effective measurement surface is about 0.4 mm in diameter. For the measurements described in the following, such a Hall probe was moved along a straight line by a spindle drive. At the same time the field-proportional electrical voltage was recorded. The direction of the advance was either in parallel to the string axis or perpendicular to it. With a parallel shift of the Hall probe an area could be sampled.

In contrast to the sound pressure measurements favored in acoustics, the magnetic flux density is not a scalar but a **vector** in space. The electromagnetic field is a vector field, each point of which in space is associated with three-dimensional field values. The Hall probe , however, reacts merely to the flux density component which is parallel to its surface vector. For a complete description of the field it would be necessary to use three orthogonally oriented Hall probes. Simultaneous operation of the three sensors results in a mutual interference, sequential operation is problematic due to the limited accuracy of the positioning in space. To make the overall measurement effort not too excessive, it was the **axial component** which was recorded. What is meant here is not the axis of the string but the axis of the cylindrical magnets or the pole-pieces; in other words the Hall probe is oriented in parallel to the fretboard of the guitar and samples the magnetic field component perpendicular to the fretboard. In the vicinity of the magnetic poles a flux density of between 10 and 100 mT is found while larger distances result in a very steep decrease of B. Figure 5.4.1 gives an impression of the field pattern above the pole area. Of course, it needs always to be considered that a pickup without string is without purpose. The field pattern with string is more important, however this is also much more difficult to determine.



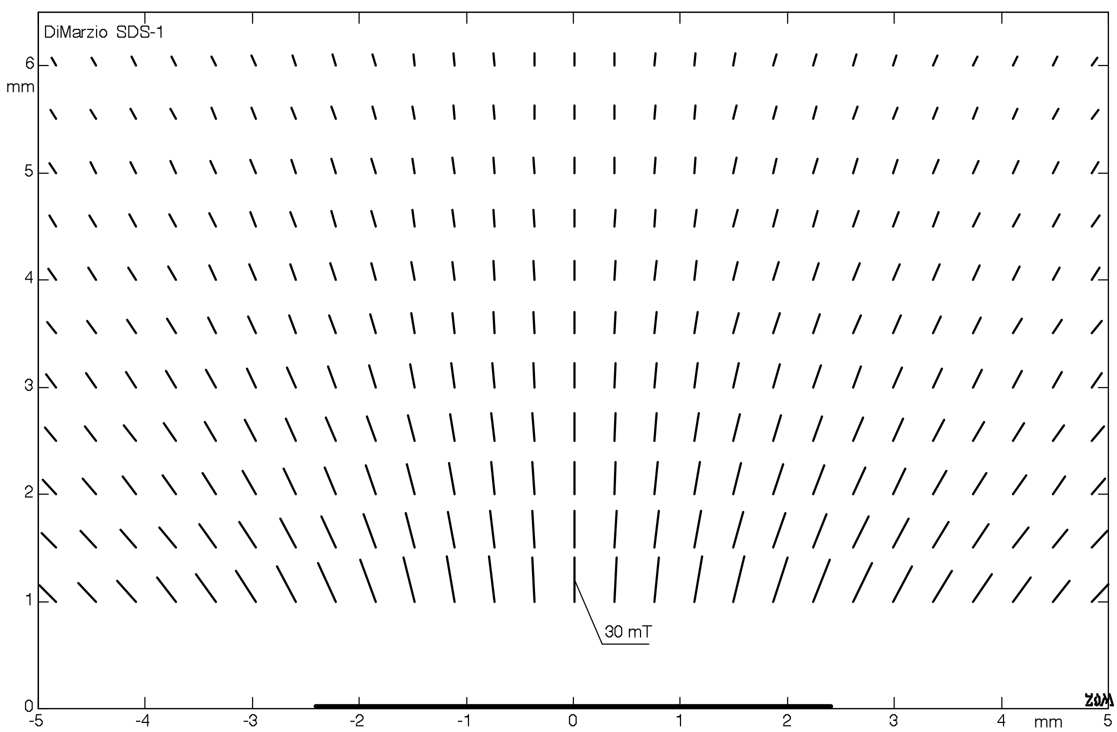


Fig. 5.4.1: Field vectors above a magnetic pole without string in the filed (measured results). For the Jazzmaster pickup (top) the field diverges more strongly than for the SDS-1 (bottom). Length and direction of the individual lines represent strength and direction of the magnetic flux density; the coordinates (given in millimeters) refer to the middle of the pole-plates (shown as thick line on the lower border of the figure. For this representation the abscissa- and ordinate-components of the *B*-vector were measured at distances of d = 1:0,5:6 mm to the magnetic pole.

In Fig. 5.4.1, the individual lines of the dashed line field represent – with their length and direction – the pattern of the field. Since the medium the field propagates in is air, both the *B*- and the *H*-Patterns can be determined: $\vec{B} = \mu_0 \vec{H}$. The magnetic field is a **vortex-field**: its flux lines (field lines) are closed lines without start- or end-point. Nevertheless, a presentation as a **point-source-field** is customary, as well, although this is a rather rough simplification. For the point-source approximation, the magnetic flux is thought of as originating from a point-source which is located within the interior of the cylindrical magnet on its axle. A first-order approximation for the distance of this point to the to the front face is the radius of the cylinder. Outbound from this source the magnetic field diverges equally in all direction. The surface area of a sphere concentric with the source point increases with the square of the radius, and thus the radially oriented flux-density will decrease with the square ($B \sim 1/r^2$). **Fig. 5.4.2** shows the measured results for the flux density at the magnet axis m; for this, the Hall probe was moving axially away from the pole-piece.

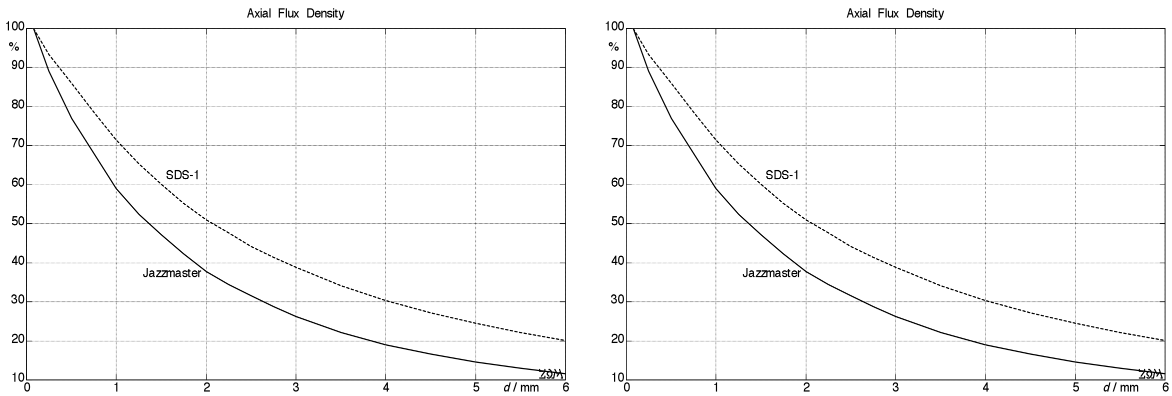


Fig. 5.4.2: Axial Flux-Density in absolute (left) and relative (right) representation,
d = distance to the pole-plate

The field of the Jazzmaster pickup is, in absolute terms, larger than that of the SDS-1 but does decrease faster. If this decrease happens according to a power law, it should show up as a straight line in double-logarithmic coordinates. **Fig. 5.4.3** shows $\log(B/B_0)$ over $\log[(d+\Delta)/d_0]$; the abscissa, however, is scaled for *d* and not for $d+\Delta$. B_0 and d_0 are reference values for the logarithms (such that they are without a dimension). + Δ is the depth of the magnetic source: it amounts to Δ = 4.7 mm for the SDS-1, and for the Jazzmaster-pickup it is Δ = 3 mm.

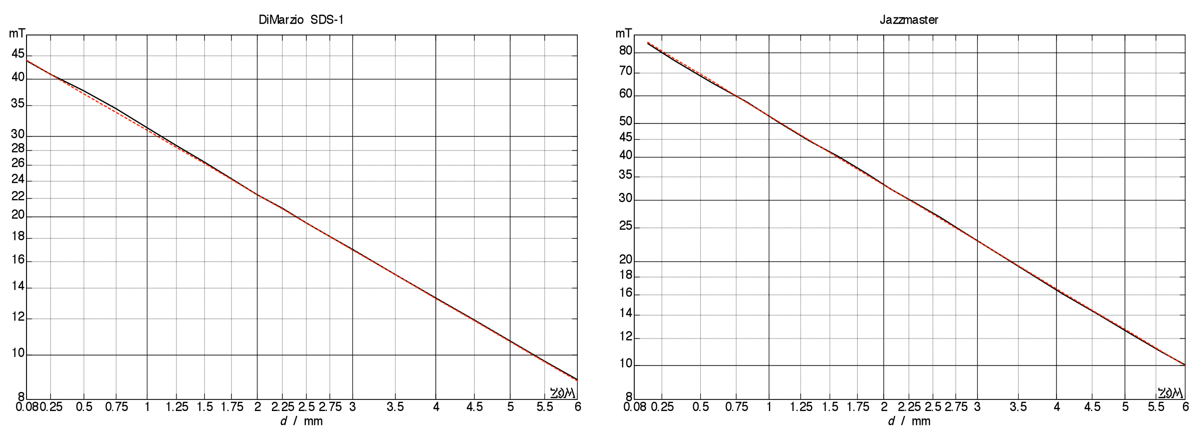


Fig 5.4.3: as shown in Fig. 5.4.2, but here in double-logarithmic scaling (measured ——, $1/r^2$-dep. -----).

The measured data shown in Fig. 5.4.3 are located almost perfectly on the given straight lines which approximates the $1/r^2$-dependence rather well. We still need to consider that only data along the magnet axis are depicted; in contrast Fig. 5.4.1 lends itself to show that the elongations of the field vectors do not met in a *single* source-point, after all. Here, the point-source-approximation reaches its limit of validity.

For the **humbucker** *both* magnet poles are positioned close to the strings; this results in a dipole field (**Fig. 5.4.4**). Directly in front of the pole plate (slug or screw) we obtain a rotationally symmetric field similar to Fig. 5.4.1, with a dependency on distance as given in **Fig. 5.4.1**. In the area between the pole plates (middle of the figure) the superposition of the anti-phasic fields results in a compensation of the vertical field component such that the magnetic flux runs horizontally i.e. parallel to the strings.

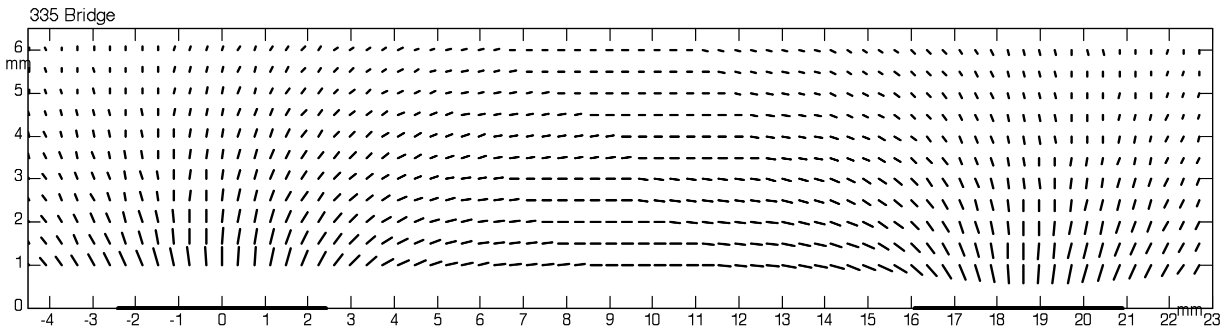


Fig. 5.4.4: Dipole-field of a humbucker (Gibson ES 335). The screw (right pole) is the south pole. No string.

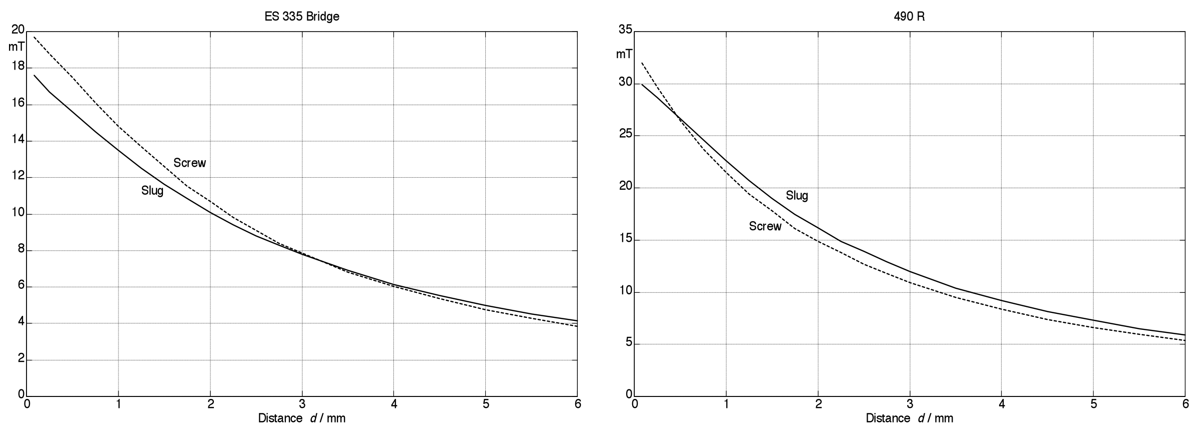
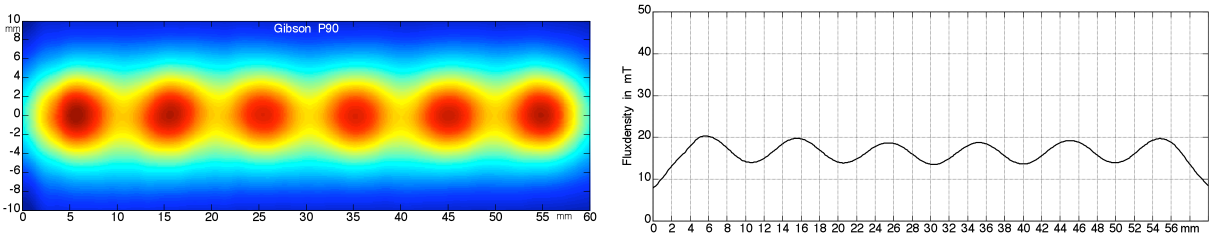


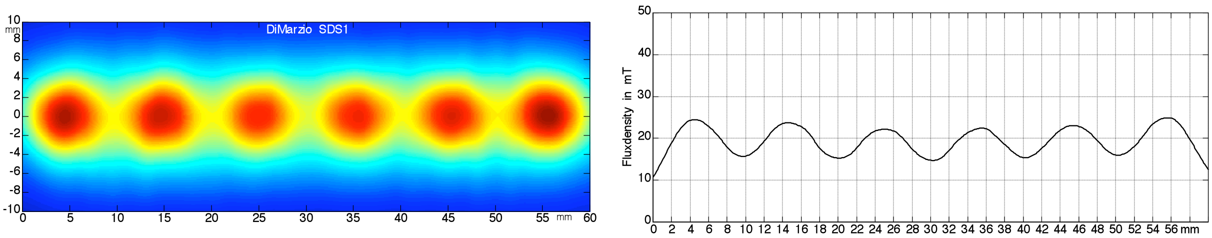
Fig. 5.4.5: magnitude of the vertical field, measured on the axis of the magnet.
The distance-dependency corresponds well to a $1/r^2$-Funktion well.
<u>ES335:</u> Δ_{Slug} = 5,1 mm, Δ_{Screw} = 4,0 mm. <u>490R:</u> Δ_{Slug} = 4,1 mm, Δ_{Screw} = 4,0 mm

Magnetic fields are vector fields; a complete characterization of the *B*-field would require a special representation of all three *B*-coordinates which is impossible to accomplish with two-dimensional figures. In order to still get an impression of the filed distribution, colored flux-diagrams are shown in the following. The axial component of the *B*-vector (corresponding to the vertical component in Fig. 5.4.1) was measured with a Hall probe at a distance of 2 mm from the pole plate. It was then recorded using color-coding. For single coil pickups the areas of small flux density are shown in blue; in contrast, the same color blue characterizes areas of high negative flux density.

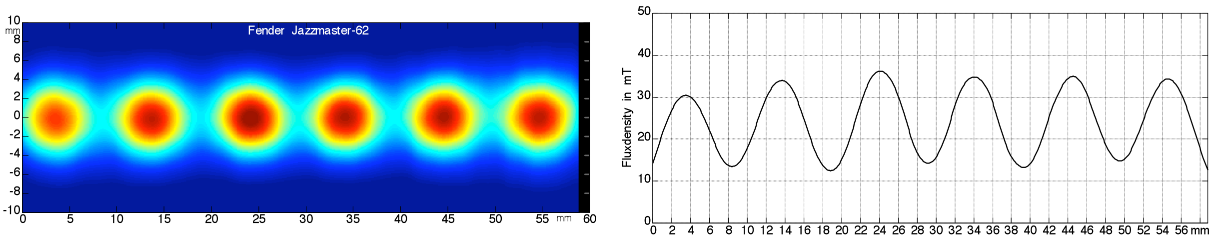
a) Axial magnetic flux density for singlecoil pickups:



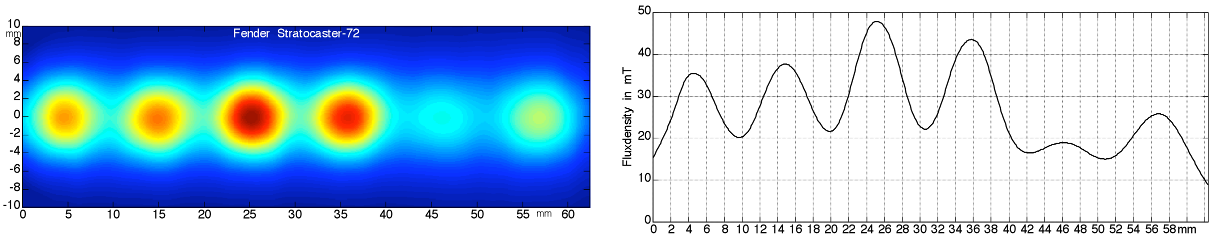
Gibson P-90, bar magnet + pole-pieces (screws)



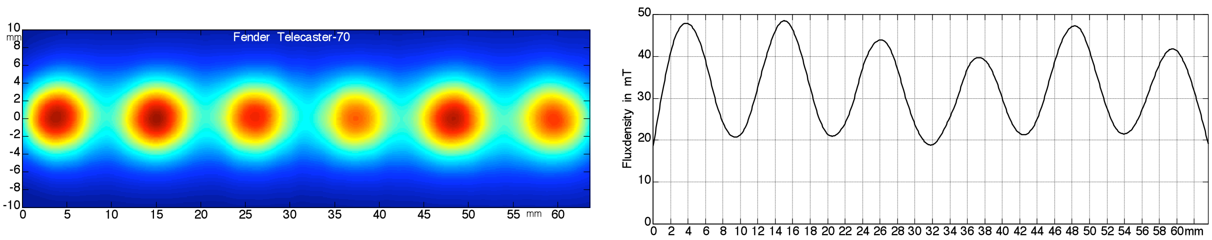
DiMarzio SDS-1, bar magnet + pole-pieces (screws)



Fender Jazzmaster, cylindrical bar magnets



Fender Stratocaster, cylindrical magnets of varying lengths



Fender Telecaster (bridge), cylindrical magnets + metal plate

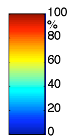
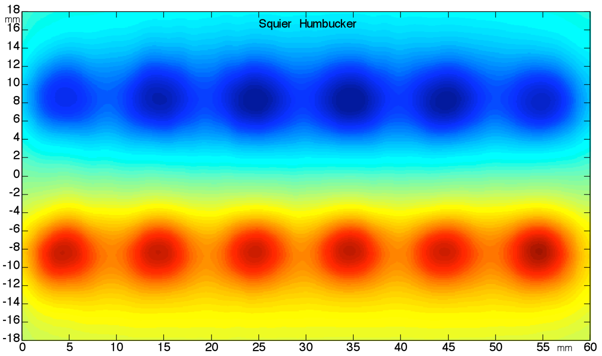


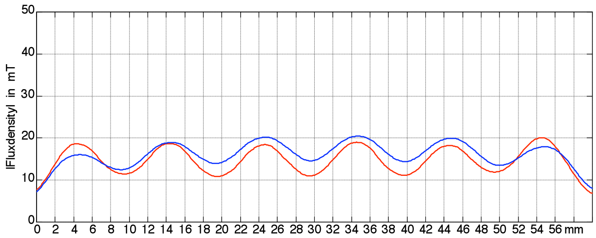
Fig. 5.4.6: The column on the left shows the distribution of standardized axial flux density in the plane of the strings. The color-scaling is as given by the color bar on the lower right
The right-hand column depicts the absolute axial flux densities 2 mm above the pole plates. d = 2mm.

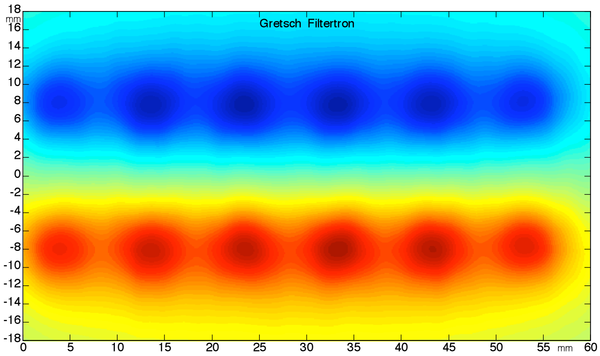
 Translation into English by Tilmann Zwicker

b) Axial magnetic flux density for humbucking pickups:

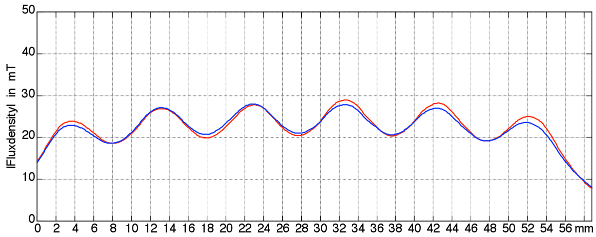


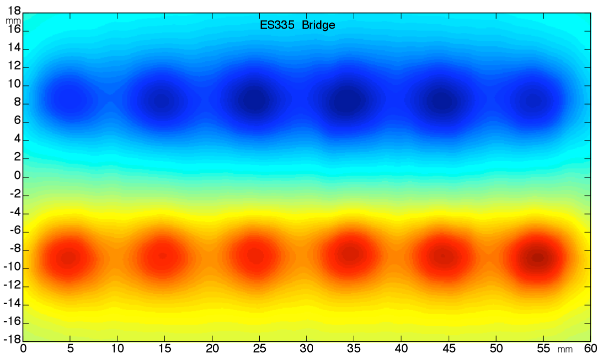
Squier Humbucker
bar magnet, 6 (pole-) screws, 6 pole pins (slugs)



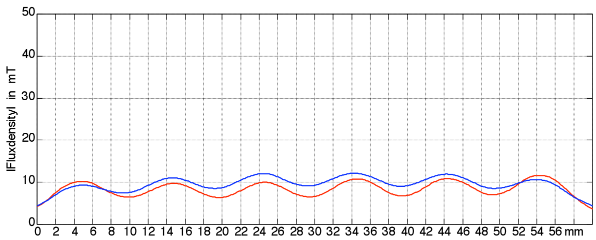


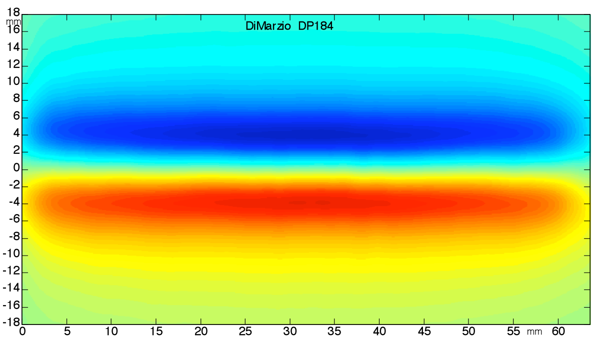
Gretsch Filtertron
bar magnet, 12 pole-screws





Gibson ES335 (square window),
bar magnet, 6 (pole-) screws, 6 pole pins (slugs)





DiMarzio DP184
bar magnet, 2 (pole-) blades

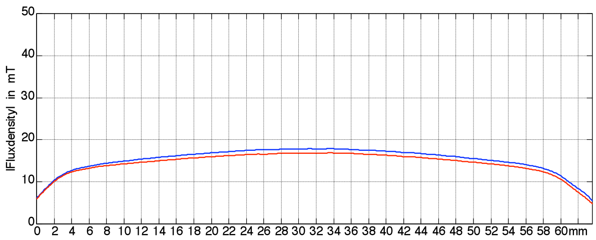
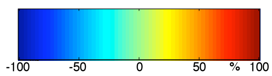


Fig. 5.4.7: Standardized axial flux density (left-hand column), magnitude of the absolute flux density (to the right); bipolar color scaling (color bar lower right); *d* = 2mm



Figs. 5.4.6 and 5.4.7 show the axial component of the static magnetic flux (measurement without string), i.e. the flux running perpendicular to the guitar top. The figure could create the impression that the Jazzmaster Pickup generates a more focused field than the P-90. However, the contrary is the case: a (locally) quick decrease of the axial component points to a strongly diverging field. For the Jazzmaster pickup (Fig. 5.4.1), the vertical (= axial) field component at 2 mm distance decreases quickly with horizontal movement of the measuring point because the direction of the field changes strongly.

Still, one should not attribute too much significance to the geometry of the magnetic field. As soon as a steel string is introduced in front of the pole-pieces the static magnetic flux changes, and as the string starts to vibrate, again entirely new field shapes result (Ch. 5,4,3). Actually, measurements of the static magnetic field are only undertaken to obtain hints as to the magnet(s), and even there merely a rough classification is advised: very strong (50 – 60 mT), strong (40 – 50 mT), medium (30 – 40 mT), weak (20 – 30 mT) and very weak (< 20 mT), with all measurements taken at a distance of 2 mm. Sure, the class borders given here are a subjective choice – if one so desires, 5-mT-intervals may also be used. Much finer steps are not purposeful, though: the measurement results depend rather strongly on the measurement position, after all, adjustment screws may be twisted, the measuring distance may be defined differently in case of tilted magnets of bent carrier plates, the 6 magnets of a pickup may result in different flux densities – with all these imponderables it is only possible to arrive at a **mean value** to the best of ones knowledge.

In the following **table** the static field measurements are listed – each taken at a distance of 2 mm above the pole plate (i.e. the slug, screw and blade, respectively). Data were collected using a Hall probe (Bell Technologies Inc., Model 5060, Gauss/Tesla Meter). The measurement error is specified by the manufacturer to ± 4%, which is adequately precise because the errors caused by inaccuracies of the sensor-positioning are – as a rule – bigger. Thus it is not sensible in the framework of the results presented here to judge e.g. the Duncan APTL-1 with its 36 mT as "stronger" relative to the Jazzmaster pickup (33 mT).

Pickup	**§)**	
Fender Telecaster Texas special (Bridge)		
Fender Telecaster-70 (Bridge)		
Fender Stratocaster (USA Standard, Middle)		
Rickenbacker (Toaster-Pickup)		
Fender Noiseless Stratocaster (Neck)		
Fender Stratocaster (USA Standard, Neck)		
Fender Stratocaster (USA Standard, Bridge)		
Fender Stratocaster-72		
Fender Jaguar (Neck)		
Fender Telecaster-73 (Bridge)		
Duncan SSL-1 (Strat-Type)		
Duncan APTL-1 (Telecaster-Type Bridge)		
Fender Jazzmaster-62 (Neck)		
Fender Jazzmaster-62 (Bridge)		
Schaller		
Fender Vintage Telecaster (Bridge)		
"Telecaster"-Fake (Bridge)		
DiMarzio DP172 (Tele-Type Neck)		with cover
Rockinger Strat (bar magnet)		
Fender Stratocaster (bar magnet)		
DiMarzio SDS-1		
Duncan APTR-1 (Telecaster-Type Neck)		with cover
Fender Vintage Telecaster (Neck)		with cover
Lace-Sensor gold		
Gibson P90		
"Telecaster"-Fake (Neck)		with cover
Rockinger P90		
Ibanez Blazer (Strat-Type Type)		
Gretsch HiLoTron		
Gretsch Filtertron		
DiMarzio DP107 Megadrive		
Joe Barden (Strat-Type, Bridge)		
DiMarzio DP184		
Gibson Tony Iommi		with cover
Squier Humbucker		without cover
Gibson Burstbucker Neck		with cover
Gibson Burstbucker Bridge		with cover
Gibson 490R		without cover
Gibson ES 335 (Neck, 1968)		without cover
Gibson 57 classic		with cover
Gibson ES 335 (Bridge, 1968)		without cover

Table: static pickup magnetic field without strings. + = north pole; measured at 2 mm distance (orientation values – the measurement precision is mere moderate).

§) the actual numbers are reserved for the printed version of this publication

5.4.2 Static magnetic field in the presence of the string

Magnetic pickups only work with ferromagnetic strings. A large part of the magnetic flux exiting the face of the magnet (pole plate) penetrates the string, splits in both directions, runs within the string for a few millimeters, and exits again after a short distance. **Fig. 5.4.8** shows the fundamental course of the flux for the example with a cylindrical **alnico magnet**. In the neutral zone – this is the plane dividing the magnet into 2 cylinders of equal size – the flux density amounts to 0,63 T; this corresponds to a magnetic flux of 12,6 μWb given a cross-sectional area of 20 mm^2. About 50% of the flux leaves the magnet via the cylinder side-wall while the remaining 50% exit via the pole plate – again about half of which flows through the string.

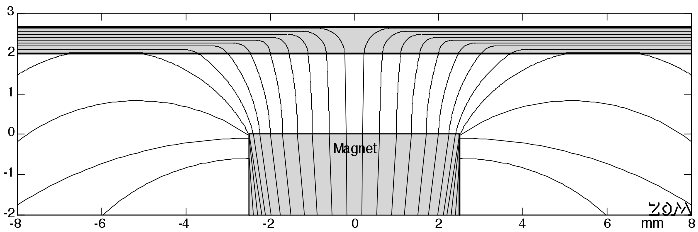


Fig. 5.4.8: Magnet, string, flux lines. The shape of the field is not calculated exactly but shown as a simplification

A direct measurement of the static magnetic flux travelling in the string is not possible. However, the continuity conditions allow for conclusions about the axial flux; a small measuring coil enclosing the string is moved axially along the string; the voltage induced in it corresponds to the axial flux change the integration of which results in the axial flux. The measurements presented in the following were done with a D'Addario-String (diameter = 0,66mm). The measurement coil had 64 turns of CuL-wire (∅ = 80μm) wound in several layers to have an inner diameter of 1 mm and a length of 2 mm. Using a synchronous motor powering a spindle drive, this coil was pushed with a speed of 6,35 cm/s along a string of a length of 18cm. Halfway along this distance an alnico magnet was positioned perpendicular to the string; the gap *d* between string and magnet was adjustable. For aiming the measurement parameters there is a troublesome conflict: the coils should be as small as possible in order to arrive at a good local resolution – given the overall dimensions even a length of a little as 2 mm is relatively long). Reducing the wire-diameter does diminish the coil dimensions .... but also the motivation of the one carrying out the procedure as the barely visible wires break again and again. The 80 μm CuL-wire proved to be a good compromise. 64 turns kept the outer diameter sufficiently small such that not too much of the field in air was sampled as well. The feed speed of the spindle drive should on the one hand be as high as possible to generate a high induction voltage but on the other hand the motor needs to be given enough time to reach a constant speed, which precludes very short measuring times. A precision spindle (with a gradient of 2,54 mm) yielded a feed speed of 6,35 cm/s and an induction voltage just short of 1 mV. These are manageable values.

Since the measurement coil is of low impedance and at the same time the coil voltage is integrated, noise interferences are not critical. The offset of the amplifier, however, poses a problem. Even though the offset voltage (approx. 18 μV relative to the input) appears rather small, the resulting error would be too large (**Fig. 5.4.9**). An induction voltage of 18 μV corresponds to a flux-density change of 0.8 T/s; given a measurement time of 2 s this would result in an offset-based deviation of no less than 1,6 T! This error needs to and can be compensated – but not entirely, because the offset voltage is not constant but drifts such that a small residual error remains. In practice these deviations are insignificant. In **Fig. 5.4.9**, a measurement with offset compensation is compared to one without it. The uncompensated measured flux density switches „on the way" – which is a no-go, of course.

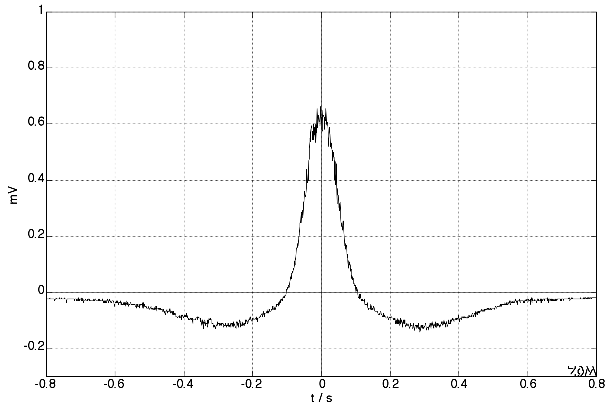
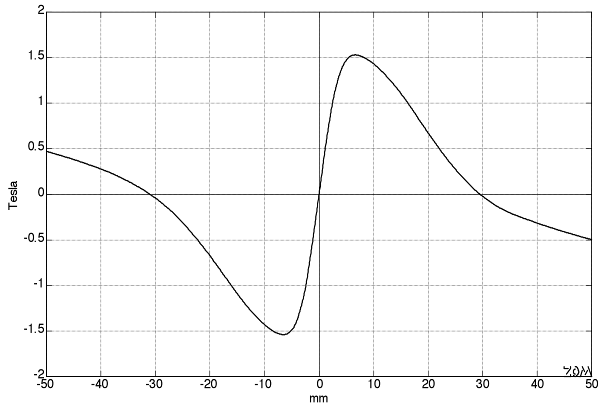
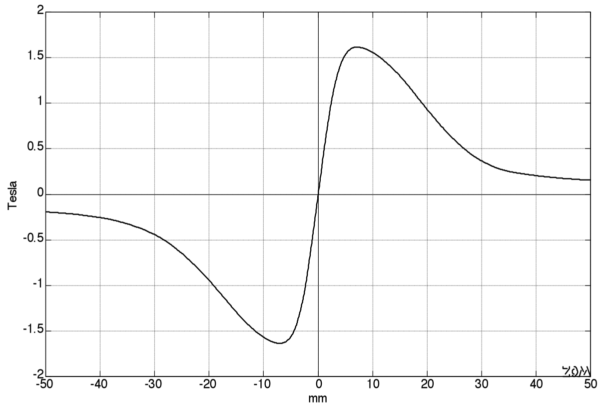


Fig. 5.4.9: Induced voltage (left) and – calculated from it via integration – magnetic flux density in the string without offset-compensation (lower left), with offset compensation (lower right):
Distance of magnet *d* = 3mm.
String : D'Addario 0.66mm.





There are two basic approaches to magnetize the string: either one starts from an un-magnetized string and brings the pickup magnet – starting from a big distance – closer up to the desired distance. Alternatively, one may first let the magnet touch the string (d = 0) and then moves it away to the desired location. Due to the **hysteresis-like** B/H-connection these two measurement approaches do not arrive at the same magnetic flux despite the equal eventual distance. The string becomes a magnetic source proper because of the external magnetic field. The overall flux through the string can be interpreted as the sum of an externally generated und an internally generated flux. As the pickup magnet is brought closer to the originally demagnetized string, an internal magnet is switched on, so to speak, and it now supports the flux generated by the external magnet. Even as the external magnet is moved away again from the string by a few millimeters, the string retains a remanent magnetization, and a stronger magnetic flux remains.

Strong magnets (e.g. alnico-5) succeed relatively easily in magnetizing the string (almost) up to saturation – **hysteresis**-effects not as pronounced: the string cannot be more than saturated and this condition can only be attained one way. For humbuckers, this is different: while between the magnet poles the string is – independently of history – saturated as well, the outwardly directed flux (i.e. the flux directed away from the pickup) is strongly dependent on the magnetic past. If a new or a demagnetized string is brought closer to the strings, the flux is more concentrated to the area between the magnetic poles; if the string already had magnetic contact a stronger flux divergence ensues.

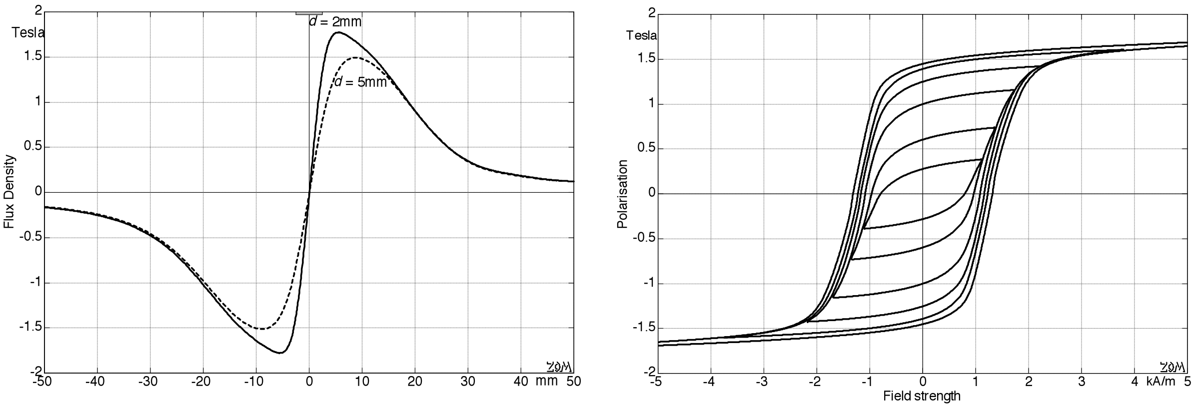


Fig. 5.4.10: Axial magnetic flux through the string for *d* = 2mm / 5mm (left); string-hysteresis (right).

Fig. 5.4.10 shows the measurement results for a string mounted above the magnet of a single-coil pickup. The strong flux densities clarify that even for *d* = 5 mm the string is almost magnetized up to **saturation**. This has far-reaching consequences for the **alternating flux** which we will discuss further below: the ferromagnetic material of a magnetically saturated string cannot accept further magnetization and – behaving as if it were located in vacuum (or air) – shows the same small permeability μ_0. Just a few millimeters away from the magnetic axis, the string already loses its good conductivity for alternating magnetic flux and barely differs from air in that way! Consequently, the alternating magnetic flux is not transported in the sting over any significant distance; rather, it leaves the string already after a few millimeters. The magnetic conductivity of the string is only high in areas where the flux density is small i.e. in the centre over the magnetic axis. Corresponding results are shown by measurements relating to the magnetic aperture (Ch. 5.4.4, 5.10.5).

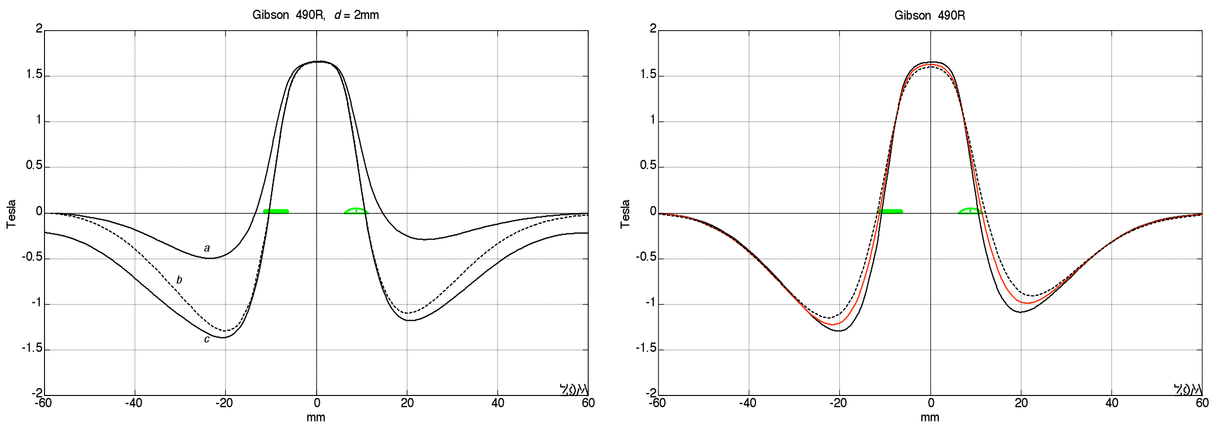


Fig. 5.4.11: Axial flux density through the string for a Gibson-Humbucker 490R. **Left**: *a* = un-magnetized string. *b* = magnetic poles at 2 mm after touching (*d* = 0) the string, *c* = after magnetization of an extended part of the string. **Right**: magnet/string-distance = 2, 3, 4mm, each after saturation.

With a **humbucker**, the string is subjected to two magnetic poles: in the Gibson Humbucker and its many copies typically the screw is the south-pole while the slug is the north pole (compare to Fig. 5.4.4). Without a string, a rather weak field (13 mT) exists between the magnetic poles. However, in contrast to single-coil pickups, the string over a humbucker bridges almost the entire air-space of the magnetic circuit such that a very strong magnetization of the string happens between the magnetic poles.

In **Fig. 5.4.11** we see the axial magnetic flux in the string for a Gibson Humbucker 490R (static field, i.e. $f = 0$ Hz). At 0 mm i.e. between screw and slug there is a large flux density with little dependency on the string-to-magnet-distance d. Both branches of the B/H-curve are almost horizontal und indistinguishable, which makes for an independence of the magnetic pre-history. However, moving beyond the limits of the magnetic poles we find a much smaller flux density for the un-magnetized string (*a*). Another striking fact (for the present measurements) is that although the screw is about 0,3 m closer to the string, it has a smaller magnetizing effect than the slug,

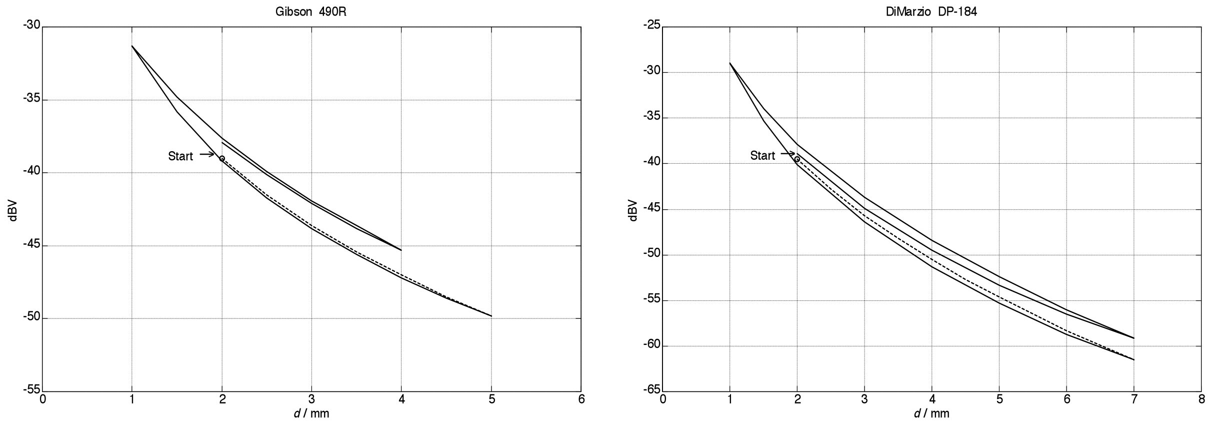


Fig. 5.4.12: Dependency of the induced voltage level on distance. Engine bench testing, rotating crank .

At least for measurement technology, the **hysteresis** effects described above must not be ignored. **Fig. 5.4.12** picks up on that theme: starting at d = 2 mm, the distance between pickup and string is first made smaller, then larger, and then again made smaller for the DiMarzio DP-184 pickup. The voltage levels obtained on the engine bench show different values for the same distance – as much as 3 dB in the extreme case. This difference would be well audible in a direct A/B-comparison.

Now let us take a look at the real world …. for example a look at a test in a commercially successful music magazine comparing humbuckers of relatively similar sound. The pickups are installed one after the other in a guitar, and if, incidentally, the person doing the test arrives at the conclusion that the loudness of the pickups is a little different ...... no, hold it – the guy will SURELY have taken into account the individual string magnetization. Man, such a string really goes through a lot in that process: slap it on, then off again, swap the pickups, slap the string back on ... wait a second, of course first we got to demagnetize it because it got stuck on one of the magnets of the pickups lying on the bench, now re-magnetize to a predefined value, o.k. - now slap it on again, do the listening test, take the string off .... and so on. And all the while keep that de-magnetizing coil (turdus amagneticus) humming. Surely this ordeal – necessary from what we learned above – is always done? Isn't it strange one never reads about it in the tests …. On the other hand, the test description does go to great lengths and notes that the test-guitar was loaded with the original 1959-Sprague-bumblebee-foil-potatoes. Well then .....

5.4.3 The alternating magnetic field

The pickup magnet generates a static magnetic flux in the space (the air) around it. This flux flows from the north- to the south-pole. As the string oscillates in front of the pole-plate of the pickup, this static flux changes. This can be understood as a superposition of a static magnetic field and an alternating magnetic field, an approach which is at least permissible in the linear medium air. While the magnet is a nonlinear system, the relative flux changes are sufficiently small (1%) to support a linearization with good approximation. Still, the above superposition must not be misunderstood in the sense that the paths in space of the static and the alternating flux would correspond! The source of the static field is the magnet; its two poles are separated by 1 – 2 cm which results in a relatively large path of flux. The main source of the alternating flux, on the other hand, is the air gap reluctance in front of the pole plate, this gap being variable due to the string oscillation. Since the associated dimensions are significantly smaller, the extent in space of the alternating flux is also limited to a smaller sector. (Strictly spoken, the two flux components of course extend indefinitely – what is meant here are the relevant field areas). Both the magnet and the string are made of ferromagnetic material – for this reason one needs to consider the hysteresis when calculating the static component, whereas calculations relating to the dynamic component require consideration of the reversible permeability.

A first insight into the spatial distribution of the alternating flux is given by **Fig. 5.4.13:** along the abscissa we have the alternating flux through a cylindrical magnet which has a string vibrating in front of its pole plate. The distance between string and pole plate is 2 mm, the amplitude of the excursion of the string is 0,15 mm with an excitation frequency of 85 Hz. A small coil (25 turns of 80µm magnet wire) wound tightly around the magnet samples the alternating flux. The ordinate in Fig. 5.4.13 presents the distance of this sampling coil from the pole plate close to the string. Clearly, the alternating fields decreases quickly along the magnet axis: less than 2% of the alternating field flowing into the pole plate under the string arrive at the opposite end. The remaining field has exited the magnet ‘along the way’ through the cylinder mantle. (The term *flowing into* applies during one half-wave – for the other half-wave all flux directions are reversed).

For such a field-geometry the induction law should obviously be applied with caution. Not every turn of a pickup coil wound around the full length of the magnet receives the same amount of alternating flux! The section of the winding pointing away from the string contribute much less to the induced voltage while not being without effect: every additional turn increases the inductivity of the coil and reduces the resonance frequency (with everything else being kept equal).

The left section of Fig. 5.4.13 schematically shows the flux paths for a Stratocaster-coil. The static current flows through almost all of the coil but does not contribute to the induced voltage. The alternating flux exits the magnet already within the first few millimeters and does not even reach the coil – this actually is astonishing given the fact that this pickup is considered as the ‚holy grail’ for electric guitars. However, a high **efficiency** is not the only development objective for the mechano-electric transmission: the Jazzmaster-pickup with its large, flat coil had a higher efficiency but was widely rejected due to its different resonance behavior.

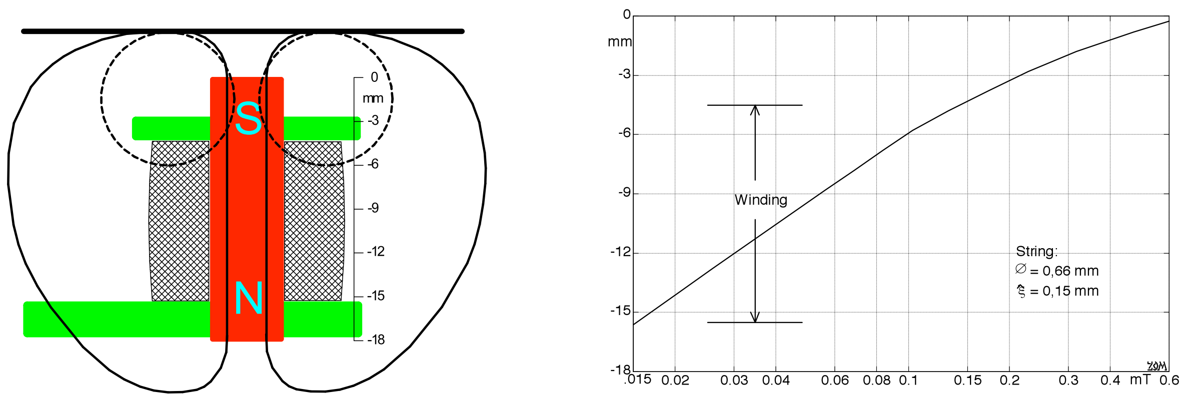


Fig. 5.4.13: magnetic flux for a Stratocaster-pickup (left, schematically). The static flux runs through the whole cylindrical magnet (——), the alternating flux mainly circles close to the strings (**----**). On the right the decrease of the density of the alternating flux along the axis of the magnet is shown (measured data).

In Fig. 5.4.13 we see the alternating flux as it runs *within the magnet*. However, only the innermost windings enclose *only* the magnet; the more outwardly positioned turns are also penetrated by the magnetic flux that runs through the air. The flux density in air is somewhat smaller than that within the magnet, but nevertheless the **field in the air** must not be completely neglected. **Fig. 5.4.14** shows the spatial distribution of the alternating magnetic flux density as measured with concentric circular coils. At a distance of 2 mm from the pole plate of a 5x18 alnico magnet, the steel string of 0,66 mm diameter follows a sinusoidal movement with an amplitude of 0,15 mm and a frequency of 85 Hz. The local flux density can be easily calculated from the measured induction voltage; for an improved visualization it is smoothed via a spline-interpolation. In the left part of Fig. 5.4.14, the maximum of the color scale corresponds to a flux density of 250 μT. This allows for a good representation of the flux density *within* the magnet while the small values of the field in air remain indistinguishable (green; ≈ 0). Changing the color maximum to 15 μT (right part of Fig. 5.4.14) pushes the values of the field running within the magnet out of range but the course of the field in air becomes visible. We now see that close to the string (upper part of the figure) anti-phasic field patterns happen already within a few millimeters. A coil winding enclosing as well a blue field area does not, however, necessarily generate an anti-phase (i.e. unwanted) voltage. Of relevance is in fact the *whole* alternating magnetic flux through each winding, i.e. the integration of the flux density in the axial direction. Consequently, the induction voltage generated by the whole coil is given by three spatial integrations: a radial integration ($dS = 2\pi r\,dr$) to include the total flux of one turn, a radial integration over all turns in one plane, and an axial integration to consider the length of the coil.

Using color-coding, **Fig. 5.4.15** shows the spatial distribution of the **flux in the winding**; its temporal derivative results in the voltage induced per turn. Close to the string (upper section of the figure) the alternating flux flowing through the winding increases with a growing radius of the winding, because the *polarity* of the alternating field is the same both in the magnet and the air surrounding it. However, as the radius grows beyond approx. 7,5 mm, the flux through the winding decreases – the field-polarity in air is in anti-phase to the alternating magnetic flux in this region. As one increases the distance between magnet and string to 4 mm, this border shifts somewhat to a larger radius.

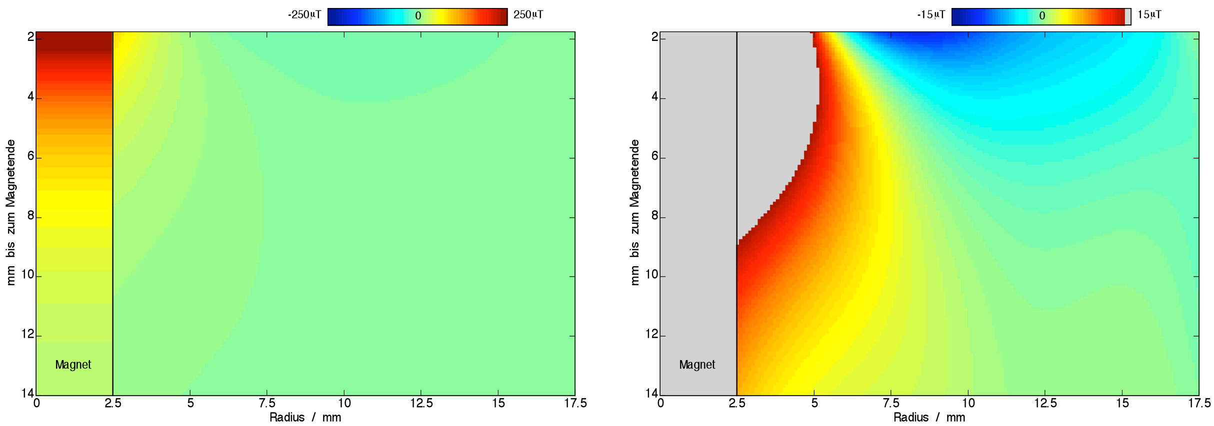


Fig. 5.4.14: Alternating magnetic flux density around an alnico-V magnet. The color-coding exemplifies the distribution of the flux density: the scale for the left section is such that the flux-density distribution within the magnet becomes visible; the scaling on the right clarifies the flux density in the surrounding air. In the ranges colored in blue the alternating magnetic field is in anti-phase to the field within the cylinder of the magnet (*d* = 2 mm). The direction of the field is axial.

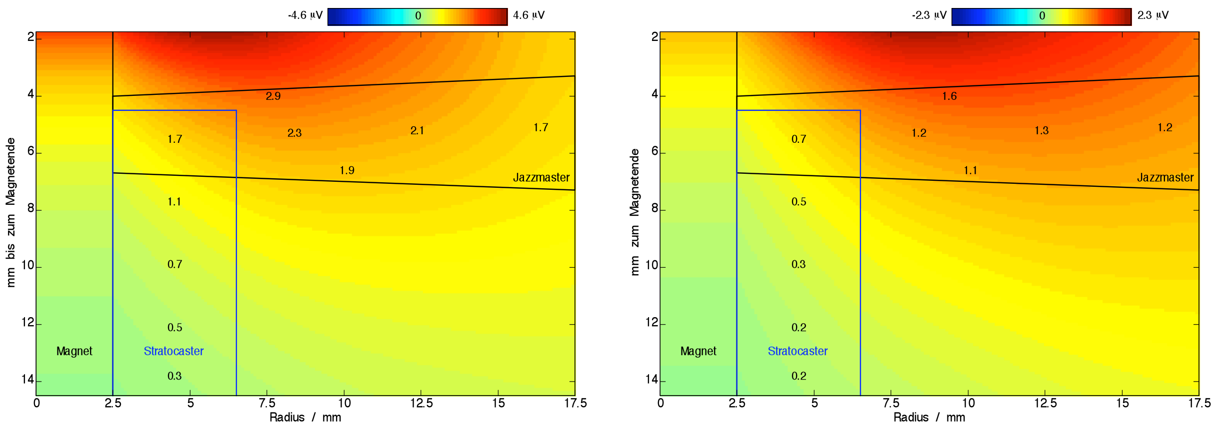


Fig. 5.4.15: alternating voltage in the winding dependent on the number of turns and the distance to the pole plate. The coil cross-sections marked are those for Stratocaster- and Jazzmaster-pickups. On the left, the distance between string and magnet is 2 mm, on the right it is 4 mm. The numbers entered in the figure have the dimension µV / turn.

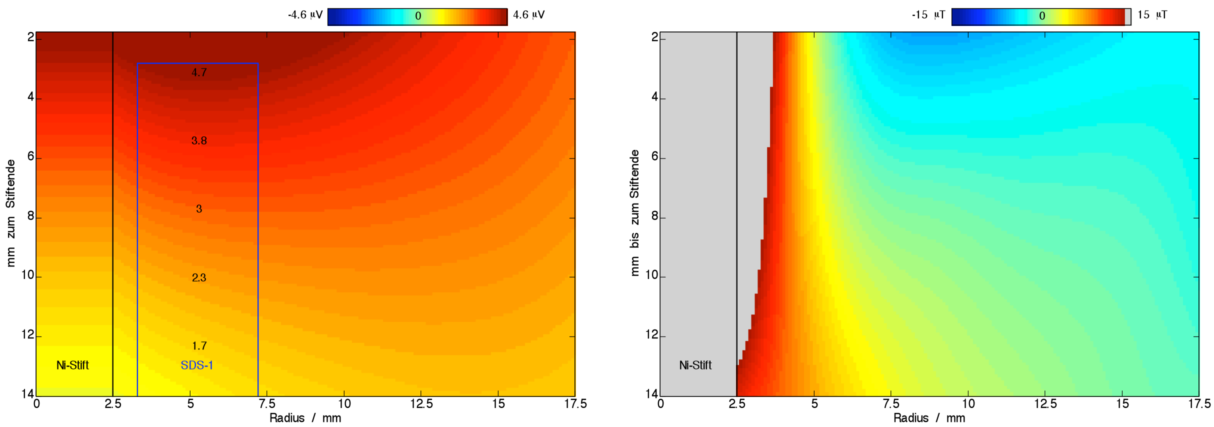


Fig. 5.4.16: for a nickel cylinder (5 mm x18 mm) with two bar magnets (3 mm x13 mm); voltage in the winding (left) and magnetic flow density (right). *d* = 2mm.

In Fig. 5.4.15 we find – in addition to the voltages in the windings – the winding cross-sections for two pickups, as well. It should be noted that for the measurements, circular coils were used while the delineated pickup coils are of an oblong shape. For the **Jazzmaster** pickup, the winding is about 4 – 7 mm away from the string and has a radius of between 2,5 and 17,5 mm. The average **alternating flux through the winding** was found to be approx. 4 nVs (Fig. 5.4.15, left section) for a distance of 2 mm between magnet and a 0,66-mm-string, the latter vibrating with 85 Hz and 0,15 mm amplitude. Via temporal derivation differentiation of the sine-shaped alternating flux a per-winding voltage of approx. 2 μV/turn (root mean square value) is found. With this approximation, a coil of about approx. 8500 turns would thus produce an overall voltage of 17 mV. Comparative measurements with an actual Jazzmaster-pickup with the same excitation yielded 19 mV. In view of the differing coil geometries and magnets, this difference is quite acceptable – especially since the number of turns of the Jazzmaster-pickup is only approximately known (being a vintage 1962, i.e. pre-CBS, it's sacrosanct in any case).

For the **Stratocaster** pickup, the integration over the surface for 7650 turns yields about 7 mV. Here the difference between calculation and measurement (10 mV) is somewhat bigger – however, we again have to deal with the already mentioned differences (magnets, shape of the coil, number of turns). The aim of the measurements is not to determine the pickup-transmission-coefficient; this can be done much better with the shaker-test-bench (chapter 5.4.5). Rather, we wanted to obtain an impression of the spatial distribution of the alternating field which indeed can be seen quite well from the figures. As a comparison, **Fig. 5.4.16** shows field measurements for which, instead of a cylindrical magnet, two bar magnets generate the magnetic field (similar to an SDS-1, Fig. 5.1.3). Towards the string, the field is focused by a cylinder made of nickel. The higher flux density obtained with this configuration can be nicely seen, just as the fact that the alternating field penetrates more deeply. Both these characteristics give a higher sensitivity; possible drawbacks should also be mentioned: higher inductivity and stronger dampening due to eddy currents (chapter 5.9).

Besides the alternating flux penetrating the coil, the **magnetic field of the string** is the second interesting quantity. The strong static flux density was already pointed to – as a consequence of it the sting is all but magnetized into saturation. The permeability of a saturated ferromagnetic material is only marginally higher than that of air which is why the string looses its good magnetic conductivity and does not represent a focusing channel for the alternating flux anymore. The alternating field leaves the string already after a few millimeters and returns to the magnet. For a string of 0,66 mm diameter, **Fig. 5.4.17** depicts the axial flux density (f = 75 Hz, $\hat{\xi}$ = 0,28 mm).

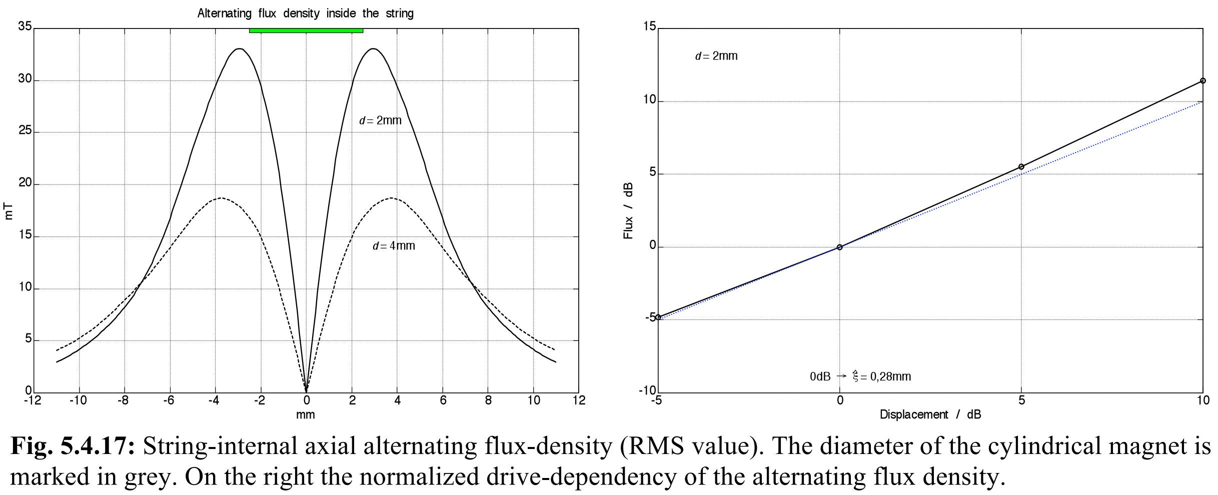
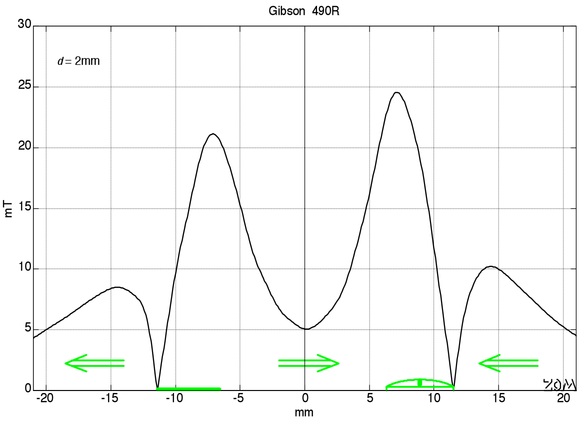


Fig. 5.4.17: String-internal axial alternating flux-density (RMS value). The diameter of the cylindrical magnet is marked in grey. On the right the normalized drive-dependency of the alternating flux density.

At a string-to-magnet distance of 2 mm we obtain a maximum flux of 33 mT at 3 mm from the axis of the magnet. Multiplied by the doubled string surface (the flux through the string flows in both string directions) we obtain an **alternating flux in the string** of 22,6 nWb. It is possible to compare this value with the alternating magnetic flux exiting the magnet (Fig. 5.4.13): there, the flux density amounts to 0,68 mT which combined with the magnet surface yields an alternating magnetic flux of 13,4 nWb. The different string frequency (75 Hz vs. 85 Hz) and the different string excursion (0,28 mm vs. 0,15 mm) need to be considered – the correspondingly corrected **alternating magnetic flux** amounts to 21,4 nWb which is a very good correspondence and a confirmation of the model we have used.

In the right-hand part of Fig. 5.4.17 the dependency of the alternating string flux on the string-excursion is shown. A linear dependency would lead to the dotted line, however the measured data increase progressively i.e. in a **non-linear** fashion. In fact, it is not surprising that we do not find a perfect linearity here: presumably this is less an effect of the non-linearity of the magnet's hysteresis but the distance-dependency of the reluctance of the field in air. In the normalized presentation which is used in the figure, 10 dB correspond to a peak-excursion of 0,9 mm. The string therefore oscillates between a distance of 1,1 and 2,9 mm from the magnet which is a *relatively* large range, but one that is not unusual in everyday guitar practice.



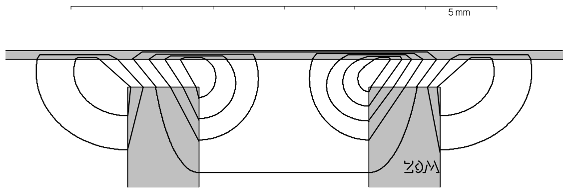


Fig. 5.4.18: left: string-internal axial alternating flux density for a humbucker (measured RMS values); above: approximate course of flux.

Fig. 5.4.18 shows the course of the alternating flux for a **humbucker**. The left part indicates the RMS-values which by definition always have a positive sign; the direction of the flux is indicated with arrows for an arbitrary moment. At the lower border of the figure slug and screw are hinted to facilitate the orientation, however the alternating flux relates to the string located 2 mm above. In the right part of the figure we see the approximate shape of the flux which is, admittedly, unfamiliar in its angularity. But how would one make a better drawing? Via the check-box method? That only works for the plane-parallel field. The field-lines exit metals perpendicular to the given surface? That only holds for materials with a large μ. The pickup-field is three-dimensional, without symmetry-planes or -lines. The ferromagnetic materials in the field are almost saturated in some areas – this complicates an exact calculation drastically, after all. For these reasons, the figure can only give a rough impression of the spatial field shape. The humbucker „squints" a bit outwardly; this was observed for other measurements, as well. Possibly it is in particular the strong static flux between the magnet poles which makes for asymmetric alternating-flux reluctances. Clearly observable is the weak coil coupling: the alternating filed is focused predominantly towards the vicinity of the pole plates; in the picture only one singe field line penetrates <u>both</u> magnetic poles.

5.4.4 Window of the magnetic field (aperture)

Magnetic pickups *pick up* the vibration of the string. Instead of *pick up* the term *sample* would also be appropriate; however this is not a sampling in time but one in space: the place- and time-dependent vibration of the string is *captured discretely* with regard to place and *captured continuously* with regard to time, and it is then transformed into the pickup voltage. As is the case for all real-world sampling processes, the place-discretization does not happen with ideal, infinitesimally small extension in space but across a range of several millimeters which is called the **window of the magnetic field** or **aperture**. The pickup so to speak "looks" through this window onto the string vibration. We find an ongoing speculation about the size of this window in literature: is it as big as the diameter of the magnet, or rather as big as the coil extends? Do wide pickups (e.g. the one for the Jazzmaster) have a larger window than thin ones (e.g. the one for the Stratocaster)? How does the window-width influence the transmission characteristics?

System theory divides its "world" into linear and non-linear systems, i.e. in less complicated and more complicated systems. Pickups belong to the latter, unfortunately. Therefore, the following considerations – which all have their basis in the theory of linear systems – may be understood merely as approximations. The principle of superposition holds in linear systems only; it forms the basis for a comprehensive application of impulse response, convolution integral and transfer function. For small string excursions at least this linearization is justified. For large excursions of the sting, considerable non-linear distortion should be expected, however the effects on the transmission frequency response nevertheless are on the small side.

The transmission characteristic of a linear system can equally be described in the frequency domain and the time domain: in the time domain via impulse excitation and impulse response, in the frequency domain via excitation by a sine function and by the transfer function [e.g. 6]. For the guitar string, both measurement principles are problematic. The excitation with a sine function results – due to the almost perfect boundary reflections – in standing waves with strongly frequency-dependent amplitudes. At the vibration nodes, the latter vanishes; the pickup cannot be excited here. Simple absorbers such as cotton wool between string and guitar neck do not give a satisfactory reflection-dampening while efficient absorbers require a big development effort. An excitation with a short impulse delivers better results but due to the dispersive propagation requires a dispersive convolution. Completely unusable results are delivered by a „sampling“ of short, shaker-driven pieces of string: with a magnetic field of entirely different shape compared to that of the regular long string, the measurements target an entirely unrealistic situation having nothing in common with the regular operating status.

Motorized test bench

In order to measure the size of the window of the magnetic field without too much effort, the following **experimental setup** was developed: in the middle of a string of approx. 12 cm length and 0,7 mm diameter, a crank of about 2mm length is bent (**Fig. 4.4.19**). The string is then fixed to the shaft of an electric motor, such that it can rotate around its longitudinal axis. The pickup under investigation is mounted to a sledge and can be moved along the string. The rotating string crank represents a place-discrete, time-periodic excitation, i.e. a local impulse. The motor speed is immaterial as long as it can be kept constant during the experiment. Moving the pickup delivers a local response-function $a(z)$.

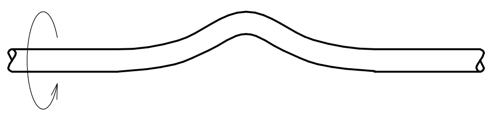


Fig. 5.4.19: Rotating steel string with crank.

If indeed the pickup were a linear system, and if the crank were limited to a very short range, then *a*(z) could be interpreted as local impulse response. Since, however, the excitation impulse (the crank) has a length clearly very different from zero, *a*(z) represents a convolution of the crank *k*(z) and the impulse response *h*(z). The result is that there is a tendency to measure too long a window of the magnetic field.

This measurement technique of course differs from the real excitation: the plucked string has a transversal wave running along its length while with the method above a crank rotates. For a freely vibrating string it is not possible to generate a singular impulse excitation, because displacement location *z* (axial coordinate) and time *t* are mutually interlinked via the propagation velocity. Every generated transversal impulse runs along the length of the string with high velocity and consequently does not generate a stationary excitation. To generate an impulse of only a few millimeters, it would – given a propagation velocity of 100000 mm/s - be necessary to control a frequency range extending considerably beyond 10 kHz (2 mm are passed through within 20 μs). The transversal wave equations require a predetermined interconnection of place and time – however, using a rotating crank, we succeed in decoupling place and time, and obtain a location change as slow as desired.

Fig. 5.4.20 shows measurement results of selected pickups. Stratocaster- and Jazzmaster-pickups both feature cylindrical magnets; the Stratocaster coil, however, is narrow and tall (WxH = 13x11) while the Jazzmaster *coil* is very wide and short (35x4). The P90 coil, as well, is wide and short, but the magnetic field is generated by two bar magnets positioned on the side of the coil pointing away from the string; 6 round-headed screws guide the field. The SDS-1 is of similar construction but incorporates hexagon socket screws. Despite the different pickup construction, the measurement results are similar. Obviously it is only those string movements which happen directly in front of the cylinder magnet (or in front of the screw) that induce a note worthy voltage – the coil geometry has no bearing on the length of the window of the magnetic field. Still, one must not conclude from these measurements that the coil geometry is generally insignificant; the transmission coefficient of the pickup (and thus the vertical position of the *normalized* curves in Fig. 5.4.20) does depend on the coil-geometry, but the window shape does not.

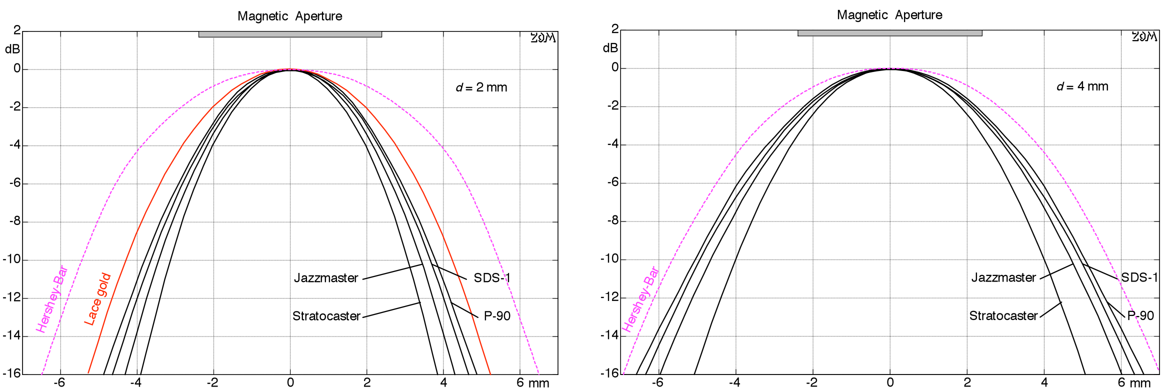


Fig. 5.4.20: local window-functions normalized to the same maximum. The width of the Jazzmaster's cylindrical magnet is included as a bar at the upper border of the figure. Pickups: P-90, SDS-1, Jazzmaster, Stratocaster. Lace: cf. Ch. 5.4.7, Hershey-Bar cf. Ch. 5.4.8.

The window functions depicted in Fig. 5.4.20 are place functions. They can be recalculated into time functions using the phase velocity valid for transversal waves – for accurate considerations the dispersion would need to be considered. Assuming linear transmission (which removes us a bit from the actual reality, see chapter 5.8: harmonic distortion), we can interpret this window shape transformed via the phase velocity as **impulse response**. The Fourier transform of the latter gives the **magnetic transmission function** of the pickup. The magnetic transmission function is complemented by the electrical transmission function mainly composed of pickup inductivity and cable capacitance.

The effect of the aperture can be demonstrated using the example of the **scanning of a film**. This scanning involves the film (which is blackened depending on the picture) running through a thin ray of light. The strength of the ray is correspondingly modulated and e.g. a photodiode can detect this. The remaining brightness of the ray is the average value across the sampled surface: the thinner the ray, the finer the resolution. If we assume that the film is blackened with a sine-shaped place function, then the scanning with the ray of light represents a local averaging which can be interpreted as a convolution in the time domain (as is the case for every averaging process). The place function (divided by the velocity of the film) transforms into a time function which – convoluted with the window function – yields the output signal of the photo diode. In the case that the width of the ray of light corresponds to a wavelength in the blackening, the averaging is done over a full period and delivers a zero in the transmission. Systems theory calls the resulting (idealized) system a **gap low-pass filter** [6, 7], the sin(x)/x-shaped transmission function is also designated **gap function**. A similar situation is found with the magnetic tape [3, chapter 11.2].

For a guitar pickup, using a rectangular window (insensitive – sensitive – insensitive) represents merely a rough approximation: indeed Fig. 5.4.20 reminds us more of a Gaussian function. The latter is invariant regarding the Fourier-transform: a spectral Gauss function (i.e. a **Gaussian low-pass**) pertains to a Gauss function in time. It would anyway not make sense to spend too big an effort on the approximation, since the non-ideal impulse function (Fig. 5.4.19) has an influence, as well. **Fig. 5.4.21** shows typical field-transmission functions. Clearly visible is a string-specific filtering resulting from the string-specific phase velocity c_p. Considering that the transmission range is limited to about 5 kHz due to the pickup resonance, it is obvious that for a single-coil pickup the window of the magnetic field has little influence on the transmission behavior.

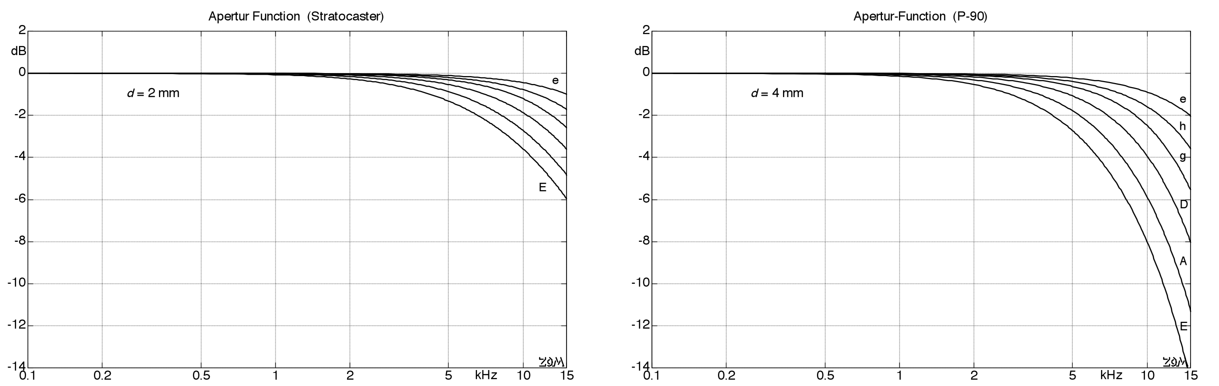


Fig. 5.4.21: frequency response (real part) of the magnetic aperture function; dispersion is considered. Left: Stratocaster; distance magnet/string d = 2mm. Right: P-90; d = 4mm.

On top of the axial **shift** of the offset (the variable of the abscissa in Fig. 5.4.20), there is a second variable: the **distance** *d* between rotating string and pickup. Enlarging the distance increases the length of the window of the magnetic field which leads to a slight dampening of the treble. The main change is in the absolute transmission gain (the sensitivity, chapter. 5.4.5).

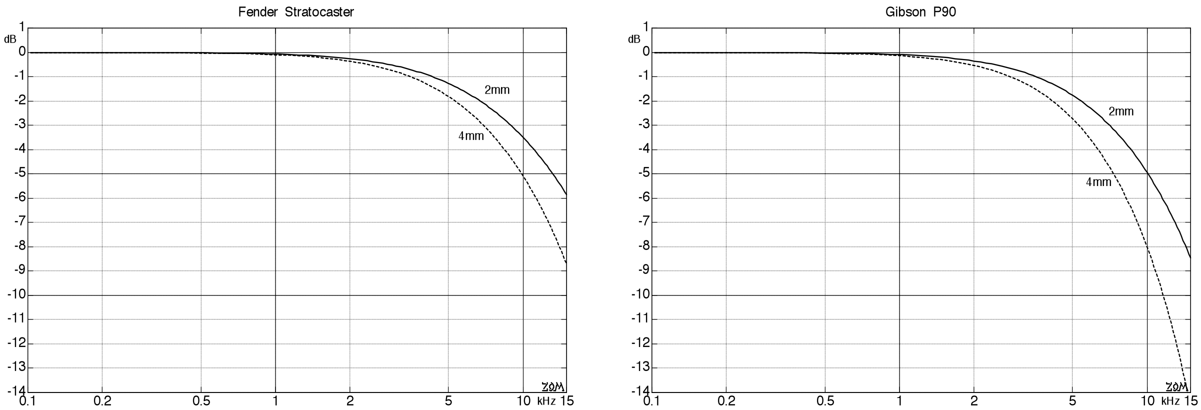


Fig. 5.4.22: Aperture-low-pass (E2-Saite) for 2mm and 4mm magnet/string distance. Normalized, dispersion is considered.

Fig. 5.4.22 shows, for two particular pickups, the normalized aperture-filter frequency response dependent on the distance *d* between the magnet and the string. As a rule, for customary distances (approx. 3 mm) the voltage level drops by 3 dB per mm distance increase (**Fig. 5.4.23**).

Fig. 5.4.23: Voltage level for variable distance *d*, the crank is directly above the magnet plate. The average increase is - (3 ... 4) dB/mm. The specific dBV-values are bench-specific.
This figure is reserved for the printed edition.

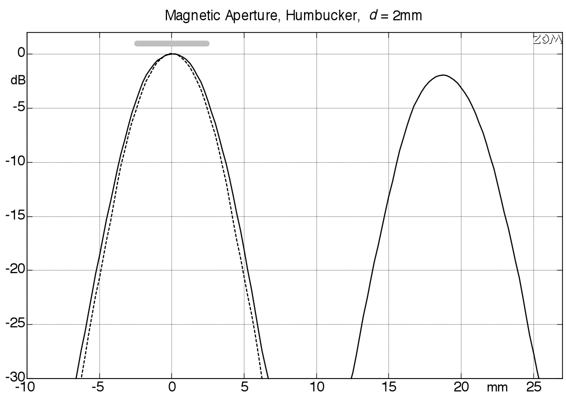
Using a logarithmic division of the abscissa (as it is done in the right-hand section of Fig. 5,4,23) and adding a fixed value *A* to the distance *d*, we obtain straight lines with good approximation. The distance function therefore is a power-function of the type:

$$L_U = 20 \cdot \log\left((d + \Delta)^{-\psi}\right) \mathrm{dB}$$ dependency of voltage level on distance

The fixed value *Δ* came to 0,5....4 mm for the pickups depicted in Fig. 5.4.23; the exponent *ψ* was 1,3 ... 2,7.

Contrary to the single-coil pickup, the classic **humbucker** samples the string vibration at *two* sections; for this reason its local window function shows **two maxima**. In Seth Lover's Gibson-Humbucker (and its innumerable copies), a bar magnet located under the coils creates the magnetic fields which is guided to the strings by 6 screws through one coil and by 6 pins (or slugs) through the other coil. The distance of these poles directed towards the string amounts to **18 – 19 mm**, the screw-head has a diameter of 5 mm, the slug one of 4,8 mm. Bar magnet, screws, string, and slugs form an annular magnetic circuit flowing through both coils. The flux-change created by the string will thus affect both coils – however with different efficiency due to the considerable degree of scattering. A movement of the string over the screw induces a voltage predominantly in the coil carrying the screws. The coil with the slugs receives a part of the alternating field, and also here a voltage is induced, but the latter is smaller than the one in the coil with the screws. The two coils are connected in series so that the voltages generated by movements of the same phase add up.

Fig. 5.4.24 shows, for selected humbuckers, the results of measurements taken on the same test bench as used for Fig. 5.4.20. In all tested pickups the coil fitted with the screws yielded a smaller sensitivity versus the coil with the slugs. On the right hand side of Fig. 5.4.24 further measurements for humbuckers of other distances of the pole pieces are depicted.



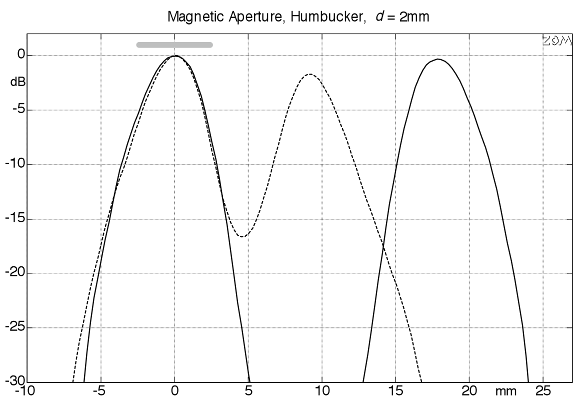


Fig. 5.4.24: local aperture functions normalized to the same main maximum (coils in series).
Left: typical Gibson-Humbucker, e.g. 490R; to compare: Fender Jazzmaster (----).
Right: Gretsch Filtertron (18mm pole distance), DiMarzio DP184 (7,6 mm pole-distance, ----);

Besides the single-coil pickup having *one* maximum and the humbucker having *two*, the measured aperture functions are very similar. The second coil allows for additional degrees of freedom in the humbucker: the distance of the poles (abscissa) and the different sensitivity of the individual coils (ordinate of the secondary maximum).

Customarily the two coils of a humbucker are connected in series and only the summed voltage is evaluated. Picking up only the voltage of one individual coil (so called **split mode** operation) makes the hum compensation disappear. As a general rule, the sound is still not that of a typical single-oil pickup because the shapes of the magnetic field are different for single-coils and humbuckers, and also because the pickup resonance is at a higher frequency.

For more details regarding the split operation see chapter 5.9.2.8 (coupling) and chapter 5.10 (measurements).

Fig. 5.4.25 shows a typical window function of the two coils of the Gibson Humbucker. The solid line marks the level of the more sensitive coil with the slugs, the dashed line represents the coil with the screws. The vertical distance of the main maximum is typically 2 – 3 dB; the secondary maximum measured for the individual coil is about 14 – 20 dB lower than the main maximum. It is not possible to be more precise regarding the secondary maximum. To achieve a larger dynamic range of the measurement, the string with the offset would have to rotate smoothly with tolerances within a range of 1/100 mm across a string length of several cm – this cannot be achieved with elastic steel wire. External to the offset there will be small eccentricities which would distort the measurement result. Supplementary measurements can be found in chapter 5.9.4.5.

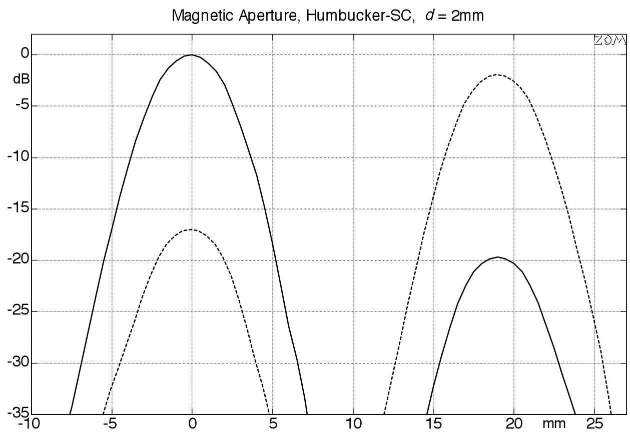


Fig. 5.4.25: same as in Fig. 5.4.24 but with the humbucker in single coil (split) mode. The result for the secondary maximum needs to be interpreted as 'in principle'; the measurement accuracy is mediocre at best here. Typically the secondary maximum is about 14 – 20 dB below the main maximum.

The **frequency response** of the humbucker-aperture-filter is obtained the same way we have done it for the humbucker: via the Fourier transformation (linearity provided). The regular humbucker setup (both coils in series) samples the string at two areas. The second maximum (provided by the second coil) can be seen – in the time-domain – as a repetition of the first, this leading according to the displacement law of the Fourier transformation to a comb-filter frequency response (**Fig. 5.4.26**). The interference gap in the frequency response corresponds to the two humbucker poles being at a distance of half a wavelength: the string moves away from the one pole but moves towards the other. If both coils have the same sensitivity, the cancellation (at the corresponding frequency) is complete. For the listening sensation it does, however, not make any significant difference whether the gap is 15 dB or 25 dB deep.

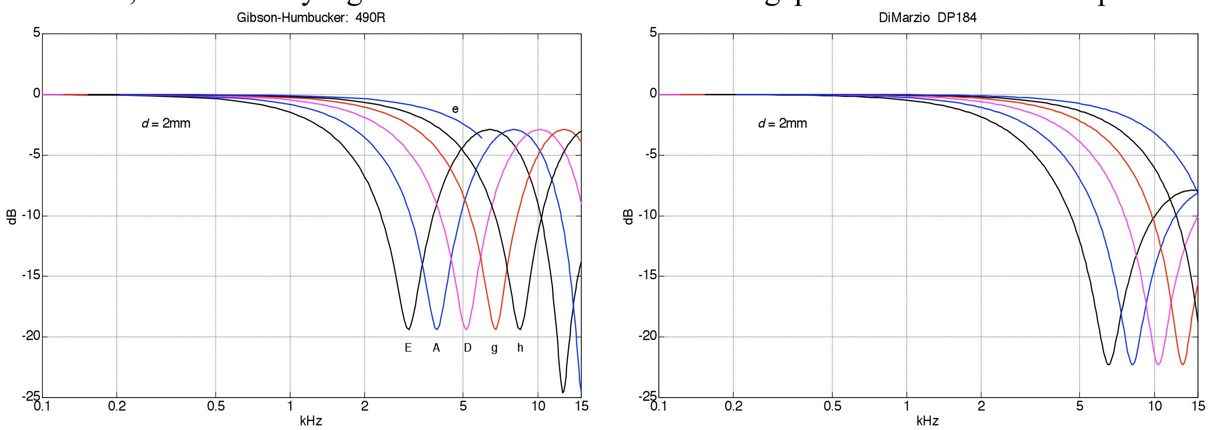


Fig**. 5.4.26:** calculated frequency response (real part) of the magnetic transmission function, with dispersion considered. Left: Gibson 490R, both coils in series. Right: DiMarzio DP-184, series connection.

More important is the characteristic between 0 dB and about -10 dB: here it is clear that in particular for the bass strings (E-A-D) a highly significant **treble loss** happens. Humbucker with a smaller distance (e.g. DP-184) between the poles show a reduced but still clearly audible treble loss. However, it is noted here once again that a pickup is not a measurement device which would have to display a frequency-independent transmission characteristic. The comb-filter response must therefore not be seen as a fault and its effect can only be evaluated on a subjective basis.

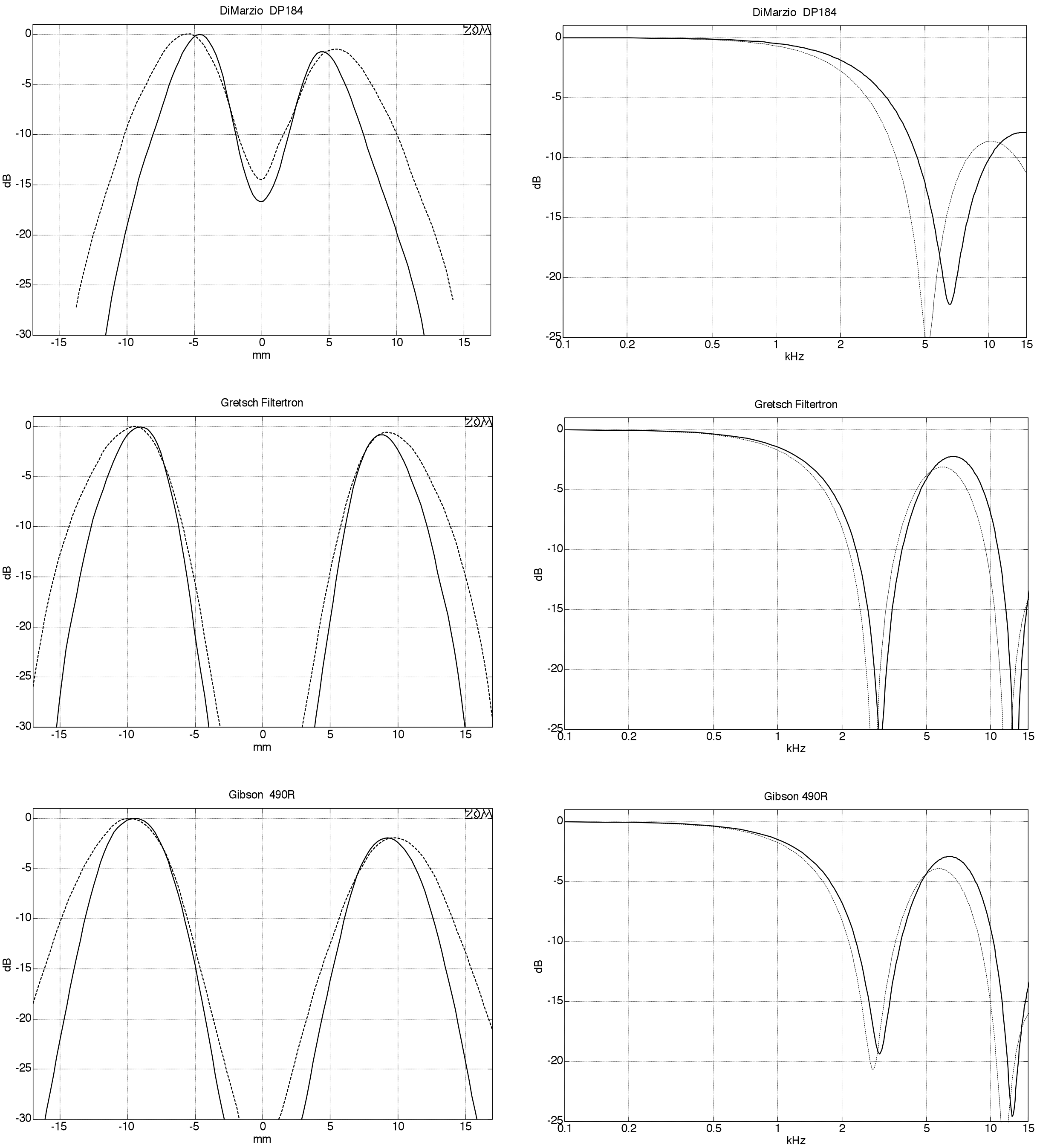


Fig. 5.4.27: left: normalized aperture window, string/magnetic-pole distance —— 2mm, ------ 4mm.
DP-184 (top), Gretsch Filtertron (middle), Gibson 490R (bottom).
Transmission behavior for the E2-string (right column).

There is a two-fold influence of the string-to-magnetic-pole distance *d* on the magnetic window: on the one hand the shape widens in the maximum (just like it does for a single-coil), but on the other hand the distance between the maxima changes (due to the divergence of the field). Both effects lead to an increasing treble loss with increasing distance (**Fig. 5.4.27**).

For the humbucker in single-coil configuration (**Fig. 5.4.28**) the interference is not as pronounced compared to the series circuit but still measurable. Despite the disconnected second coil the string continues to be scanned in *two* positions – because of the coupling via the magnetic field.

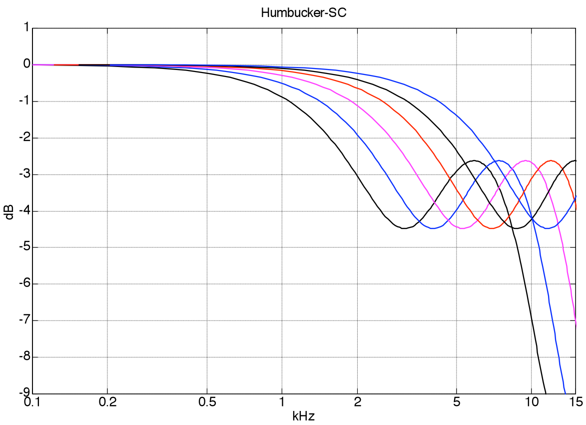


Fig. 5.4.28: Humbucker in single-coil configuration. The window-side-lobe is 14 dB below the main maximum in this example.

The **pole-screws** were almost fully tightened flush with the coil bobbin for the measurements presented so far. The distances between the string and the slugs were thus approximately equal to the distances between the string and the pole-screws. Unscrewing individual screws allows for adjusting the loudness of individual strings: the smaller the distance, the louder the string. **Fig. 5.5.29** shows the aperture functions for a Gibson Humbucker (490R). The distance between the slug and the string was 3,8 mm for both measurements. First, the screw-head protruded 0,3 mm out of the bobbin (solid line), then – for the second measurement (dashed line) – the screw was un-tightened two full turns (leading to a protrusion of 1,8 mm). The distance between string and screw decreased from 3,5 mm to 2,0 mm while the sensitivity grew by 7 dB. Interestingly, un-tightening the screw increases the sensitivity of the coils fitted with the slugs, as well (again due to the magnetic field coupling).

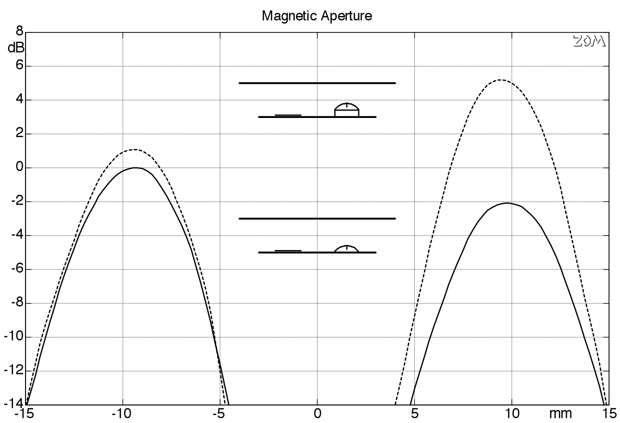


Fig. 5.4.29: change of the aperture-function dependent on the position of the screw. The left-hand maxima relate to the slug, the ones on the right to the screw.

The dependency of the pickup output on the string-to-screw distance is shown in **Fig. 5.4.30** for a Gibson Humbucker. Whether the rotating crank on the string is positioned – for the measurement – over the coils fitted with the slugs (a) or over the coil fitted with the screws (b) does not make a difference in principle; it is merely the absolute sensitivity which differs by about 2 dB. If the crank rotates above the coil with the slugs, a 15 dB lower output level is measured in the coil with the screws. As a comparison the dependency of a single-coil pickup (Gibson P-90) is also shown (dashed line); the main difference is in the absolute sensitivity. This must, however, not be interpreted such that the P-90 would have double the sensitivity of the 490R; due to the chosen excitation location only *one* of the coils of the 490R receives an input. For low-frequency transversal waves exciting both coils at the same time and in sync, both pickups have approx. the same sensitivity (see shaker test bench).

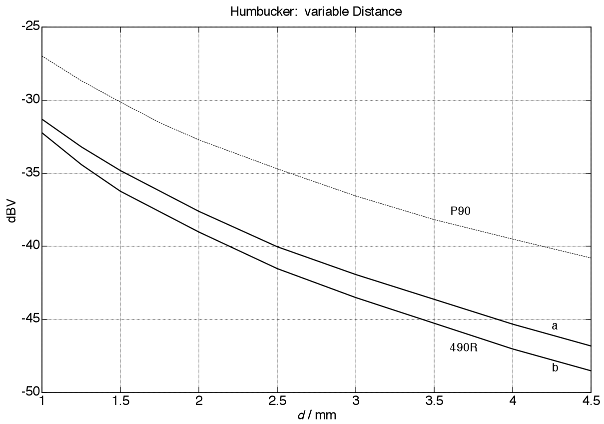


Fig. 5.4.30: voltage level dependency on variable distance; Gibson 490R (motorized test bench)
a = level of coil with slugs, offset over this coil.
b = level of coil with screws, offset over this coil.
To compare the distance dependency of the P-90 pickup is taken from Fig. 5.4.23 (dashed line)

The measurements done using the motorized bench test show without any doubt that the width of the window of the magnetic window (the main aperture) is not determined by the coil but by the pole of the magnet. An effective aperture width of approx. 1 cm creates a slight treble loss for the single-coil pickup; the loss becomes larger as the string-to-magnet distance is increased. Supplementary investigations suggest that the magnetic pole pointing away from the string also creates a (secondary) aperture. The motorized test bench does, however, not allow for a sufficient exactness to check this. Laser measurements in combination with calculations (see ch. 5.10.5), on the other hand, resulted in robust results supporting the assumption that the secondary aperture is responsible for a broad treble-loss (approx. 1 – 2 dB above approx. 1 kHz. The effect of this secondary assumption is more pronounced (chapter 5.4.7) in pickups with field-focusing guides (such as the Fender Jaguar).

5.4.5 Absolute Pickup Sensitivity

The results obtained using the motorized test bench offer conclusive indications about the local sampling of the string; the results are, however, based on a movement which is untypical for a string (rotation rather than transversal wave). In order to obtain supplementary data regarding the absolute pickup sensitivity, the same pickups were investigated again using a **shaker test bench**. An electromagnetic shaker (B&K 4810) served as drive, causing a string of 10 cm length and a diameter of 0,66 mm to vibrate with a sine movement. The string was positioned orthogonally versus the magnetic axis, moving closer to and further away from the magnet, respectively. This can be seen as an excerpt from a very low-frequency, level-polarized transversal wave. An accelerometer served as sensor to capture the measurements; most of the investigations were done in the frequency range between 80 and 95 Hz with a displacement-amplitude of approx. 0,4 mm.

Fig. 5.4.31 shows the dependency of the measured voltage level on the width of the gap between the magnetic pole and the string (the distance d); this gap was varied between 5 mm and 0,5 mm. The results for the single-coil pickups can be divided in three groups: Telecaster and Stratocaster (relatively shallow curvature), SDS-1 and P-90 (stronger curvature), and Jazzmaster (flatter evolution). In this kind of measurement, the SDS-1 proves to be 10 dB more sensitive („louder“) than the Stratocaster Pickup. On the right hand side of Fig. 5.4.31 we find the results for humbuckers. 490R represents the typical Gibson-humbucker; similar dependencies could be found for the 57-classic and ES-335 pickups. The Toni-Iommi-pickup differs from the 490R for small distances – this can be traced to a different construction.

The pickups are most sensitive with their magnetic pole axis pointing in the same direction as the movement of the string. In the guitar this corresponds to a vibration plane perpendicular to the to the fret-board. String-vibrations in parallel to the fretboard induce next to no voltage (chapter 5.10).

Fig. 5.4.31: voltage level dependent o the variable distance *d*. Displacement amplitude = 0,4 mm, frequency =84 Hz. In practice, the distance *d* often 3 – 4 mm, the associated gradient is -2 ... -3 dB/mm.

These figures are reserved for the printed version.

The different sensitivities are predominantly due to the various types of coils and their distance to the string. The distance *d* marks the clearance between string and magnetic pole; large magnet protrusions (such as for the Stratocaster) require the coil to be further away from the string compared e.g. to the Jazzmaster. The following table summarizes the measurement results.

Tonabnehmer	§)	
DiMarzio SDS-1		
Gibson P-90		
Rockinger P-90		
"Telecaster"-Fake (Bridge)		
Duncan APTL-1 (Telecaster-Type, Bridge)		
Fender Jazzmaster-62 (Bridge)		
Rockinger Strat-Type (Balkenmagnet)		
Fender Telecaster-52 (Bridge)		
Fender Jazzmaster-62 (Neck)		
Schaller		
Fender Stratocaster (Balkenmagnet)		
Fender Stratocaster (USA Standard, Bridge)		
Ibanez Blazer		
Joe Barden Strat-Type (Bridge)		
Fender Jaguar (Neck)		
Rickenbacker (Toaster-Pickup)		
Fender Telecaster Texas (Bridge, D / A)		
Fender Telecaster-70 (Bridge, mit Platte)		
Fender Stratocaster (USA Standard, Middle)		
Fender Telecaster-70 (Bridge, ohne Platte)		
Fender Noiseless Stratocaster (Neck, G)		
Duncan SSL-1 (Strat-Type)		
Lace-Sensor gold		
Fender Stratocaster-72 (G)		
Gretsch HiLoTron		
"Telecaster"-Fake (Neck)		
DiMarzio DP-172 (Telecaster-Type, Neck)		
Fender Telecaster-73 (Bridge, D / A)		
Duncan APTR-1 (Telecaster-Type, Neck)		
Fender Telecaster-52 (Neck)		
DiMarzio DP-107 Megadrive		
Gibson Burstbucker #2		
Gibson 57 classic		
Gibson 490R		
Squier Humbucker		
Gibson ES 335 (Neck, 1968)		
Gibson Tony Iommi		
Gibson ES 335 (Bridge, 1968)		
DiMarzio DP-184		
Gretsch FilterTron		

Table: low-frequency pickup transmission-coefficient T_{Uv}.
String diameter = 0,70 mm (plain), distance to the magnet pole d = 2mm.

§) The numeric values are reserved for the printed version.

5.4.6 Staggered and beveled polepieces

When picked with the same strength, the six strings of the electric guitar are supposed to generate an approximately equal voltage in the pickup. This requirement is met by a piezo pickup, but by a magnetic pickup not so much: if all 6 strings were constructed of solid material, the E_2-string would yield 4 times the output of the E_4-string (chapter 3.2). However, the winding around the lower strings is rather inefficient in terms of magnetism, and thus the bass strings produce roughly the same loudness as the treble strings. For reasons of clarity, we will in the following not look at loudness (which is dependent on numerous factors) but at the level of the fundamental of the string: **Fig. 5.4.32** shows the results for nickel-wound Fender strings. Basis for the measurement is an identical picking strength for all 6 strings. For solid strings the level is, for this case, only dependent on the fundamental frequency of the string♣ (dotted line). The E_4-, B-, and G-strings are assumed to be solid, while the remaining strings are taken to be wound, showing 4 – 10 dB less pickup output compared to the solid strings. (chapter 3.2). The dashed line gives the level for a *wound* G-string matching within the set.

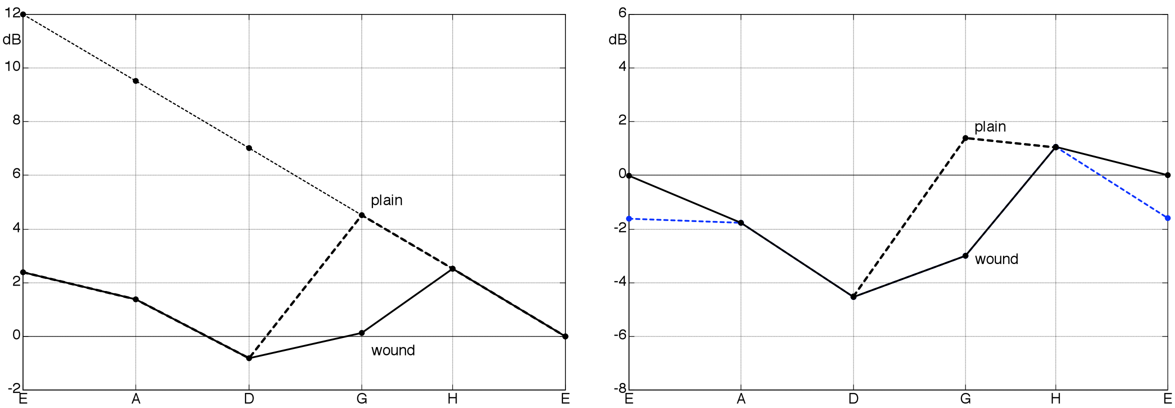


Fig. 5.4.32: level of the fundamental of the strings, Fender-150 (pure Ni-wrap): 42-32-24-16-11-09. Dashed line: with wound G-string. Left: equal string-to-magnet distance and equal pickup sensitivity for all strings. Right: convex string action across the neck as is typical for Fender; dotted line: boundary effects of the pickup.

When comparing the output level of the strings we need to weigh several effects: the magnetic efficiency of the strings (chapter 3.2), the distance between string and pickup, and the sensitivity associated with the individual pickup magnets. Due to the curvature of the fretboard (with a radius between 18 and 30 cm), the strings are not located in a plane but along an arch. In most scenarios the E_2-magnet shows a 1mm-larger distance to the string than the E_4-magnet, this leading – as an example - to the following **string curvature**: 1,0 – 1,5 – 1,7 – 1,5 – 0,9 – 0,0. For the string-specific pickup sensitivity we need to consider, on the one hand, the individual static magnetic field which can easily vary by 10%, and on the other hand the reduced sensitivity of the pickups for the **outer strings** (E_2 and E_4) typical for Fender pickups: this will be 1,5 – 2,5 dB less compared to the inner 4 strings, conceivably because the coil winding captures only part of the magnetic field of the string in the edge region. In summary, we arrive at individual level differences with small loudness deficits for the D- and G-strings, and a B-string that is a bit louder. The level differences between the strings are not dramatic but did lead to corrective measures: to compensate for level- and thus as well loudness-differences, Fender modified – as early as the 1950's – the magnet lengths such that the softer strings are subjected to a stronger magnetic field. These magnets protruding more or less far out of the pickup housing were called **staggered polepieces**, as opposed to **flush**

♣ Given these conditions, a set of higher-gauge strings is not louder, because the higher required tension reduces the string displacement and thus also the string speed

 Translation into English by Tilmann Zwicker

polepieces which are also called **level polepieces**. Not all guitars received staggered polepieces: the Jaguar and the Jazzmaster (then considered the flagships of the line) sported flush polepieces while the Stratocaster had staggered polepieces. Opinions about the principle according to which the magnet protrusions should be arranged seem to have differed over the years: the D-magnet was longest at some point, then the D- and G-magnets were of the same length but longer than the others, then again all 6 magnets were of the same length, then again they were staggered. **Fig. 5.4.33** shows some of the designs, without any claim to completeness.

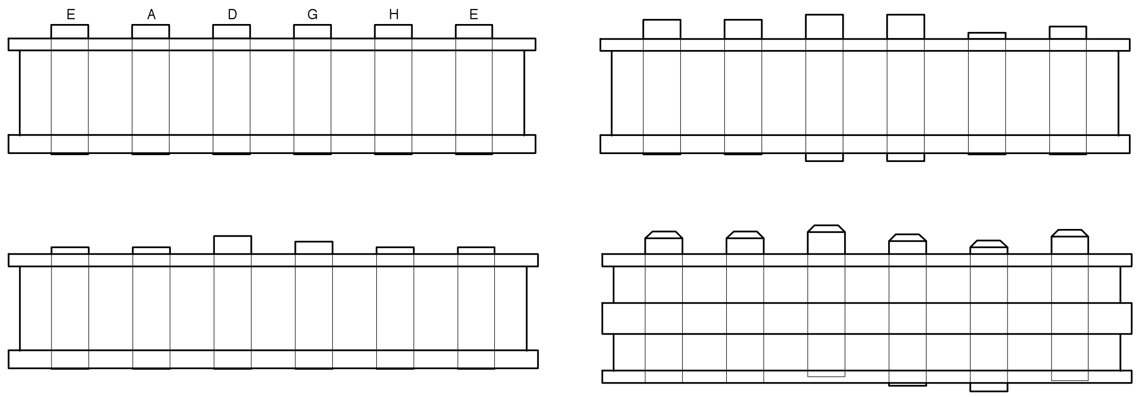


Fig. 5.4.33: different-length magnet protrusions in Fender pickups. Upper left: flush polepieces, upper right: 1972 Stratocaster, lower left: 1973 Telecaster, lower right: 2004 Stratocaster („noiseless“).
N.B.: „H“ (German) = „B“ (international)

The 1972-Stratocaster-pickup investigated for the example had extended D- and G-magnets, a shorter B-magnet and a slightly shortened E_4-magnet♣. This configuration leads to the level dependencies shown in **Fig. 5.4.34** – indeed a visible improvement over Fig. 5.4.32 – especially with a **wound G-string**, as it was the standard in the 1950's when the first Fender guitars were built! As late as 1968, the Fender brochure indicates for the 1500 string set: 12–16–26w–34–44–52 *this set supplied on all new instruments except ¾*. Alternatively the "light gauge rock 'n roll" string set was already available (gauged 10-13-15-26-32-38 and with solid „unwound“ or „plain“ G-string) – the wound G-string was still standard, however. When thinner strings with a solid G-string became the new standard, the old magnet-protrusion-profile did not fit anymore. The solution was typical for musicians: newer pickups have the

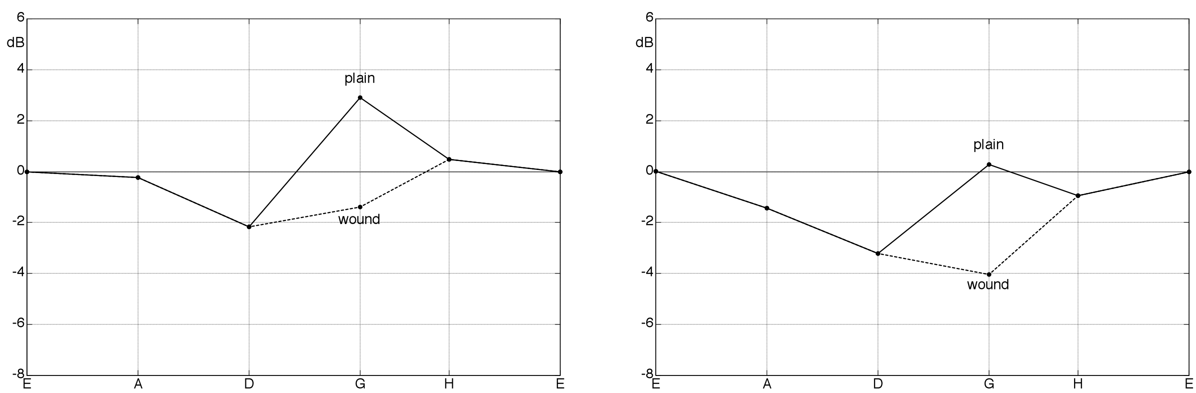


Fig. 5.4.34: level of string fundamental, Fender-150 (pure Ni-wrap): 42-32-24-16-11-09. Dashed line: with wound G-string.. Left: '72-Stratocaster, right: Noiseless Stratocaster (2004). Convex string action.

♣ In old Stratocaster-pickups the magnets were mostly flush on the lower pickup-side. Here is an example in which presumably 2 of the magnets were moved . NOT RECOMMENDED: **RISK OF DAMAGE**!

G-magnet protrude only little, but "vintage pickups" using the old profile are available new, as well. Not only a few guitar players request the vintage profile ... but still mount the light gauge strings with the "plain" G ....

How significant is a level difference of 3 dB? From a pure signal-theory point-of-view an increase of 3 dB ties in with a doubled power i.e. 200 W instead of 100 W. That would be quite substantial. On the other hand: Johannes Webers writes in his book on studio electronics ("Tonstudiotechnik", Francis, Munich) that the attenuation-per-step in stepped level controls typically amounts to 1,5 dB – this would be correspond roughly to the smallest discernible loudness difference. 3 dB would thus be twice such a minimum step: perceivable in direct comparison but not really a very big deal. **Seth Lover**, developer of the Gibson Humbucker, remembers: "My PAF prototype ... worked well. When the salesmen saw this, without any adjustment screws, it was like breaking their arms. They just didn't have anything to talk about. So, next came the punched-out holes and the adjustment screws." [Vintage Guitars, Feb. 1996]. Business as usual, then: sales has to straighten out mistakes made in R&D ... or was it the other way round?? A later development in the Gibson product line, the Tony Iommi pickup, lacks the adjustment screws again. The times they are a-changing. Or Greek-orthodox: panta rhei.

Of course, the adjustment screws give power to the guitar player, and individuality to his or her instrument: "only after I had turned the second screw a quarter-turn counter-clockwise I suddenly got this awesome sound". Immediately, however, the maestro runs into the next problem: if he doesn't tell anyone, his genius remains unrecognized. If he does tell, they all can copy his awesome sound. An improved statement, then: "of course I first need to fine-tune every guitar I receive from the manufacturer: those guy deliver such shitty stuff – even from the custom shop, it's unbelievable. However, with my extremely sensitive hearing I got every Custom to sound great. It's just that there are so many years of hands-on experience involved that can't really relate it all". O.k. then ... keep them screws turning. Incidentally, Jimi Hendrix did not modify the pickups in his Stratocaster whether or not he had access to a lefty and had to restring a righty. "We don't need another hero ..."

Next to staggered magnets the other specialty are **beveled magnets**. These are tapered like a truncated cone on the side pointing towards the string (45°-bevel, Fig. 5.4.33, Noiseless Stratocaster). One might speculate whether the pickup assembly (the press-in operation) could be done more easily, or whether Leo Fender was hoping for a stronger magnetic field. Measurements with turned magnets in a Noiseless-Stratocaster yielded practically no difference: on average the "improvement" of the response of 0,2 dB is within typical measurement tolerances and insignificant. For the harmonic distortion, as well, no difference could be found relative to Stratocaster-pickups with strictly cylindrical magnets. The theory, too, fails to point to any big differences: in the range of the facing edge (i.e. the intersection between cylinder barrel and the end surface of the cylinder), the flux-density of the cylindrical magnet is very high; the magnetic material is in **saturation** and consequently rather inefficient

It is not recommended to "sharpen" the cylindrical magnets. The sole possible working-method would be to grind them – however this would involve extreme heating of the magnetic material which can lead to a lasting change in the magnetic properties (watch den Curie-temperature!).

5.4.7 Fender: Jaguar and Lace

Both the Lace pickup distributed by Fender and the Jaguar pickup generate – with the aid of a u-shaped yoke – a special magnetic field which shall be further investigated in the following. That Lace advertising tireless tries to convince us that the Fender Lace Sensor is not a pickup but an "*acoustic emission sensor*" is merely typical sales mumbo-jumbo: every pickup is a sensor, anyway. However, at the same time the ads claim that the Lace has *the ability to accurately reproduce the sound characteristics of any existing conventional pickup*. Now that is going a few steps too far and would seem to be quite a put-on. Just looking at the Lace patent (US 4,809,578), i.e. using Lace's own reasoning, casts some serious doubts: the patent notes that all other pickups dampen the string vibrations – it's just the Lace that doesn't. If so, it does NOT reproduce the characteristics of all other pickups – in fact it lacks at least that one.

Over the years, the Fender company tried several times to bend the magnetic field of single-coil pickups, starting with the base-plate of the Telecaster bridge pickup up to the pickup with a ceramic magnet patented in 1980. Leo Fender was of the erroneous opinion that the more string-length is sampled, the better the sound would be, and for this reason the Jazzmaster receives a pickup with a particularly coil and the Jaguar pickup a special yoke. In agreement with this kind of thinking, the patent for the Jaguar discloses that in regular pickups, the magnetic field lines *pass through only very small portions [of the string], with small harmonic content*. In contrast, the teethed yoke of the Jaguar pickup is supposed to magnetize a approx. 2 cm long area (**Fig. 5.4.35**), and for the Lace pickup the magnet strips allegedly push the magnetic field outward, i.e. they make it broader (**Fig. 5.4.36**). But aren't the aperture width and the frequency bandwidth in a reciprocal relationship? Of course they are: the shorter the sampled piece of string, the better the treble reproduction – that's also exactly why the old tape recorders had the smallest possible magnetic gaps in the tape heads.

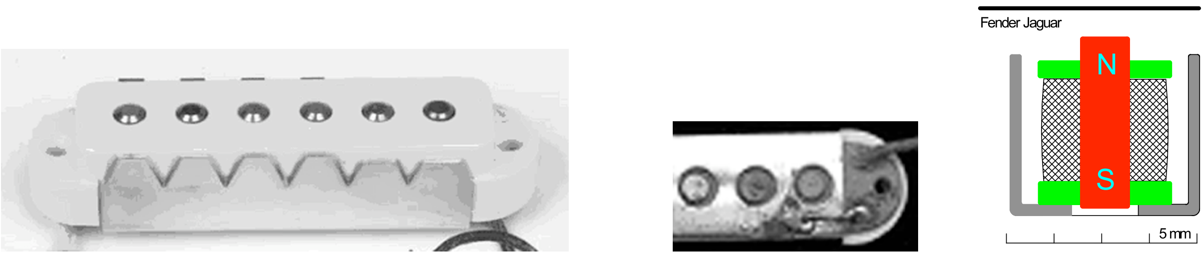


Fig. 5.4.35: Fender Jaguar pickup [www.guitar-parts.com, www.jimshine.com]; the teethed u-shaped "claw" leads a part of the magnetic flow returning from the string back to the south-pole

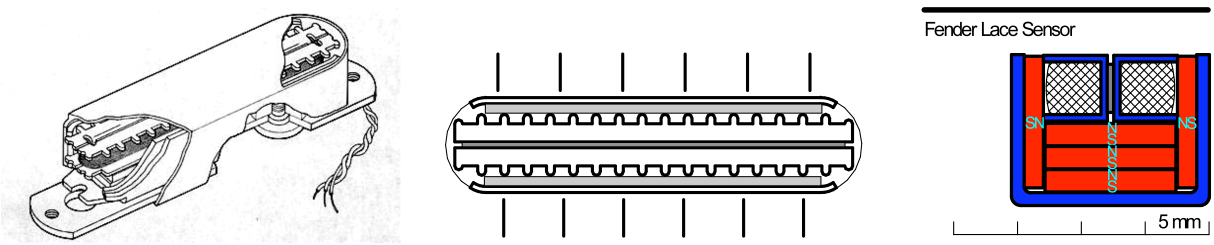


Fig. 5.4.36: Lace-Pickup [Fender-Actodyne]. The ferromagnetic coil bobbin has a teeth-shaped upper side to generate a magnetic field "as inhomogeneous as possible". The distance of the teeth has no regular relation to the distance of the strings (in the middle section above two typical cases are hinted: top: 51 mm, bottom: 49 mm) .

Luckily, the magnetic field lines ignore the patent publication for the most part and instead follow the laws of physics when seeking their path. **Fig. 5.4.37** shows, in its left section, the magnetic window of the **Lace pickup** measured with rotating string, while the right-hand section depicts the aperture-frequency response derived from the window. Yes indeed, there is a difference to the Stratocaster pickup, but the treble-loss is still limited, as also verified via the transfer measurement using the laser-vibrometer (**Fig. 4.5.38**, measurement setup as given in chapter 5.10.5).

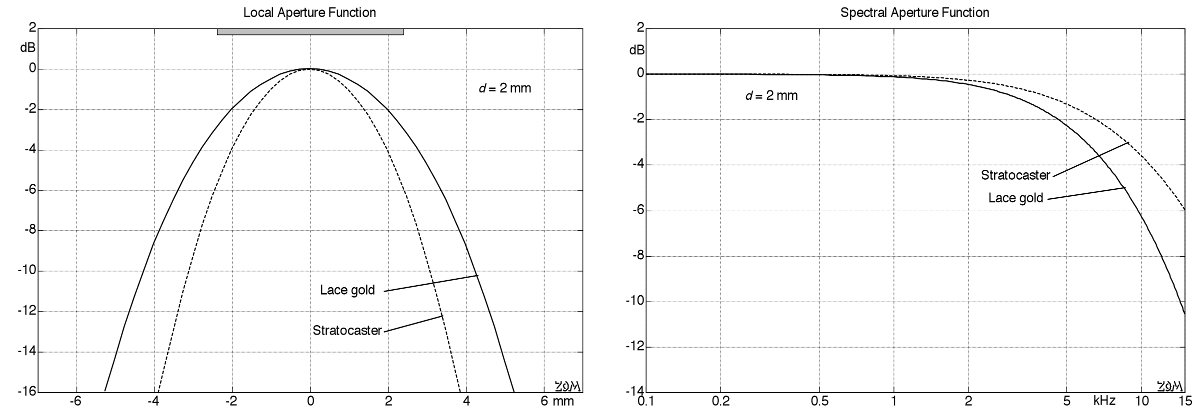


Fig. 5.4.37: left: aperture of the magnetic field; right: aperture-frequ.- response (E_2, with dispersion, b = 1/8000).

The impedance-frequency-response (**Fig. 4.5.38**) reveals further differences: the yokes lead to stronger eddy current losses and consequently the emphasis of the resonance in the Lace pickup is a bit less than that of the regular Stratocaster pickup. Similar differences can easily be achieved as well via changes on the resistance of the connected potentiometers, and thus Lace and Stratocaster pickups are very similar regarding their transmission. There are, however, big differences in the **sensitivity to hum** (chapter 5.7) and in the strength of the **magnetic field** – the latter is about 60% less than that of the customary Stratocaster pickup. That's not really "Leo-compliant" since he thought it to be patentable to generate – in the Jaguar pickup – a magnetic field stronger than that of conventional pickups. Conversely, the allegedly patentable subject matter in the Lace is a magnetic field weaker than that of conventional pickups. Who would have thought .....

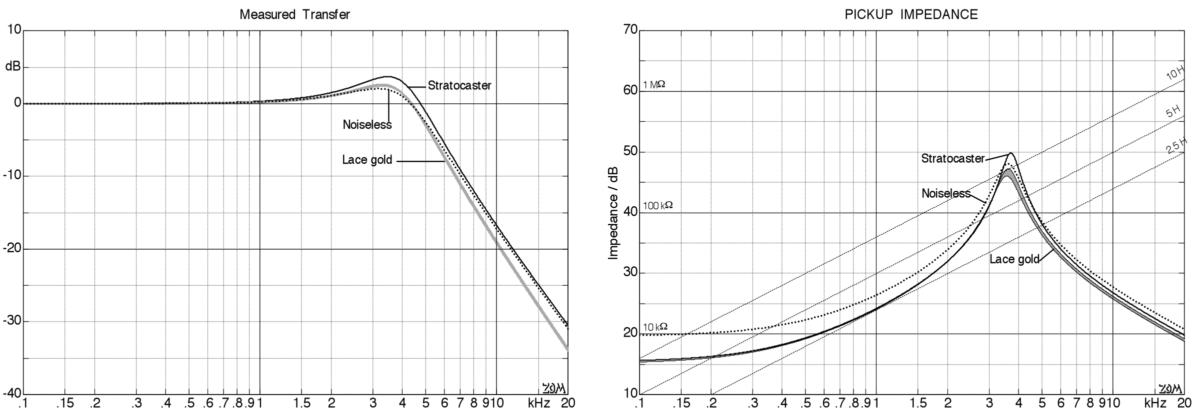


Fig. 5.4.38: left: frequency response measured with the laser-vibrometer. right: impedance-frequency-response. Two specimen of the Lace were analyzed. Noiseless. (Noiseless = Fender Noiseless-Strat-Pickup).

Now then: is the Lace good or bad? In a nutshell: the advertising may be dubious but the pickup is quite o.k. It features a good hum rejection♣ with only a slight treble loss.

♣ However, the Fender Noiseless-Strat-pickup shows an improvement of another 13 dB in its hum rejection.

Incidentally, Mr. R. Blackmore responded to the question whether he was happy with the Lace: "well ... sure – would I use it otherwise?" (in a German music magazine in May, 2005). Seems the interviewer was actually in luck that he didn't get smacked. By the way, it appears that both have fallen out of fashion a bit: Fender almost never installs the Lace anymore, and that Blackmore guy ... who was that again ... anyway, there's probably enough lace of the other kind in Blackmore's Night.

The **Jaguar pickup** is not in a front-row position anymore, either, despite it being better than its reputation. If indeed the u-shaped yoke would generate a 2-cm-wide aperture window, it would face a significant treble loss. As it is, nothing really changes much. That is connected to the fact that, contrary to the patent, Fender does not mount the yoke directly and without any gap to the magnet but leaves a 1-mm-wide annular air-gap (**Fig. 5.4.35**). Off to the patent office right away, and only afterwards do some testing ... ain't that so, Leo? Without the air-gap, microphonics could take over too much, and that's not what we want, do we? And then: the magnetic field doesn't have to be that strong, anyway, and we can make the yoke a bit thinner than in the patent, and shorten it by tow teeth, and change (1964) to staggered magnets ... it's a fit!!

Measuring the impedance (**Fig. 5.4.39**) shows 3,8 H with the yoke and 3,15 H without it; that is more than for the "normal" Strat pickup which had approx. 2.2 H. The DC-resistance is higher than that of the Strat (6,8 kΩ versus 5,7 kΩ) which indicates a larger number of turns. The ferromagnetic yoke increases the inductivity but also reduces the emphasis of the resonance due to the resulting eddy currents. The main differences to the Strat-pickup are: the resonance frequency is lower, the resonance emphasis (Q-factor) decreased, but on the other hand the Jaguar pickup is louder and receives significantly less hum (chapter 5.5, 5.7)

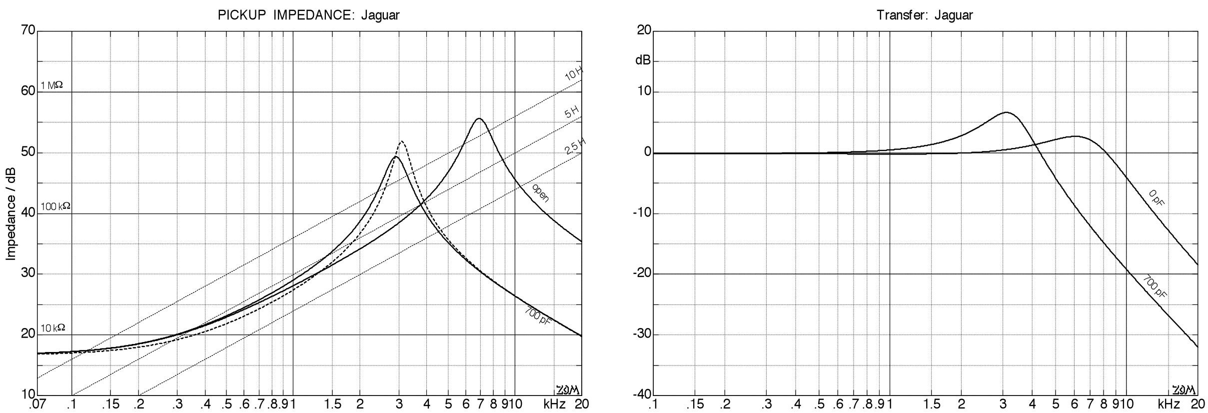


Fig. 5.4.39: Impedance-frequ.-response (--- = w/out yoke). The transfer is for a 333 kΩ load (amp = 1 MΩ).

Comparing both *guitars* divulges a further peculiarity: for the Strat the pots have 250 kΩ each, for the Jaguar 1 MΩ each! That's why the resonance emphasis for the Jaguar in fact even *bigger*. However, the 1-MΩ-pots are not really purposeful: turning down the volume just a bit all the treble is lost (chapter 9). But that's not all, folks: the Jag holds a **secret** which has occupied the fan community for decades: why are two teeth shorter and which way 'round should the pickup be installed? It appears that even in the Fender company there was controversy about this, and the shorter teeth were installed underneath the E2- und A-string ... but also underneath the H- und E4-Saite. Had the issue been solely the loudness of the individual strings, it would have been solved by the staggered magnets. Probably there was the wish to give the two bass strings more brilliance. Not a bad thought in principle – however the improvement is only a few tenth of a dB, and we can check off the issue. Myth busted ....

The comparison between the calculated transfer function (H_{Uv} chapter 5.9.3) and measurement with a laser (chapter 5.10.5) show a slight treble loss (**Fig. 5.4.40**), the cause of which quite surely is the special magnet aperture. The left hand part of the figure shows the local weighting function belonging to the transfer function – it is obtained via the inverse Fourier transform. The saddle-shaped drop around 5 kHz is a consequence of the secondary maxima of the aperture function: without the secondary maxima the transfer function has the shape of the dotted line.

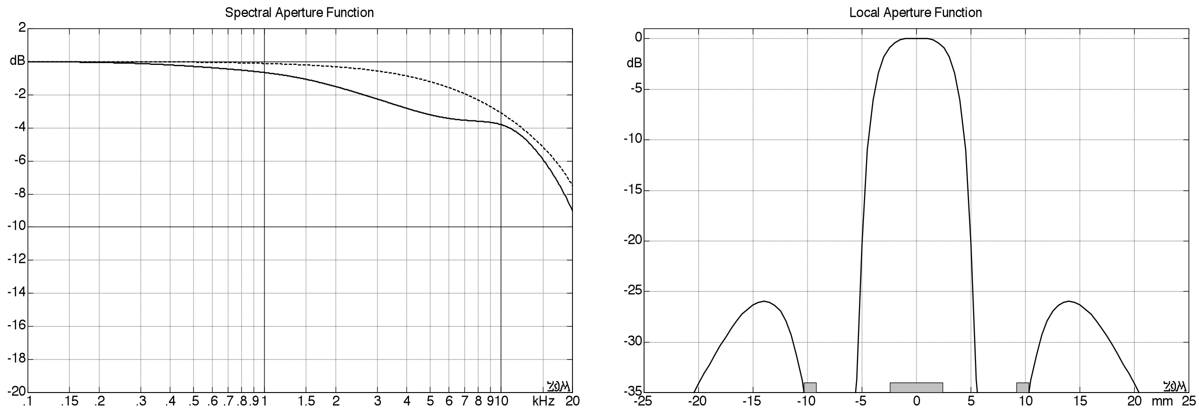


Fig. 5.4.40: Jaguar pickup, left: aperture frequency response (— with & **---** w/out second. maxima); right: local weighting. Wound string, outer diameter = 1,1 mm; string-to-magnet distance = 4 mm, f = 82 Hz for the 65-cm-scale. The dimensions of magnet and heads of the "teeth" are indicated in grey at the bottom of the diagram.

For the analyzed Jaguar pickup, the magnetic field enters the string over the pole (N) and exits it again from approx. 7 mm (compare to Fig. 5.4.8). The flow back to the south-pole generate the **secondary maxima** of the aperture function which are located a small distance outside of the "teeth". The u-shaped yoke including the teeth is able to focus these flows somewhat; this causes the saddle-shaped treble loss – in addition to the reduced sensitivity to hum. Of course, without the yoke with its teeth, the flow back to the south pole is also present – but it is more distributed in space and thus with less attenuation of the treble. The secondary maxima show up in measurements at -40 dB but can be determined only as an approximation since the measurement accuracy is dropping considerably from 5 kHz up.

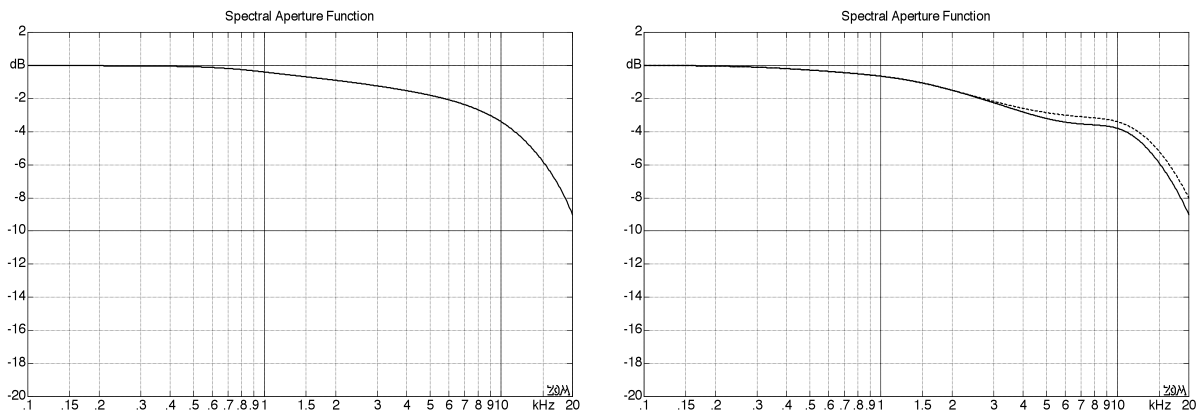


Fig. 5.4.41: left: Jaguar pickup without the teethed yoke, otherwise as Fig. 5.4.40; right: measurements with teethed yoke, above the D-magnet (——) and the A-magnet (----, shortened "tooth"), respectively.

In **Fig. 5.4.41** we see the transfer function without the teethed yoke on the left; on the right the treble gain caused by the shortened tooth shows but it's in fact, not worth mentioning. The shielding, however, is quite a success and reaches second place of the investigated (true) single coils.

 Translation into English by Tilmann Zwicker

5.4.8 DeArmond pickups

Harry DeArmond (Ohio) was one of the pickup-pioneers: as early as the 1930's he developed magnetic pickups and sold them via his business partner H. Rowe to many guitar manufacturers. Common were at that time flattop and archtop acoustic guitars which could be "electrified" with a pickup. If they sported a round soundhole, the pickup was mounted in there, if they had f-holes, a pickup as flat as possible had to be installed between top and strings (e.g. fitted to the pickguard or the end of the neck). DeArmond's **FHC** was attached to a rod running parallel to the strings, its position could be correspondingly adjusted between neck and bridge. A difficulty encountered with this retrofit of pickups related to the loudness of the individual strings. The "plectrum guitars" used back then did already use steel strings but he lower 4 strings (EADG) were wound with brass or bronze. Here, only the thin steel core is magnetically active and the voltage induced in a magnetic pickup is much lower than for the two solid top strings (chapter 3). DeArmond solved that problem with a very special magnet design for which he even obtained a patent: the bar magnet under the coil is not continuous but has a gap under the B-string. Above the coil two ferromagnetic metal strips focus the field (A, C, **Fig. 5.4.42)**; a metal bridge (B) attenuates the magnetic field further.

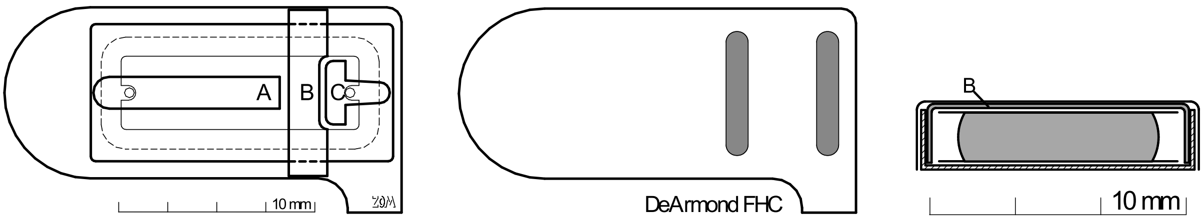


Fig. 5.4.42: DeArmond FHC (US-Patent 2,455,046).

The invention does meet its purpose: the B-string is picked up 8 dB weaker than the bass-strings, the high E-string features a 5 dB drop. The static flux density (measured 2 mm above the lid of the housing) is – at 17 mT – relatively weak; strong single coils easily reach triple this value. There is another difference in that the aperture of these "other" single coils is narrower (chapter 5.4.4). **Fig. 5.4.43** shows the aperture windows compared to the Stratocaster pickup. There is little effect of the extended width of the aperture of the B-string: the wave velocity of the latter is relatively high (chapter 5.4.4). However, for the bass strings there is a loss of brilliance. The dominant treble absorber is the ferromagnetic sheet mounted below the pickup: the eddy currents generated in it (chapter 5.9.2.4) have hat effect of a pronounced treble loss.

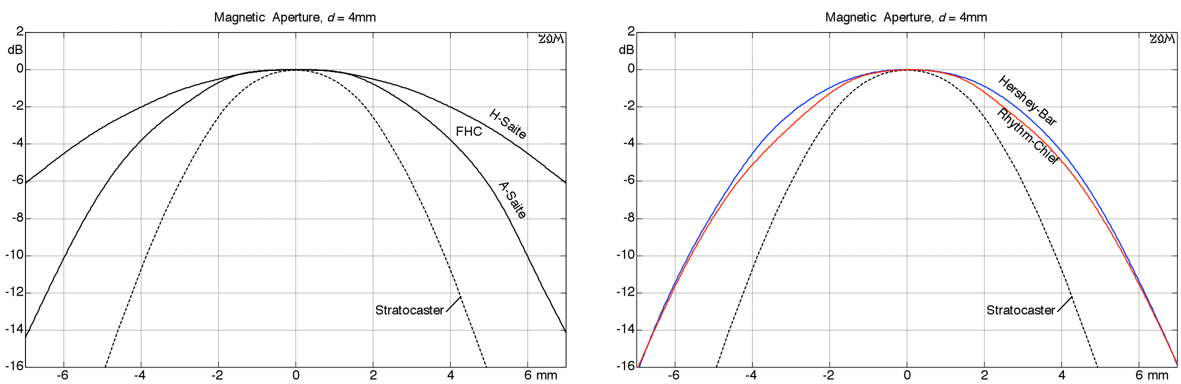


Fig. 5.4.43: Aperture window; DeArmond FHC (left), Rhythm-Chief and Hershey-Bar (right).

The relatively strong eddy-current losses also show up in the frequency response of the impedance (**Fig. 5.4.44**). The inductivity is rather strong but the resonance emphasis only weakly developed. The broken-line curve indicates that the (non-magnetic) cover of the pickup housing reduces the Q-factor, as well. For the impedance the effect is small but fort he transfer function strong. An even more dramatic treble loss results from loading the pickup with a potentiometer – back in the day this device often had only 50 kΩ which killed the treble completely: 8.2 H and 50 kΩ yields a 1-kHz-lowpass having its effect on top of the aperture- and eddy-current-losses (in Fig. 5.4.44 it is not even considered yet). Still: that's the "golden tone" for which these pickups are sought after and change hands for substantial amounts of money.

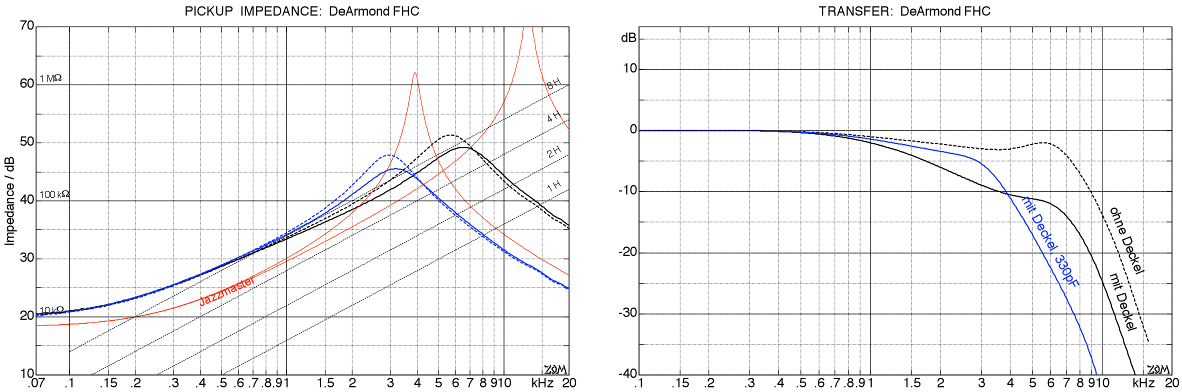


Fig. 5.4.44: Impedance. No load (black), w/load of 330pF (blue); Jazzmaster for comparison (red). The broken lines show the frequency response of the impedance as it is measured without pickup cover. The right part above shows the transfer measured with the laser vibrometer (chapter 5.10.5).

A further development based on the FHC is the **Rhythm-Chief**. Early variants were given a divided winding with a reduced number of turns below the B- and E-string to compensate for loudness as indicated above. The next step, the Rhythm-Chief 1100, features adjustable pole screws. Watch out: these work rather differently than e.g. in a P-90. The particularity starts with the magnet: for DeArmond this often is a plastic magnet (also called rubber magnet). Despite the name the magnetic active substance is a metal powder which is molded to shape using plastic or rubber as binder. In the RC-1100 the magnet consists of the whole (oblong) coil core and the screws are inserted into it. This is indeed **very unusual**, since the screws are directed in parallel to the magnet and short-circuit it partially. Two cases are shown in Fig. 5.4.45: if the screws are deeply inserted (second section of the figure from the right), the magnetic circuit is closed mainly via the screws and the external field is relatively small. Unscrewing the screws to a large extent (as shown in right-most section of the figure) renders them field-focusing and -amplifying. In the end the result matters, and indeed: yes – it works! And even with a little less treble loss than in the FHC. The RC-1100, as well, has the dampening effect of the eddy currents and also the non-negligible aperture dampening (Fig. 5.4.43). The connecting cord is fastened rather amateurishly and easily torn off – which the collectors are not too unhappy about since the collectors value of surviving specimens increases .... to presently approx. $ 1200. Trend: going up.

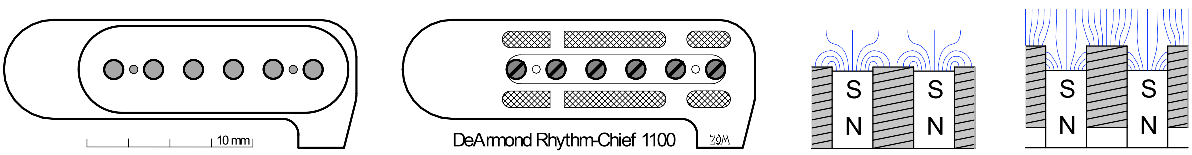


Fig. 5.4.45: DeArmond Rhythm-Chief 1100.

In **Fig. 5.4.46** the impedance frequency responses are shown. The "naked" coil with the plastic magnet inserted in it has a high Q-factor. Installing the 6 screws increases the inductivity (right section of the figure). An even bigger push towards more inductance is generated by the ferromagnetic bottom plate (left part of the figure), but this component also reduces the Q-factor by a considerable amount (eddy currents)

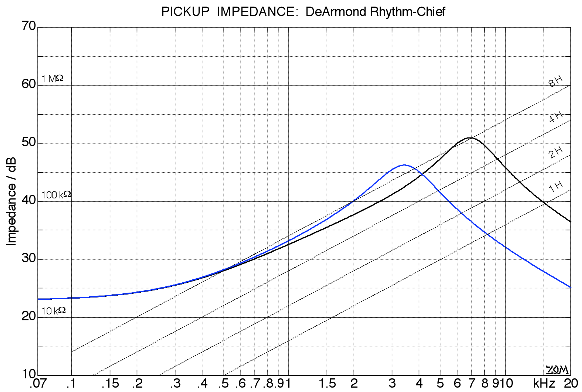
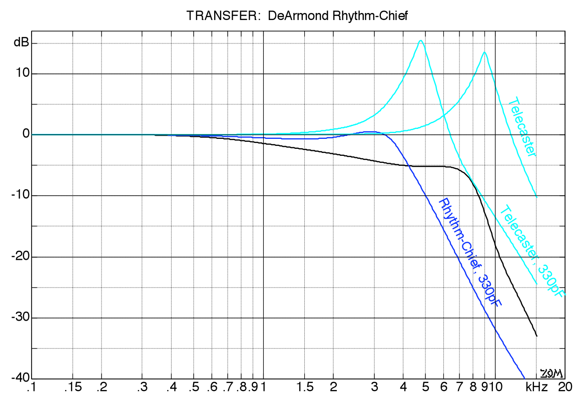
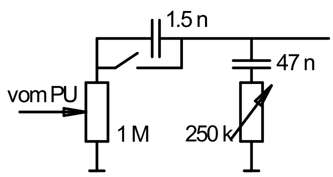


Fig. 5.4.46: impedance DeArmond Rhythm-Chief 1100. Left: original condition, w/out load and w/330 pF load, respectively. Right: coil w/out housing, w screws (——) and w/out screws (-----).

The Rhythm-Chief has directly attached to it a small **control unit** (volume and tone controls plus a lead/rhythm switch). In **Fig. 5.4.47**, the frequency response of the unloaded pickup is shown in black while the condition with a load C_{load} = 330pF is shown in blue. In contrast to the very low-impedance controls they used elsewhere, DeArmond suddenly switches to high values here aiding a better treble response – as long as one does not turn down the volume.





Circuitry of the DeArmond control unit

Fig. 5.4.47: transfer frequency response for the Rhythm-Chief 1100; Telecaster Bridge-pickup fro comparison.

A much simpler representative of the DeArmond pickup line is the so-called **Hershey-Bar** (named of course after the well known chocolate bar). Take a flat, rectangular plastic magnet with a coil wound around it, fix it to a ferromagnetic base plate, slam on a non-magnetic cover – done. Just 7 mm tall, no adjustment possibilities, no treble – perfect. O.k., not perfect for everybody but this pickup, as well, found its fans. The magnetic window is about as broad as the one of the Rhythm Chief (Fig. 5.4.43), and the flux density is (at 19 mT measured 2 mm from the pickup) about as weak as with the FHC, but the coil has either fewer turns or a bigger wire: the DC-resistance is only 3,8 kΩ versus 9.7 kΩ (FHC) and 14 kΩ (Rhythm-Chief), respectively. Interestingly, the Rhythm-Chief is the softest of the three: still about 2 dB more sensitive than the Strat pickup (used as reference, chapter. 5.4.5), but the Hershey-Bar is 4 dB more sensitive and the FHC even 9 dB. This again shows that the DC-resistance has little bearing on the transfer coefficient (see also Fig. 5.5.19).

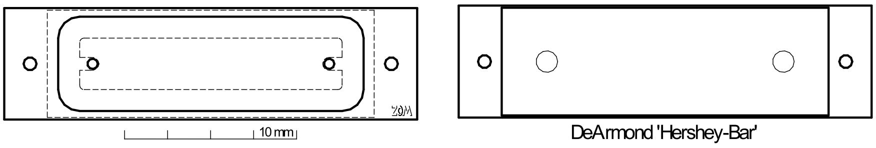


Fig. 5.4.48: DeArmond Hershey-Bar

Hershey-Bar-measurements are shown in **Fig. 5.4.49**. The original-accessory-volume-control has merely 50 kΩ and significantly cuts the treble. Those desiring more treble can switch to a 250-kΩ-pot without any issues.

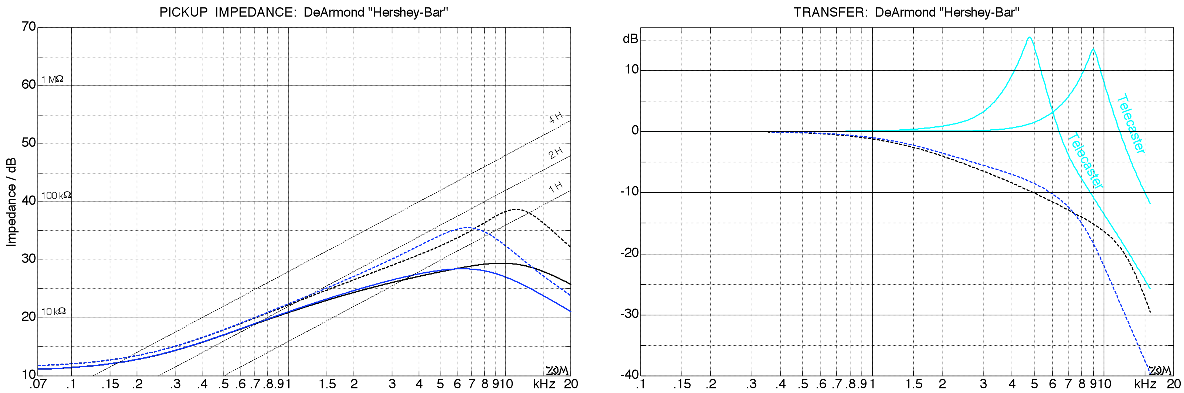


Fig. 5.4.49: DeArmond "Hershey-Bar". Left: impedance frequency response, w/out load and w/330 pF load. Loaded w/original 50-kΩ-potentiometer (———); w/out potentiometer (-----).
Right: transfer-frequency-response; Telecaster-bridge-pickup fro comparison (330 pF, 0 pF).

To **complement** the information about these rather special pickups: 1) designations such as FHC or Guitar-Mike are not unambiguous, they specify merely a group of similar but not identically constructed pickups 2) Such old pickups may have incurred shorts in the winding, or a torn off connecting wire. 3) Because the pickups were often defective, there are many that where repaired somehow but failed to regain the original state after the repair. 4) Some of the pickups are attached to very long cables, and the latter may have significant losses capacities (e.g. 250 pF/m). 5) The aperture attenuations measured via the laser-vibrometer are string dependent! 6) And just to mention it: enthusiasts willing to pay in excess of $ 1000 for a pickup might inspire obvious ideas ....

In closing here a look at the signal-to-hum ratios (chapter 5.7): FHC = 3 dB better than the Strat used as reference, Rhythm-Chief 1100 = 4 dB worse, Hershey-Bar = 2 dB worse.

http://theunofficialmartinguitarforum.yuku.com http://www.harmonycentral.com

Fig. 5.4.50: DeArmond pickups: Rhythm-Chief and FHC.

5.5 Elementary Pickup Parameters

The market offers a large number of different magnetic pickups which differ in basic construction, in their dimensions and in the transmission behavior. Some of the electric parameters can be measured easily – these are therefore often listed in overview tables and connected to sound attributes such as: brilliant, muffled, loud. Of course, the pickup in itself does not generate a sound – that requires a vibrating string, an amplifier and a loudspeaker. In fact, the sound attributes are absolute, categorical judgments, although they are meant as comparing, ordinal judgments: calling a pickup "loud" actually reads: "louder than most others". "Shrill" therefore stands for "this pickup generates – using a customary guitar connected to a customary amplifier with a customary control setting – a sound with much more treble-emphasis than most others". What then causes a pickup to sound louder or shriller than others?

5.5.1 DC resistance

The **DC resistance** is seemingly the most important parameter. It can be determined very easily with an Ohm-meter. Sometimes alternatively the term '**impedance**' is used, other times the term 'loudness '. The former use is not actually wrong since it is possible to connect DC to an impedance – the frequency should, however, be specified. In other words, one should either talk about 'impedance at 0 Hz', or simply of 'DC-resistance'. Statements like 'loudness = 8 kOhm' or 'Output = 8 K' are plain incorrect. For one, the quantity and the unit are already a mismatch, and even more importantly there is no simple connection between loudness and DC resistance. This is easily seen when taking the magnet out of the pickup: the DC-resistance remains the same, but the loudness approaches zero fast.

The DC-resistance R is determined by the specific resistance ρ of the coil wire, the area S_{Cu} of the wire cross-section, and the length l of the wire: $R = l\rho \,/\, S_{Cu}$. **Copper wire** is almost always the chosen material for magnetic pickups, for it we get: $\rho \approx 0.018\ \Omega\text{mm}^2/\text{m}$. Depending on additions and impurities there will be small variations in ρ while larger variations should be expected on the wire diameter. More recent data sheets specify AWG-42-wire with a diameter tolerance (due to manufacturing processes) of ±5% an. Since the cross-sectional area and the diameter have a quadratic interdependence, that cross-sectional area S_{Cu} and thus the resistance value R has a spread of ±10%.

The **diameter** D is very small – often as thin as approx. 63 µm and thus thinner than a human hair.
US-literature specifies the diameter as **AWG** (American Wire Gauge) an. AWG-42 – a wire very often used in pickups – has a copper diameter of 2,5 mil = 63,34 µm. The following approximation can be used for conversions in the range 30 < AWG < 50:

$$D_{Cu} = 10^{0{,}902 - AWG/20}\,\text{mm}^{\clubsuit} \qquad \text{e.g.: AWG-42} \rightarrow D_{Cu} = 63.3\ \mu\text{m}$$

The nominal value of the resistance per meter for this wire (AWG-42) is: **5,4 Ohm/Meter**. Manufacturing variations lead to a scatter of 4,9 to 5,9 Ohm/Meter (modern manufacturing). It also depends on the temperature: R rises per °C by 0,39 %.

♣ more precisely: $D = 0.127\text{mm} \cdot 92^{(36-AWG)/39}$

A thin **layer of varnish** applied to the cylindrical copper wire serves as insulator. As a consequence, the diameter grows by 10% for a *single build* wire (one coat of insulation) and for a *heavy build* wire (2 coats of insulation) by 20%. Since merely very tiny voltages are generated in pickups, one coat of insulation is sufficient.

The maximum applicable length of wire depends – other than on the wire diameter – on the winding space on the coil bobbin and on the fill factor. Winding by hand results in the wire of individual turns crossing the wire of other turns, and more air and less copper is in the coil. Exactly positioning every turn next to the other is achieved via winding by machine; the fill factor is higher. The **pull** has next to no influence: in order to firmly layer the turns, a small braking force is applied. However, since such delicate wire breaks very easily, there is not much margin here. One manufacturer recommends winding AWG-42-wire with approx. 0,33 N pull. The strain in this case is only about 0,1% and the transversal contraction even less. Any resistance increase due to the pull is therefore negligible.

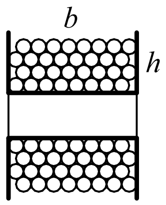
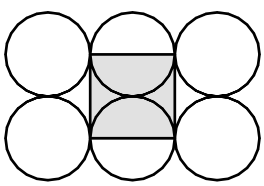


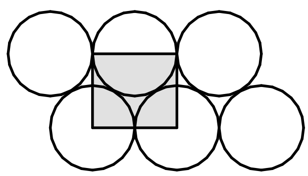
Fig. 5.5.1: Cross-section through a pickup coil. Winding width b and winding height h define the interior dimensions of the bobbin. The wire diameter is shown drastically enlarged.

Fig. 5.5.1 shows the cross-section through a pickup coil. For customary pickups the width b varies between 4 – 12 mm and the height h between 5 – 15 mm; very small coils (e.g. Gretsch) have a height of merely approx. 2.5 mm. Often the available winding area $S = b \times h$ is between 30 und 60 mm^2. For an AWG-42-wire the cross-sectional area including the varnish is approx. 0.004 mm^2. To calculate the largest possible number of turns from these data we need to estimate the proportion of air in the winding. **Fig. 5.5.2** presents two ideal cases: the **fill factor** F is the quotient of circular wire-area to rectangular winding area.

The right-hand section of Fig. 5.2.2 shows the desirable objective: all turns fit tightly into the notch between the wires below and the fill factor is in excess of 90%. A winding of such precision is only achievable with a correspondingly precise feed rate control. Given that the feed is merely 71 µm per turn, only smaller fill factors will be achievable in practice (F = 70 – 85%). The Stratocaster pickup, for example, offers a winding area of approx. 40 mm^2. The application of 7600 turns (a usual value for CBS-Fender in the 1960s) results in 30 mm^2 wire area and approx. 75% fill factor. Given an average length of 14 cm per single winding turn the overall wire length comes to 1064 m which can be calculated to a DC resistance of 5.7 kΩ. This value is quite nicely confirmed with measurements.



$$F = \frac{\pi}{4} = 0.785$$



$$F = \frac{\pi}{2\sqrt{3}} = 0.907$$

Fig. 5.5.2: Fill factor F for ideal wire positioning. The cross-section of the copper itself is – for a wire with a single layer of varnish – approx. 80% of the full wire cross-section area; for a double layer of varnish approx. 70%. Depending on manufacturer, insulation type and manufacturing method other values may result!

5.5.2 Inductivity of the coil winding

As electric current flows through a conductor, a magnetic field surrounding this conductor is generated. Strictly speaking, a magnetic field is also generated within this conductor but this effect is mostly neglected. **Fig. 5.5.3** schematically shows a wire through which a current passes from bottom to top. The technical current direction (from plus to minus) and the direction of the magnetic flux (from north to south) are connected unequivocally: using your right hand and pointing with the thumb in the direction of the current will make the remaining (bent) fingers point in the direction of the magnetic flux.

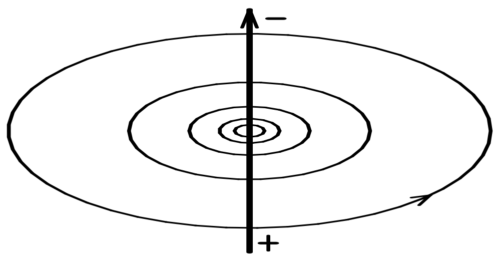


Fig. 5.5.3: Magnetic field around a conductor through which current passes

It has already been mentioned that magnetic flux must not be seen as a concrete means of transport. Flux and flux density are assumed as analogies from fluids. The same approach is found in other areas of physics (e.g. the flow of current). A straight wire of infinite length through which a current *I* flows generates – at a radial distance of *R* – the magnetic **field strength** of *H* and the magnetic **flux density** of *B*:

$$H = \frac{I}{2\pi R} \qquad B = \mu \cdot H \qquad \mu = \mu_r \cdot \mu_0 \qquad \mu_0 = 4\pi \cdot 100\text{nH/m}$$

The quantity μ_r is called **relative permeability** and identifies the magnetic property of the material penetrated by the magnetic field as a multiple of the **permeability of air** μ_0 (strictly speaking μ_0 is valid only for vacuum but the difference to air is negligible).

In **Fig. 5.5.4** we see a rectangular wire frame though which electrical current flows. Again, a magnetic field results which for this representation has an orientation perpendicular to the paper plane. Fields running in the viewing direction are customarily shown as crosses while the opposite direction is given by dots.

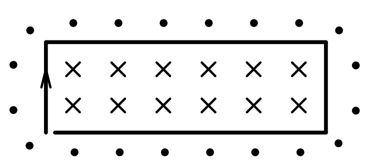


Fig. 5.5.4: Wire frame carrying a current, magnetic field. The field strength decreases with increasing distance.

The magnetic flux density *B* specifies the area-specific magnetic flux. Integrating *B* over the field-penetrated area *S* results in the overall **magnetic flux** Φ:

$$\Phi = \int_S \vec{B} \cdot d\vec{S} \qquad \vec{B} \cdot d\vec{S} = B \cdot dS \cdot \cos\alpha \quad \text{(scalar product)}$$

In air, there is a linear correspondence between the current I and the magnetic flux Φ generated by it. The coefficient characterizing this proportionality is the **inductance** L. Given material and topology, L can be calculated from the build and is (in linear systems) not dependent on the current. For the magnetic guitar pickup, the coil inductance L is the most important electrical parameter. It has a major influence on the sensitivity, the impedance frequency response and the resonance frequency.

If an **alternating current** is flowing through the wire frame shown in Fig. 5.5.4, a time-variant magnetic field results. The **law of induction** tells us that an electric voltage is induced in a current loop (through which a magnetic field is flowing). This voltage corresponds to the variation over time $d\Phi/dt$ of the flux penetrating the coil. For a sine-shaped current and with complex nomenclature the time-differential corresponds to a multiplication with $j\omega$:

$$\underline{U} = d\underline{\Phi}/dt = j\omega \cdot \underline{\Phi} = j\omega \cdot L \cdot \underline{I}, \qquad \text{with:} \quad \underline{\Phi} = L \cdot \underline{I}; \quad j = \sqrt{-1}; \quad \omega = 2\pi f .$$

The quotient of the voltage $\underline{U}$ and the current $\underline{I}$ is called **impedance** $\underline{Z} = j\omega L$ in the framework of complex calculation. $\underline{Z}$ is a system quantity and thus <u>in</u>dependent of the signal (as required in linear systems). The impedance of the wire frame in Fig. 5.5.4 is proportional to the inductance L and proportional to the frequency f.

Shown in **Fig. 5.5.5a** are <u>two</u> square wire frames through which the (same) current is flowing. The magnetic fields generated by these two frames should not superimpose which can be achieved either by a big distance between the frames or via fields with perpendicular orientation. In Fig. 5.5.5b the two frames are laid on top of each other such that the magnetic field penetrates both frames in the same way.

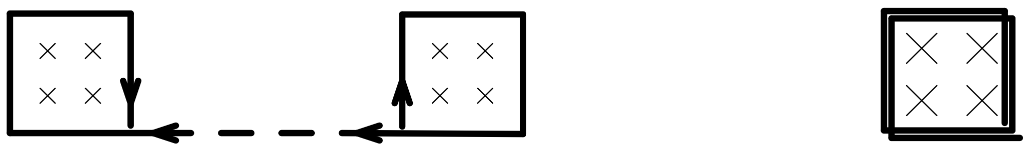


Fig. 5.5.5: two square wire windings connected in series carrying the same current.
a) separate location (left), **b)** on top of each other (right).

Each of the two frames in Fig. 5.5.5a generates the flux $\underline{\Phi}$, and in each frame the voltage $\underline{U}$ is induced; the overall voltage induced in the series connection of the two frames therefore is $2\underline{U}$. Relative to *one* frame of the same size, the inductivity has doubled (assuming the connecting wire to have no inductivity). In Fig. 5.5.5b the superposition of the magnetic flux generated by the two frames results in double the overall flux. The voltage induced in each of the two frames is double that found in the scenario of Fig. 5.5.5a, i.e. the series connection results in the quadruple overall voltage and – correspondingly – the quadruple inductivity. Thus, if a wire is wound with N windings, its inductivity may increase by a factor of N or by a factor of N^2 – depending on how the windings are **coupled**. Of course, wire windings can never share the exact some location – the individual turns will in reality have to have a certain distance and cannot be completely coupled. Still, real coils exhibit $L \sim N^k$ with $k > 2$ because an increase in the number of turns will also require an increase in the area.

The typical shape of the winding of a pickup is oblong (**Fig. 5.5.6**). Its inductivity can be calculated with good approximation [Hertwig]:

$$L = 4 \cdot N^2 \cdot \left[(x+y) \cdot \ln \frac{2xy}{b+h} - x \cdot \ln(x+d) - y \cdot \ln(y+d) + 2d - \frac{(x+y)}{2} + 0{,}447 \cdot (b+h) \right] \cdot 1\,\mathrm{nH}$$

Here N is the number of turns and $d = \sqrt{x^2 + y^2}$ the diagonal. The dimensions need to be entered in cm. For a Stratocaster pickup (N = 7600, without magnets) the result is L = 1,7 H. With magnets, the inductivity rises by approx. 30% to 2,2 H.

The above formula makes it also possible to calculate the effects of changes in the number of turns. Since x, y, and h also changes, a power function with an exponent larger than 2 results: $L \sim N^{2,14}$. Increasing e.g. N by 10% pushes the inductivity by 23%. Since the resonance frequency is dependent $\sqrt{1/L}$, the resonance frequency decreases by 10% in this example (keeping the capacitance constant).

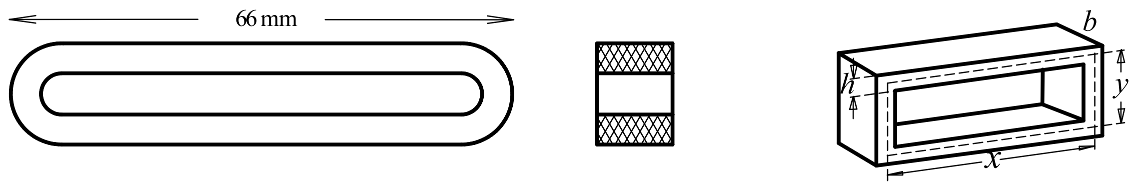


Fig. 5.5.6: Shape of a Stratocaster coil and cross section. Idealized rectangular coil.

The inductivity is dependent on number of turns of the winding and the geometry of the coil, but also on the magnetic conductivity of the space penetrated by the magnetic field. Most materials differ from air only marginally in magnetic terms; their magnetic conductivity, the permeability $\mu = \mu_r \cdot \mu_0$, is $\mu = \mu_0$ with very good accuracy, since the relative permeability of these (diamagnetic or paramagnetic substances) is almost exactly one. Ferromagnetic materials, on the other hand, react rather differently: their relative permeability is considerably larger than one and moreover not constant but dependent on the field strength. Alnico-pickups and polepieces, and also screws and shielding plates made out of ferromagnetic material (e.g. iron or nickel) are ferromagnetic. By means of their better magnetic conductivity (relative to air), such ferromagnetic materials decrease the magnetic resistance and thus increase the inductivity. A particularly strong increase in inductivity is possible if the complete magnetic field flows through the ferromagnetic material – this is, however, as a matter of principle not possible in guitar pickups (5.4). Due to the fact that the field running through air forms the largest part of the magnetic resistance, the magnets in the Stratocaster pickup can increase the inductivity by only 30%, for example.

The non-linear permeability μ of a ferromagnetic material bends the magnetic flux into such complex curves that an analytic description is not viable anymore. On top of this, **eddy-current-** and **skin-effects** aggravate any calculations even further since they contribute an additional inductive share which is dependent on frequency in a rather complicated manner. For pickups without cover which contain on top of the coil only alnico magnets (e.g. Stratocaster), stating *one single* inductivity is an acceptable compromise; here the losses in the magnets are rather small.

However, as soon as a pickup comprises polepieces and/or mounting panels, the **equivalent circuit diagram** contains either a single albeit frequency dependent inductance difficult to interpret, or several inductances. Characterizing such a pickup with a *single* inductance is a drastic simplification. For this reason, **inductance-measuring meters** are to be used only with great caution for magnetic pickups (chapter 5.6). Such instrumentation determines e.g. the inductive part of the complex impedance at one special frequency (e.g. at 1 kHz) and implying a series equivalent circuit: $\underline{Z} = R + j\omega L$. Since, however, polepieces subjected to the skin-effect do not result in an imaginary part with an ω-proportionality, this measurement approach is not suitable. More appropriate is to record a complete impedance-frequency-response $\underline{Z}(\omega)$ from which the components of a better suited equivalent circuit can be calculated using methods of network synthesis (chapter 5.9).

5.5.3 Coil capacitance

The capacitance is defined as the proportionality between electric charge and electric voltage. A small capacitance exists between two turns each of a coil; this capacitance is dependent on the length, the distance and the dielectric constant ε. In vacuum (or air) we find $\varepsilon = 8.9$ pF/m, insulators (such as the varnish and the bobbin) have 2 to 5 times that value. The overall capacitance of a pickup can only be calculated as an approximation, because there are capacitances between all turns of the coil. Given the height h, the width b (Fig. 5,5,1) and the average length ξ of one turn, the result for the coil capacitance C_w is:

$$C_w \approx 2\frac{b}{h}\cdot\frac{\xi}{\text{cm}}\cdot\text{pF}$$

Coil capacitance using regular varnished wire [17]

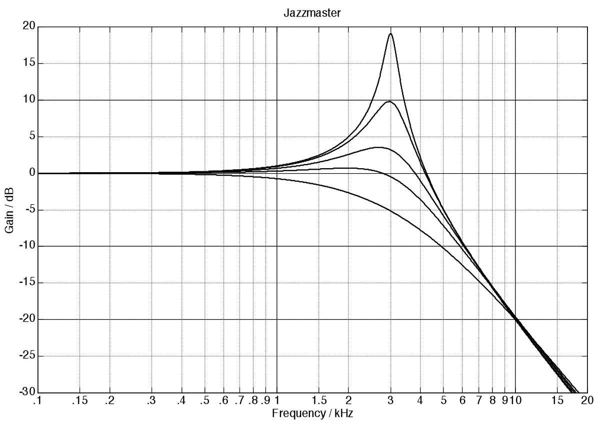
Customary pickup coils have capacities in the range of 10 ... 150 pF. The capacitance of wide, shallow coils (which seem to have a large surface area when observed from above i.e. from the direction of the string) is smaller than the capacitance of compact coils with approximately square cross-section of the winding. For example, Jazzmaster- or P90-pickups have a smaller capacitance than Stratocaster pickups. For machine-wound pickup coils the individual turns are closer together which results in a slightly higher capacitance compared to hand-wound pickups. Increasing the thickness of the varnish layer has the opposite effect: the individual windings have a larger distance, and the capacitance decreases.

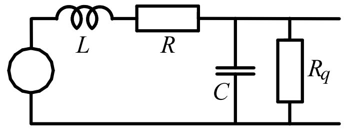
Installing the pickup in the guitar leads to an increase of the capacitance. The main reason is the **pickup connecting cable** the capacitance of which can vary between a few picofarad (unshielded two-wire cable) and several hundred picofarad (old Gibson cables). The second reason for the increased capacitance is the presence of **stray capacitances** towards metal parts which are close-by, in particular towards shielding sheets.

Working in conjunction with the coil inductance, the capacitance is the basis for the **pickup resonance** (at 2 – 5 kHz). However, much more important than the coil capacitance is the **cable capacitance** (chapter 9) which has the main contribution to the overall capacitance. Several components are involved in the **resonance damping**; of there the loss resistance connected to the coil capacitance (chapter 5.5.4) has the smallest effect.

5.5.4 Resonance quality factor *Q*

The interaction between inductivity of the pickup (approx. 2 – 10 H) and the capacitance of the cable (approx. 300 – 600 pF) forms a resonator with a resonance frequency in the range of 2 – 5 kHz. The **quality factor** *Q* is a measure for the resonance dampening. A strong dampening results in a low quality factor, weak dampening makes for a high quality factor. A small *Q*-factor must not be equated with 'bad'. A high *Q*-factor implies that the pickup frequency response has a strong resonance emphasis at the resonance frequency. Its effect can be equated to that of an equalizer boosting a certain frequency band (presence filter). Give that the equivalent circuit of the pickup includes only *one single* coil, *one single* capacitor plus resistors, the resonance quality factor can be stated unambiguously. If, however, skin effects and eddy current losses require a more complex equivalent circuit, it is necessary to define several poles with several *Q*-factors. A *single* value for the *Q*-factor can only be specified as an approximation.





$$H = \frac{1}{1 + \frac{p(RC + L/R_q)}{1 + R/R_q} + \frac{p^2 LC}{1 + R/R_q}}$$

$$Q = \frac{\sqrt{LC(1 + R/R_q)}}{RC + L/R_q}$$

Fig. 5.5.7: Varying resonance emphasis for a Jazzmaster pickup. Different parallel resistors result in different resonance dampening, or different resonance quality factors *Q*.

Fig. 5.5.7 shows the low-pass transmission of a **Jazzmaster** pickup. Setting the denominator-polynomial to zero results in two poles of the transfer function (2nd-order low-pass). Different resonance dampening can be achieved by varying the parallel resistance R_q. The *Q*-factors associated with the 5 graphs in the figure are: 9,0 ; 2,5 ; 1,4 ; 0,9 ; 0,5. The highest *Q*-factor (Q = 9) belongs to the lowest dampening with an emphasis of 19,1 dB. This behavior can be achieved by loading the pickup exclusively with a 600-pF-capacitor. The results would be, however, not very usable since it produces a shrill, whistling guitar sound. In normal use the pickup is not just working in conjunction with a purely capacitive load but also with parallel resistors constituted by the volume- and tone-controls plus the input impedance of the amplifier. With these components, we arrive at a $Q \approx 3$. The **resonance emphasis** seen in Fig. 5.5.7 can approximately be estimated via 20 lg(Q) in dB. For low *Q*-factors, this approximation becomes increasingly inaccurate, though.

The resonance *Q*-factor is the second-most important transmission parameter right after the resonance frequency. The above calculation shows, however, that the *Q* is dependent on the connected circuitry. Already a change in length of the guitar cable results in a change of the *Q*-factor (see also Fig. 9.14). Consequently, specifying a *Q*-factor value is problematic: the *Q*-factor of the disconnected pickup does not allow for any conclusions regarding the *Q*-factor of the installed pickup. Even the *Q*-factor of the pickup combined with the other components in the guitar is not very meaningful. Only after additionally specifying cable and amplifier, a value for the *Q*-factor can purposefully be interpreted.

Even more problematic is specifying the Q-factor for pickups which contain further metal parts on top of magnet and coil. From a systems-theory point-of-view they represent systems with an order of higher than 2. Stating a single Q-factor value is insufficient. The specification of a resonance emphasis in dB is ambiguous, as well, since despite equal emphasis different band-widths are possible. **Fig. 5.5.8** compares a measured and a calculated transmission curve. For both cases, *low-pass* behavior (not band-pass) was taken as a basis, and *one single* coil of a Gibson Humbucker was measured. The slugs (polepieces) make for pronounced eddy-current losses with skin-effects contributing, and thus a system of higher order results. The 2nd-order transfer function shown in comparison has in principle a similar shape but clearly differs.

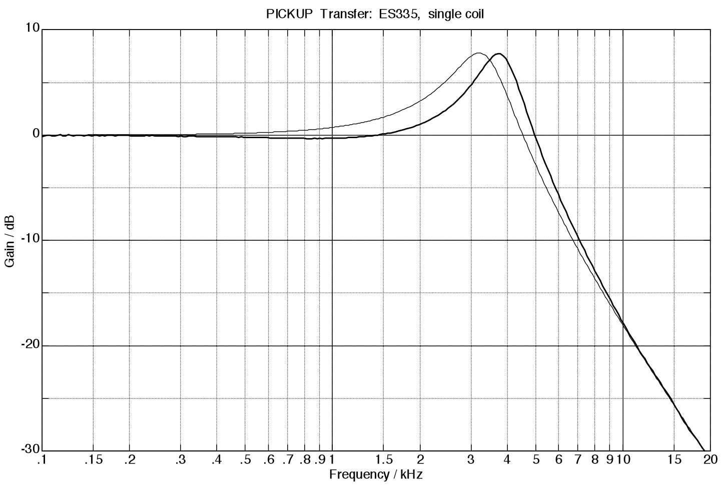


Fig. 5.5.8: comparison of a measured transmission curve (bold) with a calculated curve (fine). Despite the same emphasis height and equal asymptotes, the shapes are different.

In closure it needs to be noted that – in contrast to the resonance quality factor Q – the quality factor Q_L of the coil itself has even less significance. In the RL-series equivalent circuit of a coil the Q-factor of the coil is defined by $Q_L = 2\pi f L/R$. It is dependent on the frequency and therefore subject to an arbitrary frequency definition. For example, DUCHOSSOIR defines the coil-Q-factor at 1 kHz and lists Q-factors of 2,1 to 3,5 for the Stratocaster pickup. **Fig. 5.5.9** shows how small the effect of the coil-Q-factor is on the transmission behavior. Increasing the coil resistance R by 50% decreases Q_L by 33% but changes the resonance emphasis only very little.

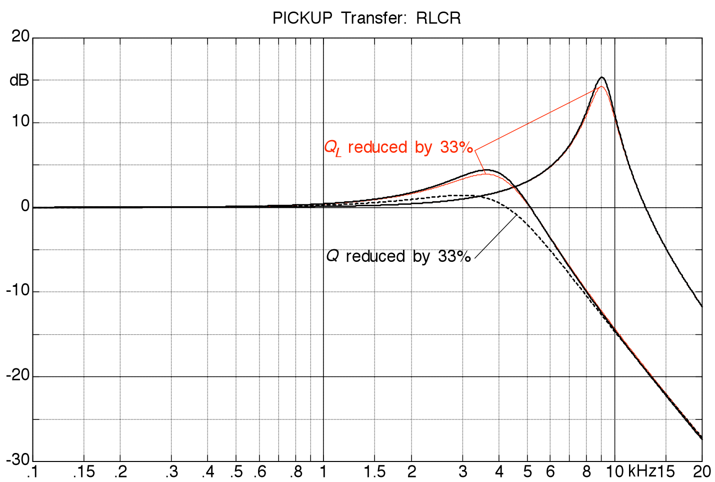


Fig. 5.5.9: transfer Function. Disconnected Stratocaster pickup (resonance at 9 kHz), and with 111 kΩ load plus 600 pF cable capacitance. The thin lines show the transmission behavior with a coil resistance increased by 50% i.e. a coil-Q-factor reduced by 33%. For comparison, a 33% reduction of the Q-factor is shown by the dashed line.

5.5.5 Polarity

The polarity of the voltage generated by the guitar depends – on top of the string vibration – also on the polarity of the magnet, the direction of the coil winding and the wiring. Old Fender pickups sported a yellow (or white) and a black (or blue) wire; the yellow wire fed the switch while the black went to ground. Very early Fender pickups had the north-pole of the magnets pointing towards the strings but as a rule (from which there are exceptions) the south-pole points "up". Stratocaster pickups are wound clock-wise, Telecaster pickups counter-clock-wise. For the Jazzmaster pickup, the south-poles point "up" for the neck-pickup and "down" of the bridge-pickup. Both are wound in opposite directions so that their signals are added when they are both "on" but the hum-voltages cancel each other out – an advantage which 1970s-Stratocaster pickups also profited from (the middle pickup was reversed in coil winding and magnet orientation). From all this it can either be derived that pickup polarity does not matter much for the sound, or that here lies a secret of the "vintage sound".

For a long time after the publications by G. S. Ohm (1843) and H. v. **Helmholtz** (1863), the hearing system was seen as phase-insensitive: accordingly only the level of the partials define the sound but not their phases. Initially there were contradicting experimental results regarding this assumption until around the middle of the 20th century comprehensive psycho-acoustical experiments could prove without doubt the phase-sensitivity in hearing. However, not all phase changes are audible – which complicates matters. All following considerations refer to **diotic** presentation (i.e. both ears receive the same signal) although, in fact, listening to music involves **dichotic** conditions (i.e. there are different signals at the two ears). However, switching the phase of a pickup results in a diotic signal *change* (i.e. the *differences* at both ears are the same).

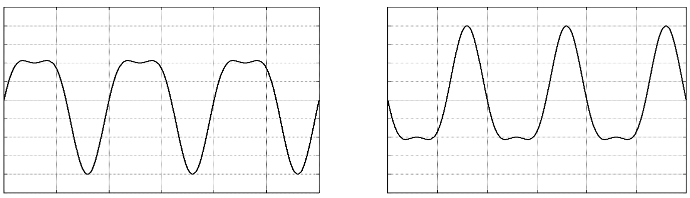


Fig. 5.5.10: time function, compound from 1st and 2nd harmonic; can be projected onto each other via reversing the polarity.

Fig. 5.5.10 depicts two pure ac-time-functions differing only in polarity. With e.g. a fundamental frequency of 200 Hz and a presentation loudness which is not too low, switching between the two signals results in perceiving a small **sound difference**♣. This indicates that the ear can distinguish the absolute phase – in other words, an inward push of the tympanic membrane gives a perception different from the one caused by an outward pull. Physiological experiments measuring the potential in inner-ear-receptors (hair-cells) support this insight: the hair-cells preferably react to an excitation of **one** polarity (bending of the stereocilia in the direction towards the modiolus). This property of the hearing system alone would be reason enough to consider the pickup polarity; still more important, however, is the fact that guitar amplifiers almost always include non-linearities the effect of which is polarity-dependent. Even in the so-called "clean mode" at least the attack of the sound is slightly overdriven, and via "crunch" towards "lead" the **harmonic distortion** increases to an extreme degree – which is not a deficiency but desired tone-shaping. Reversing the input signal would only result in a pure reversal of the output signal in the case that the characteristic curve of the transmission were symmetric re. the origin (odd-numbered distortion products). For even-order distortion, the shape of the signal changes with polarity reversal and so does the level-spectrum of the output (Fig. 5.5.11).

♣ However, at higher frequencies no sound differences can be perceived when switching.

The left section of **Fig. 5.5.11** shows a non-linear characteristic as it can be found e.g. in a tube pre-amplifier. Using one of the signals from Fig. 5.5.10 as input on the abscissa, the ordinate (output) yields the time functions given in the middle and right-hand sections of Fig. 5.5.11. Even without formal and quantitative description one can directly see the polarity-dependent unbalances resulting from the non-linearity. Depending on the polarity of the input signal two different output signals are created. Only for special half-wave symmetries are the sound differences due to the polarity-reversal limited to the signal attack phase (and therefore remain insignificant); in the general case the phase reversal of a pickup can – depending on the circumstances – lead to audible sound differences.

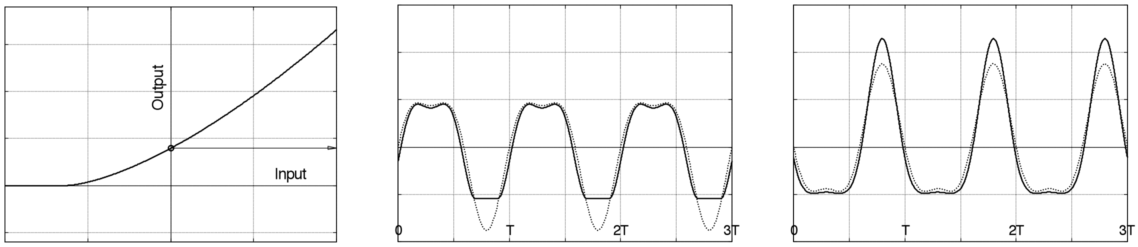


Abb. 5.5.11: nonlinear transmission curve (left), time functions of the signals from Fig. 5.5.10 (-----), after having passed though the nonlinear transmission curve (——). All signals without DC-component.

Next, we will have to look at the question whether – and if so to which degree – the voltage half-waves of magnetic pickups differ. For this, the neck pickup voltage of a Stratocaster (USA) was investigated. Above the magnet pole of the neck pickup, the E_4-string was depressed with a pick and let go abruptly (force step, chapter 1 and 2). The result is a rectangular velocity curve (**Fig. 5.5.12**) to which a triangular displacement corresponds. Due to the non-linear characteristic of the magnet (chapter 5.8), the tip of the flux-density-curve is bent (the tip of the triangle belonging to the linear model is shown as a thin line in Fig. 5.5.12). A differentiation of the flux-density function results in the induced voltage: this is rectangular in the case of a linear magnetic characteristic, and pointed for the non-linear model. The measured voltages show a clear similarity with the slight oscillations being results of the dispersion which is not modeled here (chapter 1.3.2).

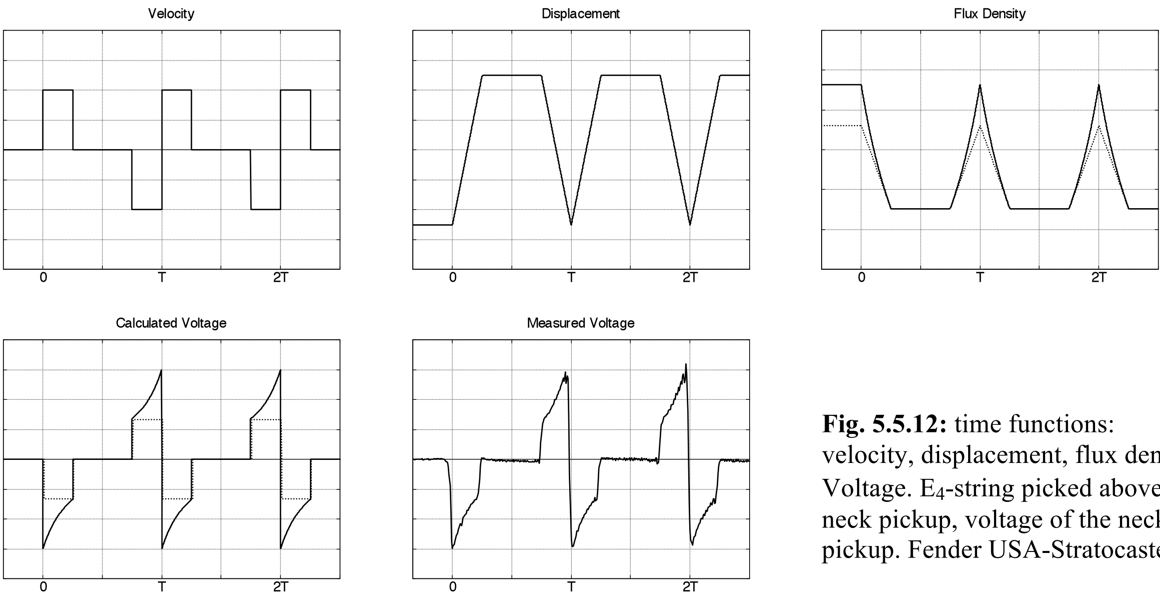


Fig. 5.5.12: time functions: velocity, displacement, flux density, Voltage. E_4-string picked above the neck pickup, voltage of the neck pickup. Fender USA-Stratocaster.

In order to strongly dampen the resonance formed by coil and cable, the Stratocaster pickup was loaded with a 1-kΩ-resistor for these measurements. In the relevant frequency range, coil resistance, coil inductance and the 1-kΩ-resistor act as a first-order low-pass the real pole of which was mathematically compensated by a zero. Additionally, a real pole at f_x = 9000 Hz was included so that the induced voltage was in total filtered by a first-order **low-pass** with a cutoff frequency of 9 kHz.

Both calculation and measurement show that with a dispersion-free model of the string pickup voltage is created which remains symmetric to the time-axis – even if a non-linear characteristic of the magnet is used as the basis. Dispersion-effects play no role for the thin guitar strings, and consequently calculation and measurement are in good agreement. However, on the E_2-string the frequency-dependence of the wave-propagation velocity (**dispersion**) leads to deformations of the time function already after one single period (**Fig. 5.5.13**); the half-cycles loose their symmetry and thus the possibility arises that the sound changes when the polarity of a pickup is reversed. Still, changes in the time-function do not always lead to audible sound changes. The hearing system in not an oscilloscope; rather, the sound-signal is split up into frequency bands (**critical bands**), and only the output of these analyzing band-filters are subject to the time-dependency analysis. Phase shifts occurring between signals falling into different critical bands may not cause any changes in he perceived sound. Phase shifts within a critical band may on the pother hand very well lead to audible roughness- and/or pitch-changes [Fleischer 1978].

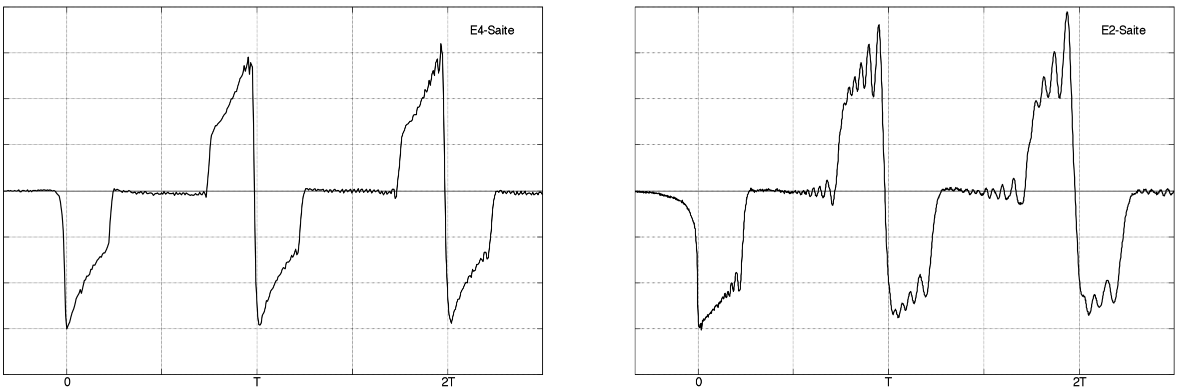
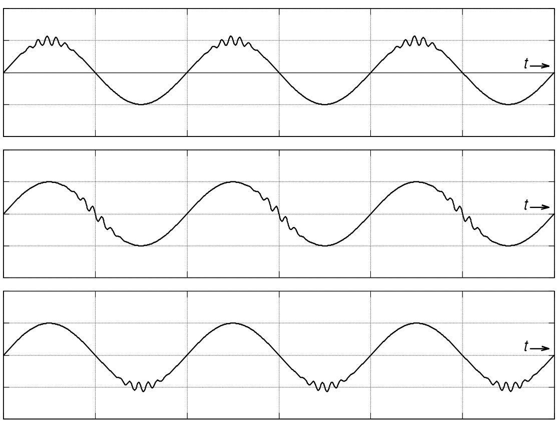


Fig. 5.5.13: measured pickup voltage (Stratocaster), normalized. For the E_2-string the dispersion-caused oscillations are particularly striking (compare to chapter 1.4). The E_4-string is, however, not entirely dispersion-free, either: after about 7 periods clear dispersion-caused unbalances are visible (not shown in the figure),



The superposition of a low- and a high-frequency oscillation shown in Fig. 5.5.13 is reminiscent of the measurements regarding masked-period-patterns carried out by Zwicker [12]. Whether the tone-burst is audible depends on its position within the phase of the lower-frequency tone. (**Abb. 5.5.14**). Despite equal magnitude spectra, the three signals shown in this figure sound differently – the masking effect of the lower-frequency component is phase-dependent.

Fig. 5.5.14: test signal for masking-period-pattern experiments [12].

Before we apply the masked-period-patters to guitar signals, we need to rather consider that the time functions shown in Fig. 5.5.12 and 5.13 are derivatives of the string velocity; i.e. the signal will never reach the tympanic membrane in this shape. First, already the pickup resonance effects changes on the signal, then guitar amplifier and loudspeaker add their own considerable part, plus last the sound wave has to travel through the listening room until it finally reaches the ear of the listener or the player. In **Fig. 5.5.15** the pickup voltages as they show up for a Stratocaster loaded with 513pF // 1MΩ. Along the time axis non-symmetries can appear which appear significant o the eye – however the eye does not judge the sound. In fact, the hearing system struggles despite the obvious non-symmetries to recognize any sound differences. Even more explicitly this is shown by **Fig. 5.5.16**: both these impulses sound the same!

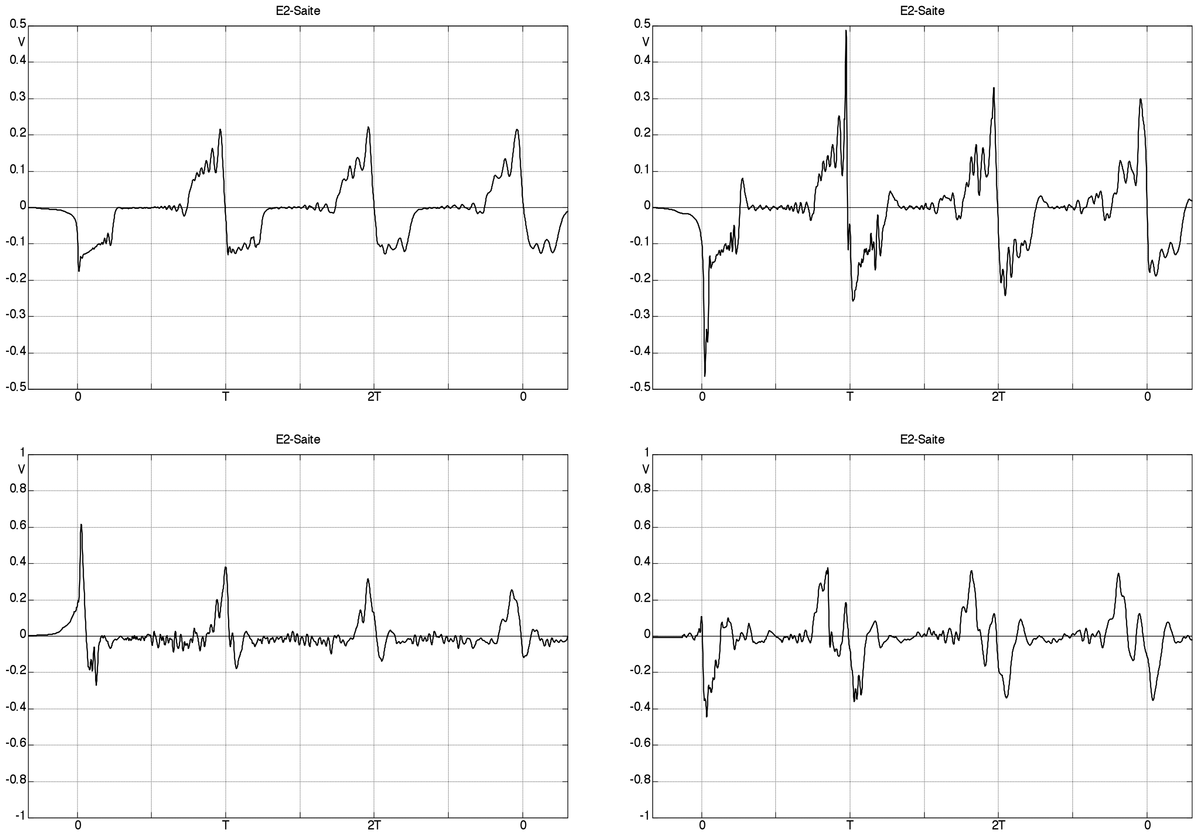


Abb. 5.5.15: pickup voltages, USA-Stratocaster, neck pickup. E_2-string pressed down above the neck pickup with a pick and then released (top left and right); virtuoso-like" picked (bottom left and right). Left and right show two different attempts.

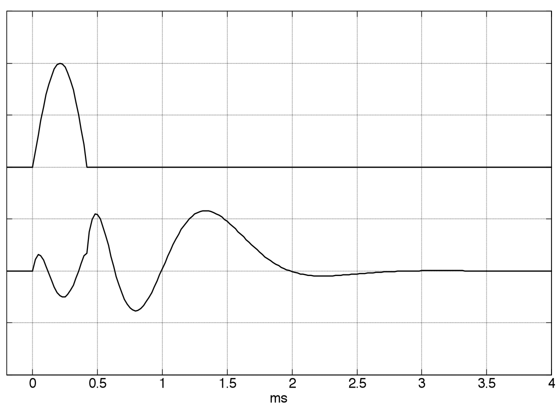


Fig. 5.5.16: two impulses which can be projected upon each other via all-pass filtering. Since the group-delay distortions remain below the threshold of 2 ms (as it is relevant to the ear), this filtering is not audible.

As shown in Fig. 5.5.11, the nonlinearities occurring in amplifiers cause a polarity-dependent limiting of the guitar signal, but the main differences most often happen with the short impulse peaks – the limiting of which changes little in the overall sound. The signal is subject to significant alterations only as it is radiated off the loudspeaker: in **Fig. 5.5.17** the voltages generated by two **microphones positioned within a listening room** with a distance of 50 cm. Despite major divergences in the time function, these differences are perceived merely as a general change in the treble content without any special significance.

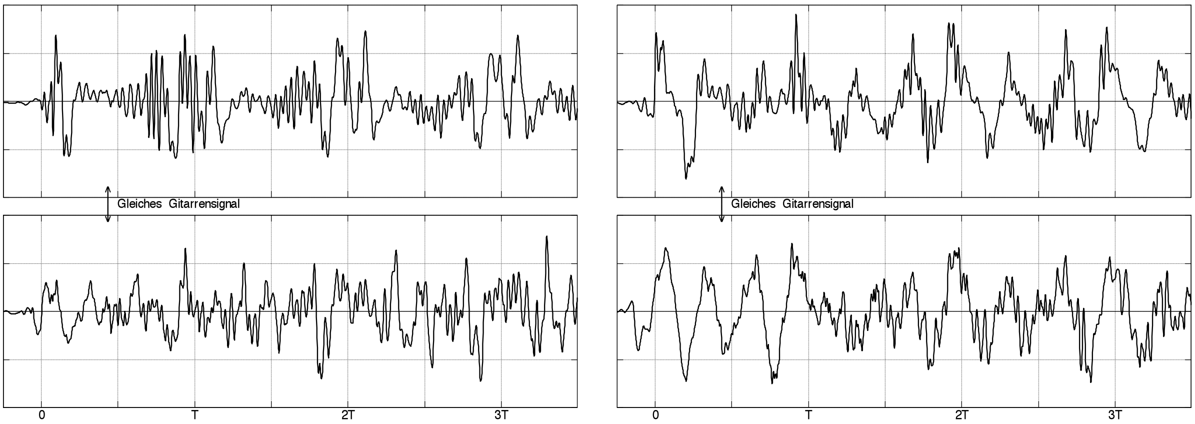


Fig. 5.5.17: microphone voltages at 0,5m in front of the amplifier (top) and inclined at 1 m in front of the amplifier. Fender-Stratocaster, Fender-Deluxe-Amp. Two different attempts shown left and right, respectively.

We note as **intermediate result**: reversing the polarity of a pickup leads to clearly *visible* differences in the voltage-time function. Our hearing, however, does not observe these differences at all, or just marginally. In no way are differences due to polarity-reversal obtainable in the sense of *clearly better* or *clearly worse*. Consequently, no recommendation is possible regarding which polarity would be preferable. Still, two special operating states merit additional consideration: the combination of several pickups and the feedback via the air.

As the guitar is played loudly using amplifier and loudspeaker, an air-wave emitted by the loudspeaker strikes the guitar body and excites vibrations in it and also in the strings. These vibrations are fed back to the amplifier and thus we obtain a **feedback circuit**. With a sufficiently high gain within the feedback circuit the guitar starts to play "by itself" [literature: control engineering]. The pitch of this self-oscillation depends on a number of factors including the polarity of the closed-loop-gain: reversing the pickup polarity leads to a change in the sound. However, the same happens as one changes the position of the guitar by e.g. 10 cm (i.e. the phase in the feedback loop changes); as such the pickup polarity is irrelevant even when considering feedback.

The fact that the sound changes drastically as the polarity of one pickup in a **combination** of pickups is reversed requires not a lot of explanation. More interesting is the question whether there are audible differences if both direction of the turns in a coil and the polarity of the magnet are reversed (e.g. for the middle pickup of a Stratocaster) to achieve hum-suppression in the combination of pickups (RW/RP middle pickup). Indeed, we could expect an effect if the two pickups were magnetically coupled to a significant extent. Measurements, however, show merely a 0,6%-coupling-factor which is much too little to give audible effects. The measured level differences are, with 0,05 dB, far below threshold. Incidentally, for the forces of magnetic attraction the rule applies that they are not polarity dependent!

5.5.6 Time variance

In systems theory, resistors, inductances and capacities are initially taken to be linear and time-invariant such that at every point in time the same laws of proportionality hold for the quantities of voltage and current. For small drive values, every guitar pickup is indeed sufficiently linear whereas time-invariance cannot be fundamentally taken for granted. The pickup parameters introduced on the previous pages do change over time (intra-individual scatter), and for another specimen of the same type, any specific values only hold with reservations (inter-individual scatter).

The **DC-resistance** of each pickup is temperature-dependent, it rises by 0,39 % per °C. Within the temperature interval of 17° – 30° the DC-resistance therefore changes by 5% (e.g. from 6000 Ω to 6300 Ω). This needs to be considered for the values given in literature which are sometimes surprisingly precise as seen e.g. in a specification for the Stratocaster: 6100 Ω (Vintage reissue), 6210 Ω (Texas special). Due to manufacturing tolerances, the wire diameter will have a scatter of typically ±10%, which renders the comparison of two pickups problematic: do we have the same type but with slightly differing wire strength, or is it the other type with a different number of turns?

The **coil inductance** is given – other than by the coil geometry – by the space filled by the field. As ferromagnetic and/or conductive materials are introduced into this space, the inductance may change. Not just pickup covers but also other guitar parts can change the coil inductance. These include the metal mounting plate of the Telecaster bridge pickup just as shielding foils under the pickguard which enclose the pickups and enable eddy currents to flow. We should not expect dramatic deviations but for precision-measurements, the environment should be clearly defined. For the time-variance of magnet-parameters see chapter 4.5.

For the **coil capacitance** as well, the space filled by the field should be considered. If a hygroscopic material able to absorb water is used for the insulation of the coil wire the capacitance will depend on the give water-content. In case of potted coil-winding an increase of the capacitance will happen because all potting material have a dielectric number larger than 1. However, since the major share of the overall capacitance is given not by the pickup but by the cable capacitance, the effects of changes in the pickup-capacitance are – as a general rule – only of secondary importance.

An environmental influence which is often overlooked results from the **acoustical surroundings**. As soon as the pickup signals are amplified and radiated by a loudspeaker, the pickup becomes part of a **feedback loop**. While this does not change the parameters mentioned above, we need to enhance equivalent circuit of the pickup by controlled sources. A complete description requires a (as far as possible) complete description of the transmission coefficients of air-borne and structure-borne sound, the coefficients themselves being dependent on time-variant mechanical dampening factors. It is, for example, conceivable that rubber bearings stiffen over the course of decades and influence the sensitivity to structure-borne sound. Depending on personal preferences, such an effect can be either classed as insignificant and ignored, or be defined as belonging to the guitar body, or be seen as effect of the pickup aging.

5.5.7 Insulating varnish, wax

The pickup coil is wound from very thin copper wire onto which a film of varnish is deposited in order to protect from short-circuit and aggressive substances in the air. The substances most often used as insulating varnish are "Plain Enamel", "Formvar", "Polysol" and "Polyurethane-Nylon". The resulting insulated wire is often called magnet-wire – it is of course non-magnetic (or, more exactly, paramagnetic) and has the same magnetic resistance as air has.

The noun **enamel** also stands for glaze, lacquers in general or special lacquers (e.g. synthetic resin varnish). The verb *to enamel* also means *to varnish*. "Enamelled copper wire" therefore is **varnished copper wire**, and as such every magnet wire used in pickups merits the designation *enamelled copper wire*. The situation is, however, not that simple since enamel is often used in a more specialized sense:

The name **plain enamel** designates one of the first industrially produced insulating varnishes. It is an oil varnish manufactured with oil which oxidizes while drying and generates an irreversible film. In order to increase hardness and gloss, resins are added. The also used designations *oleoresinous email* and *oleoresinous insulation* are derived from this oil/resin mixture. The *plain enamelled wire* used in old (i.e. "vintage") pickups has a brown or voilet color.

Formvar (sometimes incorrectly spelled "Formivar") was a trademark of the *Monsanto Chemical Company* (St. Louis, Missouri, USA). It was renamed from Formvar to Vinylec after the sale of a business unit to *Structure Probe, Inc*. Formvar varnishes contain polyvinyl-acetal = polyvinylformal. In a two-step process first polyvinylalcohol is manufatured from polyvinylacetate; the polyvinylalcohol is then acetalyzed. To produce magnet-wire, the phenolic resin polyvinylformal (also called *modified polyvinyl acetal resins*) is added. Formvar magnet wire is of a glossy-gold color and cannot be soldered.

Polysol varnish is a polyurethan lacquer which can be soldered and is mixed as a two-component varnish. It usually is of a glossy bright-red. Or it could be brown-violet if a "vintage" vibe is asked for ☺.

Polyurethan-nylon is a polyurethan insulation with a nylon coating.

It should not be assumed that the designations for varnish as given above seek to be a 100%-correct material designation. While e.g. the chemical formula *NaCl* unambiguously designates common salt, a term such as *oil varnish* merely indicates a group of substances which are similar but individually chemically and physically different lacquers.

No big demands are placed on the **insulation properties** of the copper-varnish-wire used in pickups since the voltages to be handled are very small. Even considering a peak voltage of 5 V (which is quite a high value) and a varnish thickness of 2x2,5 μm = 5 μm we obtain a "worst-case"-field-strength of about 1 kV/mm – which is rather undemanding for an insulator. Formvar, for example, is specified to handle up to 80 kV/mm – but such high field strengths cannot be reached in a pickup.

The **magnetic** properties of the insulators mentioned above are highly similar; they all show a permeability of very close to 1 and can be seen as non-magnetic as a good approximation. Regarding the **dielectric numbers**, however, differences can be measured. The ε_r of such insulators is typically between 2 and 5 – exact numbers are not published by the manufacturers. Variations in the dielectric number correspondingly change the capacitance of the coil. Considering a change in capacitance from 50 pF to 100 pF (which is very much on the high side) would lead – in conjunction with a 450-pF-cable – to a 10% capacitance change corresponding to a 5%-change in the resonance frequency. The same resonance shift would occur with changing the cable length by 11% i.e. increasing it from 3,75 m to 4,15 m. It cannot be excluded that such small changes are noticeable in a true A/B-comparison. The internet is full of speculations regarding the contribution of the varnish insulation to the sound of a pickup, or regarding the sound differences due to different lacquers. Since however rarely any guitarist will consider (in order to obtain a different sound!!) whether he/she should today use the 3,75-m-cable rather than the 4.15-m-cable, it seems rather excessive to attribute a big significance to the type of varnish. Anybody in doubt is cordially invited to listen to the difference caused by a 50-pF-capacitor connected in parallel to the guitar output ... and if indeed it does sound much better with the capacitor: grab the soldering iron and install it!!

Apart from the potential dielectric differences, there are occasional reports that a specific varnish was applied more thickly than another, this leading to a different coil geometry. Of course the coil inductance and coil capacitance depend on the geometry – however the **thickness of the varnish** is not generally typical for a type of varnish. It must not be assumed that all manufacturers produce a 42AWG-wire with the exact same thickness of the varnish – even if the insulating material would be the same. The dimensions of copper and varnish are subject to manufacturing tolerances; it also should be considered that many manufacturers offer a special wire (e.g. 42AWG, Formvar) deliberately with different varnish thicknesses. For high-voltage installations a thicker (multiple) insulation layer is desirable while for pickups a single varnish process is sufficient. Even though some manufacturers use wire with multiple varnishing for pickups.

So: what changes if, instead of wire with a single coat of varnish, one with a double coat is used? That depends on which parameter is kept constant. With an equal number of turns the coils grows larger. Conversely, filling up a given bobbin with wire of a thicker insulation will lead to a smaller number of turns. As an approximation we can assume that a double-insulated wire will require 20% more cross-sectional surface than the single-insulated wire.

- For a constant coil cross-section (i.e. wind until the bobbin is full) we obtain a 17% smaller number of turns – connected to a reduced inductance, diminished sensitivity and smaller DC-resistance.
- Keeping the number of turns constant (i.e. wind unto the counter shuts down the process) enlarges the surface of the winding. However, this does not necessarily lead to an increased sensitivity because the turns are located also in the range of smaller flux density. Sensitivity and inductance cannot be calculated in any simple manner; for the DC-resistance we get an increase of about 2%. This increase is so relatively small despite the 20% surface area change because the coil is oblong, not circular.

The pickup parameters depend only little on the thickness of the varnish if the number of turns is kept constant; larger effects will be connected to keeping constant the cross-section of the winding.

Besides the varnish, there is another dielectric between the turns of the coil in many pickups: they are **immersed** (*potted, dipped*) **in wax** in order to give more stability to the coil. In the middle of the 1960s a mishap occurred in the guitar production at Fender [Duchossoir]: the newly introduced polysol-insulation dissolved in the wax bath and the pickups suffered from short circuits. From that point in time production continued without wax-potting (apparently the differences were not that serious), and not until the 1980s did Fender (now post-CBS) return to the old recipes. Wax can solidify the coil windings and reduce pickup self-oscillations (microphonics) on the one hand but also increase the coil capacitance on the other hand. However, compared to the all-dominating cable capacitance only marginal changes in capacitance are to be expected. For **microphonics** see chapter 5.14.

The **losses** within the insulation between the windings of the coil do not play any role at all: the loss resistance in parallel to the coil capacitance is larger than 10 MΩ and thus negligible. However, depending on the material it may be necessary to consider **hydroscopicity**: the insulators may be able to absorb water which can – due to its high dielectricity – cause a noticeable capacitance increase (see table)

Material	ε_r at 1kHz	$\tan\delta$ in ‰
Casting resin	4 – 8	20 – 80
Cellulose acetate	3,5 – 6	12 – 25
Cellulose ethyl	2,5 – 3,5	5 – 25
Vulcanized fiber	4	80
Polyurethane	3,0 – 5,5	5 – 50
Paraffin	1,9 – 2,3	< 5
Shellac	3 – 4	10
Bakelite	4,8 – 5,3	10
Pertinax	4,8 – 5,4	25
Water	approx. 80	

Table: dielectric properties of insulating materials. The numbers should be taken as guide values, the material compositions vary depending on the manufacturer.

As a **bottom line** it should be noted that potting a pickup in wax on one hand, and the material and the thickness of the varnish on the other hand, can lead to small, measurable differences in capacitance. The significance of these differences is, however, subordinate in practice. Microphonics can be efficiently fought by potting.

5.5.8 Bobbin, coil former

In old Fender pickups the 6 cylindrical magnets were pushed through 2 planar coil formers made of vulcanized fiber (hydrate cellulose): these coil formers kept both the magnets in position, and the would wire on the magnets. An urgent warning needs to be heeded: the axial position of the magnets in these pickups must not be manipulated by "light hammer-blows". Doing this will in many cases rupture the fine winding wire which necessitates replacing the pickup (or rewinding it). It is inconceivable why some authors recommend this kind of "adjustment" – possibly they are sponsored by the pickup manufacturing industry ..... Much better mechanical protection is afforded by pickups with complete plastic die-cast bobbins.

Regarding any influence of the bobbins or coil formers on the sound, what was said for insulators holds again: the materials used may have varying ε and thus potentially could have an effect on the coil capacitance and the resonance emphasis. Compared to the cable capacitance and the dampening afforded by the potentiometers, such differences are however to be taken as *highly* secondary.

5.5.9 DC-resistance vs. loudness

In chapter 5.5.1 it was already noted that the dc resistance of a pickup has little bearing on its loudness. While it is of course true for an individual pickup that unwinding a few thousand turns will reduce both the resistance and the loudness, it must not be concluded that a 7-kΩ-pickup is generally louder than a 5-kΩ-pickup. Unfortunately, this is however exactly what is suggested in many tests which e.g. read: *"the guitar is equipped with two different pickups. While the alnico-2-magnet at the neck makes for singing highs, its colleague at the bridge with the ceramic magnet yields a brutal punch. Our measurements reveal just how significant this difference is: 12 kΩ (bridge) versus 8kΩ (Neck)."* Does that mean the "colleague" at the bridge is 50% louder? Another example from a guitar comparison: *" the pickups of this guitar have the lowest output power of all candidates: they show merely 8 kΩ; all others are at 10 – 18 kΩ."* And one last example: *"the neck pickup corresponds in its power to a Gibson PAF (8 kΩ)."* From a physics point-of-view, such texts are more than problematic.

Pickups are almost always wound with copper magnet wire, and therefore only the wire cross-section and the wire length figure for the **DC resistance** R_{DC}. Measuring the resistance is easy – even inexpensive R_{DC}-instruments have a tolerance better than 1%, and 1‰ is achievable without much effort. If indeed such a high accuracy is the objective, the temperature needs to be specified exactly as well within a ¼°C. Test reports often include four-figure resistance details: for the Gibson **498-T** e.g. 12,23 kΩ, or – in another guitar – 13,40 kΩ. The reader is however left in the dark about whether such differences are due to the instrumentation (which is almost never specified at all), or due to manufacturing scatter ... or at least in part due to the often applied practice not to disconnect the volume potentiometer for the measurement: this changes the reading of a 13,00-kΩ-resistance to 12,67 kΩ (for a 500-kΩ pot) or to 12,36 kΩ (for a 250-kΩ pot), after all. Such small differences would not be of any significance if they were not the reason to draw the conclusion that with 13,40 kΩ that last bit of "punch" would be achieved which the 12,23-kΩ-contestant unfortunately missed. Reading such a test report, indeed not few guitarists will invest $200 to profit from that "punch".

The pickup industry happily picks up on this resistance diversification and offers a vast variety of pickups. The Gibson **BurstBucker** is available in three versions: slightly underwound, normal, and slightly overwound. The DC resistances differ by 7% each – and these are not unavoidable manufacturing tolerances but deliberate production♣. Or so the Gibson advertisements state. On the other hand, the Gibson **498-T** is only available in a single version. Tests in a German music magazine (in Summer 2003 and Winter 2005) report that there are resistance tolerances of 9,6% between two specimen of this pickup.

In many test reports the DC-resistance of a pickup receives a multi-digit specification; however, it is quite often not designated with "resistance" but with "**output power**". The skillful reader will interpret this as loudness und is generally not entirely wrong with this approach. Indeed an **SDS-1** (9,1 kΩ) will yield more output voltage as a vintage Strat pickup with its modest 5,8 kΩ. On that basis, a Gibson **Tony-Iommi**-Signature pickup would really hit home, wouldn't it, having not less than 17,8 kΩ DC resistance! That's almost the double "output power" relative to the SDS-1. However, given the same string vibration, the Tony-Iommi generates <u>less</u> voltage than the SDS-1, its high resistance does not increase the transmission coefficient T_{Uv}. The latter value – defined as quotient of pickup voltage and string velocity (chapter 5.4.5) – is well suited to investigate correlations between the DC resistance and transducer efficiency.

♣ The '57-Classic-Plus sports as little as "3% more winding" versus the '57-Classic [Gibson special issue of the German "Gitarre & Bass" magazine].

The frequency dependence of the transmission coefficient H_{Uv} follows a more or less complicated low-pass function (chapter 5.9.3). For the Stratocaster pickup we obtain a simple 2nd-order low-pass with a resonance emphasis of about 5 dB (**Fig. 5.5.18**). Increasing the number of turns by 10% (e.g. from 7600 to 8360 turns) will increase the DC resistance by 10%, as well. Calculating more precisely and considering that the additional turns are located on top of the coils and will therefore be a bit longer we obtain an 11% increase of the DC resistance. The effects of the CD resistance on the transmission function are, however, so small that over-exaggerated requirements as to the precision are not purposeful. The inductivity of the pickup will rise by about 23% (chapter 5.5.2), the capacitance is determined predominantly by the cable, and equally the load resistance. All these contributions combined will result in an increase of the transmission factor (the log of the transmission function) by 0,9 dB while the resonance frequency drops by 10%. In a direct listening comparison these changes will be just about noticeable with the increased number of turns the pickup features a little less brilliance. In the treble range we even incur a very small loudness drop while a minimal loudness increase happens in the low end. From a psychoacoustic perspective [12] the most appropriate parameter to describe these changes would be the sharpness: it drops with increasing number of turns.

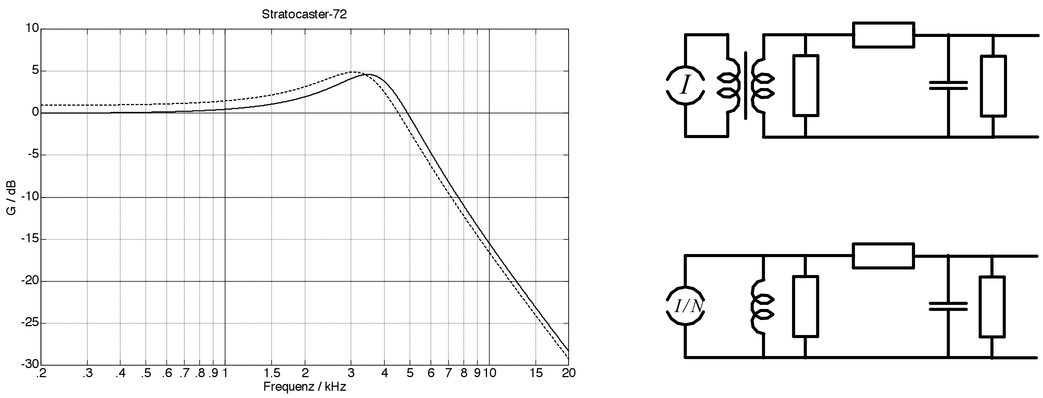
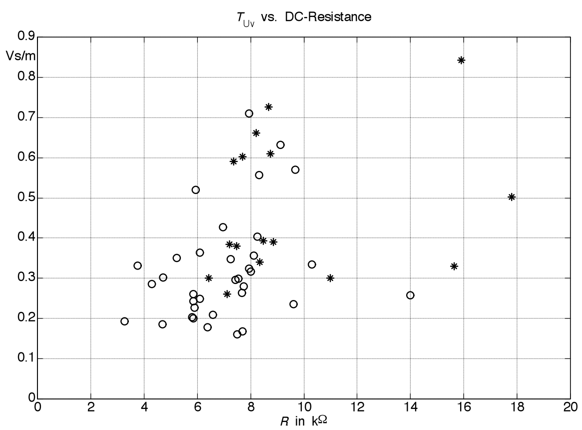


Fig. 5.5.18: changes of the transmission factor $G_{Uv} = 20 \cdot \lg(H_{Uv})$dB for a 10% increase of the number of turns N.

To conclude any assessments of loudness based on the pickup DC resistance is difficult because the former depends on so many parameters. Other than the frequency response of amplifier and loudspeaker, the room acoustics also determine the final perception of the sound, and added to this are subjective preferences (e.g. attack vs. sustain). For the following analysis (**Fig. 5.5.19**) we will therefore not evaluate the loudness but the low-frequency transmission coefficient T_{Uv} and compare it with the DC resistance (see also chapter 5.4.5).



The large scatter of the pairs of values clearly shows that the transmission coefficient and the DC resistance correlate only little. For identical DC resistances the transmission coefficient can vary as much as a factor of 4!

Fig. 5.5.19: Comparison between low-frequency transmission coefficient and the DC resistance. Transmission data as in chapter 5.4.5.
o = singlecoil, * = humbucker.

5.6 Instruments for measurements on pickups

How do I measure an electric pickup parameter? In most cases presumably with an instrument the inner workings of which are not really known to the user. A popular choice is the so-called RLC-instruments able to meter R (resistance), L (inductance) and C (capacitance). If the pickup were an ideal basic two-terminal network, there would be no objections against this approach. Basic two-terminal networks consist either of an ohmic resistor, or of an ideal inductor, or of an ideal capacitor. In a pickup, however, all three of these elements operate in conjunction – the pickup thus is a composite two-terminal network.

In the simplest case the pickup impedance is modeled via an electrical resistor *R* connected in series to the inductance *L* of the winding, with the capacitance of the winding connected in parallel to this series connection. The resistor *R* is the DC-resistance of the wound copper wire as was already described above – it is also called copper resistance. As has been elaborated in the chapter *Magnetodynamics*, the *DC*-resistance of an ideal inductor is zero; the *DC*-resistance of an ideal capacitor is infinite. Indeed, at $f = 0$ Hz only the value of *R* remains, since the other two components in the network do not contribute anything at this frequency. Consequently, if *R* is to be measured, this should be done at 0 Hz – kind of obvious, isn't it. However, RLC-instruments do not work at 0 Hz but at other frequencies, e.g. at 1 kHz. They will determine the real part of the complex impedance $\underline{Z}$ – which may well be different from the copper resistance.

The formal description of the impedance works best with the aid of the complex notation [see e.g. 18, 20]. The **complex impedance** $\underline{Z}$ of an *RL*-series-connection (i.e. to begin with without the capacitance *C*) is:

$$\underline{Z} = R + j\omega L \qquad \mathrm{Re}(\underline{Z}) = R; \qquad \mathrm{Im}(\underline{Z}) = \omega L; \qquad \text{Complex impedance}$$

The real part of the complex impedance is *R*, the imaginary part is ωL (the imaginary unit *j* is not a section of the imaginary part!). As evident, the real part is independent of the frequency and can – *for this specific two-terminal network* (!) – measured at any frequency. As soon as the capacitance is connected, however, this situation changes: the capacitance *C* is, in the simple equivalent circuit, connected in parallel to the *RL* series circuit. The complex impedance $\underline{Z}$ of this *RLC* is calculated as:

$$\underline{Z} = \frac{R + pL}{1 + pRC + p^2 LC} = \frac{R + p(L - R^2 C) + p^3 L^2 C}{1 + p^2 (2LC - R^2 C^2) + p^4 L^2 C^2} \qquad p = j\omega$$

Breaking down this complex impedance as a sum of a real part and an imaginary part yields a value which an RLC-instrument will show as loss-resistance if a coil is to be measured:

$$\mathrm{Re}(\underline{Z}) = \frac{R}{1 - \omega^2 (2LC - R^2 C^2) + \omega^4 L^2 C^2} \qquad \text{real part of the } RLC\text{-circuit}$$

This real part is not constant anymore but dependent on the frequency! For DC i.e. at $\omega = 0$, the correct DC-resistance *R* is still the result, however for every other frequency a diverging and thus incorrect value is measured.

These deviations are not always dramatic – BUT they should be looked against the background that an "expert" for example *has* to know that the Texas-Special-Pickup sports 6210 Ohm whereas the 'Vintage Reissue Pickup" throws *a mere* 6100 Ohm (i.e. a full 1,8% less!) into the ring. Incidentally, the expert hopefully is also aware of the fact that the same 1,8% resistance change can also be caused by a temperature change of as little as 4,5°C ☺. How large the differences can be due to the instrumentation is shown by **Fig. 5.6.1**: using an RLC-Instrument working with 1000 Hz to measure the Stratocaster-coil-resistance will give a value which is too large by 6%. Which amounts to about the difference between a '80s-Standard-Pickup' and a 'Late-60s-Pickup. At the same temperature …..

Pickups with a relatively low resonance frequency (e.g. Gibson P90), on the other hand, show significantly larger deviations (Fig. 5.6.1). Connecting a cable changes the real part, as well, even if the **cable** is defined as ideal capacitance having exclusively an imaginary effect (in the sense of the imaginary notation system ☺). For the P90 pickup, the addition of a cable of 600 pF has the effect that at 1 kHz the real part of the impedance increases by 40%.

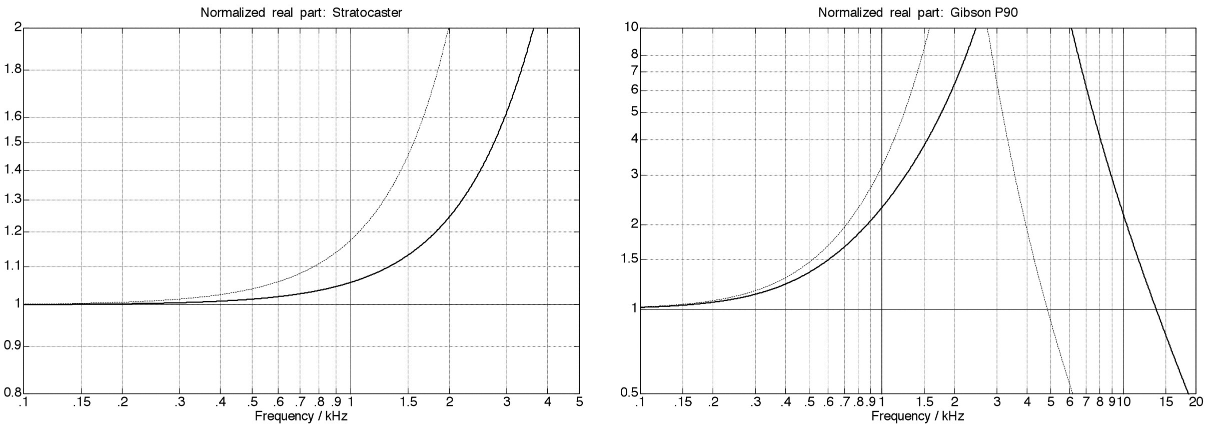
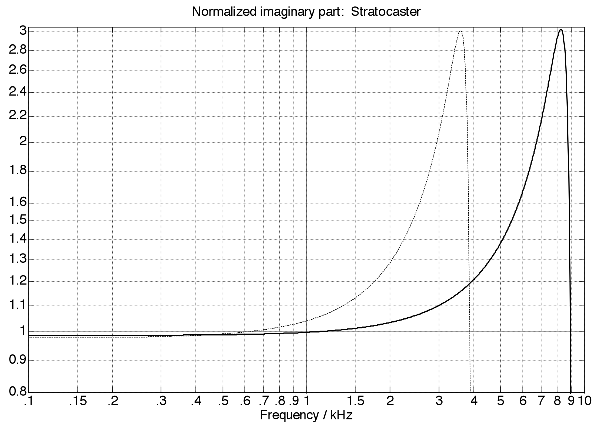


Abb. 5.6.1: Real part of the pickup impedance referenced to R_{Cu}. Left: Stratocaster, right Gibson P90. At f = 1000Hz the real part (without cable) diverges by 6% respectively 130% from the 0-Hz-value (———). Narrow lines: with 600-pF-cable. To clarify at which frequency the impedance meter is operating, the measuring frequency can be checked e.g. via an oscilloscope during the measurement.

Besides the DC resistance R, the **inductivity** L is the second important electrical parameter. If only R and L were cooperating in a pickup, we could measure L without any issue as imaginary part of the impedance – at any frequency except 0 Hz. However, the capacitance connected in parallel has the effect that below the resonance frequency the normalized imaginary part rises; above the resonance frequency it even becomes negative. An RLC-instrument, which displays in the "coil measurement" setting merely the imaginary part of the impedance divided by $2\pi f$, will follow the curve shown in **Fig. 5.6.2**. Up to 1000 Hz the deviations for the Stratocaster pickup are actually not too significant yet; for higher frequencies, the error keeps mounting – as it does for pickups with lower resonance frequency.

The real problem with inductance measurements starts if the pickup impedance should be described by more than one inductivity. As we will see in the chapter about equivalent circuits, this comes into play especially if eddy-current losses can not be ignored, i.e. for pickups with slugs made of soft iron or nickel, and/or with metal covers. In complete analogy, a mechanical system including 3 independent masses connected via 2 independent springs could not be characterized for oscillations of every frequency by one and the same spring stiffness, either.



Imaginary part of the impedance of the *RLC*-circuit:

$$\mathrm{Im}(\underline{Z}) = \frac{\omega(L - R^2C) - \omega^3 L^2 C}{1 - \omega^2(2LC - R^2C^2) + \omega^4 L^2 C^2}$$

Fig. 5.6.2: Imaginary part of the pickup impedance (Stratocaster), referenced to *ωL*.
Thin line = 600-pF-cable added.

In such a case a possible way would be to first define a suitable **equivalent circuit**, and then to determine the element values in this equivalent circuit via measurements. RLC-meters in fact use the same approach, and in some cases even include options: to measure a coil two equivalent circuits are offered – an *RL*-series circuit and an *RL*-parallel circuit. These two are however not compatible. For example, the series connection of a 6861-Ω-resistor and a 2-H-coil may be described at 1 kHz by an equivalent parallel circuit of a 30-kΩ-resistor and a 2,6-H-coil. The equivalence is valid only for 1 kHz; at every other frequency different values will result for the elements. Both the *RL*-series circuit and the *RL*-parallel circuit are moreover too simple for a pickup; suitable equivalent circuits should at least include a capacitance (see also the chapter on equivalent circuits).

As an alternative to measuring the inductivity with an RLC-meter it is possible to draw the frequency response of the amount of the impedance in a double-logarithmic representation. Since the impedance is dependent on the frequency according to a power function, curves result which – in sections – can be approximated by straight lines. Or so the theory according to Bode says. However, this only holds for simple networks such as an *RL*-series circuit (**Fig. 5.6.3**). Or so the author says.

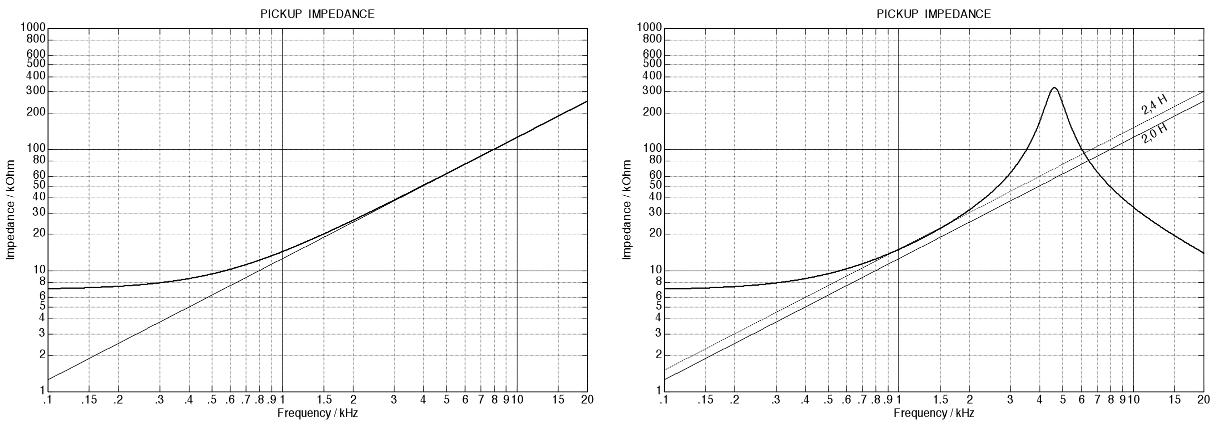


Fig. 5.6.3: Amount of the impedance of an *RL* series circuit (left), and of a *RLCR-equivalent circuit* (right).

Plotted in the left part of **Fig. 5.6.3** is the amount of the impedance frequency response of an *RL*-series connection (R = 7 kΩ, L = 2 H). The curve approximates towards low frequencies a horizontal straight line Z = 7kΩ), whereas towards high frequencies we get an increase according to the slanted straight ($Z = 2\pi fL$). The inductivity L can be determined graphically from this measurement by shifting the approximative straight line to best match the curve. The proportionality coefficient L is the inductivity.

However, as soon as a capacitance C (600 pF) and a dampening resistor R_p (1 MΩ) are also included, this high-frequency approximation is not possible any more (Fig. 5.6.3 left). One can try the approximation at medium frequencies (e.g. at 1,5 kHz) but this will result in a inductivity result which is 20% too large. In fact, that would not be a dramatic error but it all depends on the desired measurement accuracy. DUCHOSSOIR specifies the following, for example: *Late-60s-Strat*: 2,2 H, *Vintage-Reissue*: 2,3 H, *1980s-Standard*: 2,37 H, *Texas-Special-Neck*: 2,47 H, *Texas-Special-Middle*: 2,50 H. If indeed such small differences (as far as they are of any significance to begin with) are to be determined, 20% tolerance would be unacceptable. As a precaution it is noted here that determining the intersection point with the straight line dropping off at high frequencies (due to capacitances) brings an improvement only in theory: in practice there are parasitic disruptive effects which falsify the theoretically expected 1/*f*-drop-off.

Measuring the **pickup quality factor** *Q* with an RLC-Meter is even more misleading that the measurement of *R* and *L*. What is actually measured here is the coil quality ($Q_L = 2\pi fL/R$) and thus a frequency dependent parameter. DUCHOSSOIR assumes, in his books on the Fender Stratocaster and Telecaster, relatively arbitrarily f = 1000 Hz. He notes: *a pickup with a higher Q emphasizes a narrower frequency band, and vice versa a pickup with a smaller Q emphasizes a wider frequency band.* This clarification would hold if *Q* were meant to be the resonance quality factor, however, DUCHOSSOIR does not list resonance quality factors, but the coil quality. The influence of the latter on the resonance emphasis cannot be described by a simple function. Fig. 5.5.9 shows how changes in the coil quality have only small effects on the resonance emphasis. If on the other hand both *R* and *L* are changed similarly, e.g. both by 50%, Q_L remains constant but the resonance emphasis drops by about 2 dB on the Stratocaster.

As a closing example a pickup from a **Gretsch** Tennessean is investigated. Its DC-resistance amounts to 3260 Ω, however taking an impedance measurement at 1 kHz yields 7155 Ω in series with 1,2 H. An equivalent circuit built from these two components indeed shows the same impedance at 1 kHz (**Fig. 5.6.4**) but behaves much differently at other frequencies.

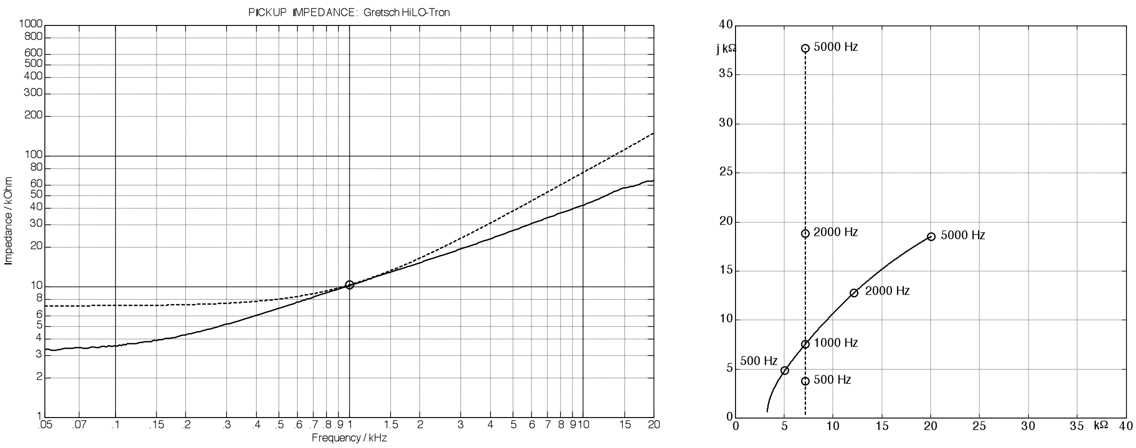


Fig. 5.6.4: Measured impedance amount of a Gretsch pickup (——). A RL-meter operating at 1000 Hz measuring frequency shows 7155 Ω and 1,2 H. Measuring such an RL-series circuit (-----) reveal, however, major differences. The right figure depicts the impedance locus (50 – 5000 Hz). The reason for these considerable deviations is the strong eddy current dampening of this special pickup.

5.7 Hum-sensitivity

Magnetic pickups generate an electrical alternating voltage from a magnetic alternating field. This voltage is the wanted signal as long as the alternating field results from the string vibrations. All alternating fields, which are not due to the string vibration, generate, in contrast, undesired **interference**. In the environment of the electric guitar the most common source of interference results from 50-Hz-fields caused by the 230-V-power-network (or 60 Hz at 110 V in the US, or other frequencies and voltages, depending on the country and local power system). A 50-Hz-field coupled into a guitar pickup comes through as a low-frequency interfering tone (49 Hz equals the pitch of G_1) which is called *hum*. Hum interference rarely is of a single frequency – more often it is a complex tone with harmonics at multiples of the fundamental (50, 100, 150, 200 ... Hz – or in non-European power supply systems the harmonics of the local supply frequency). Filtering the fundamental therefore does not help a lot.

The principle of **magnetomotive force** provides us with the basis for the quantitative interference: around a long, straight conductor a magnetic fields with the flux density of $B = \mu_0 I/(2\pi r)$ is created. In this formula, I is the current strength, r is the radial distance, and μ_0 represents the permeability of air $4\pi \cdot 10^{-7}\,\text{Vs/Am}$. Accordingly, a line carrying 10 A generates a flux density of 1 μT at a distance of 2 m. This seems not to be a lot – however, in a coil of 10 cm^2 with 10000 turns, the resulting flux is 10 μVs, after all, and the corresponding voltage at 50 Hz is 3 mV. For a signal of 100 mV, the signal-to-noise ratio is a mere 30 dB i.e. not a lot. In practice, things are a little different, though – not so much because the magnets on a pickup have a fields-amplifying effect (about +2 dB) but because power current is supplied via two-wire lines. The forward and backward flow generates anti-phasic fields which attenuate each other in their effect. For the situation as given above this results in an improvement of the signal-to-noise ratio by about 50 dB to about 80dB. This would seem adequate – a tape recorder would be very happy with such a dynamic range. Guitar players, however, are no tape recorders (even if they tend to copy and repeat licks ...). They will overdrive their amps, depending on the style of music, by 10 – 30 dB. This again reduces the signal-to-noise ratio in our example to as little as 50 dB, and given e.g. an SPL of the music of 100 dB (VERY moderate Hardrock), a clearly audible hum interference remains. The 50-Hz component is not the actual issue (it may eve be below the hearing threshold, but the almost always present harmonics will be rather disturbing. Also, power transformers, CRT screens, fluorescent lights, switched power supplies or electrical motors can create much stronger interference.

Fig. 5.7.1 shows time function and spectrum of two typical interference signals: the one of a CRT screen causes an impulse-like noise, while the stray field of the mains transformer of a power amplifier generates a distorted sinus wave. The derivative of the sawtooth-shaped ray-deflection in the CRT-screen results in the needle-shaped peaks in the upper signal shown in Fig. 5.7.1; it reaches about 12 mV as a maximum. This interference was recorded with a Stratocaster about half a meter away from the screen, and while this signal does not hold a lot of power, it may already lead to overdriving the amplifier due to its high peak values. The spectrum diminishes only little towards the high frequencies; the guitar amplifier generates a hard, buzzing tone. The stray flux of the power amp transformer includes mainly the 1st, 3rd and 5th harmonics (due to saturation in the core and the hysteresis), and the peak value of the time function is about 0,9 mV. The sound of this interferer is a low hum similar tot he sound of an electrical bass guitar.

 Translation into English by Tilmann Zwicker

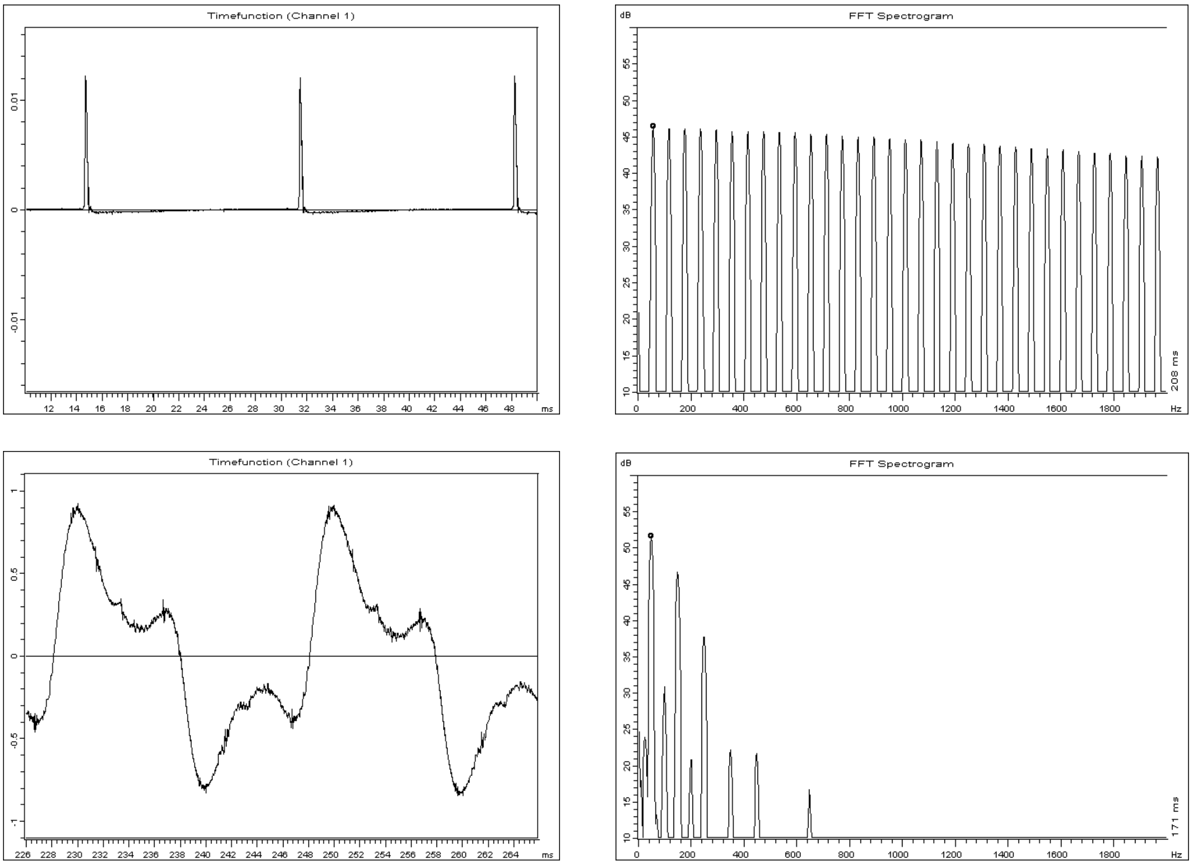
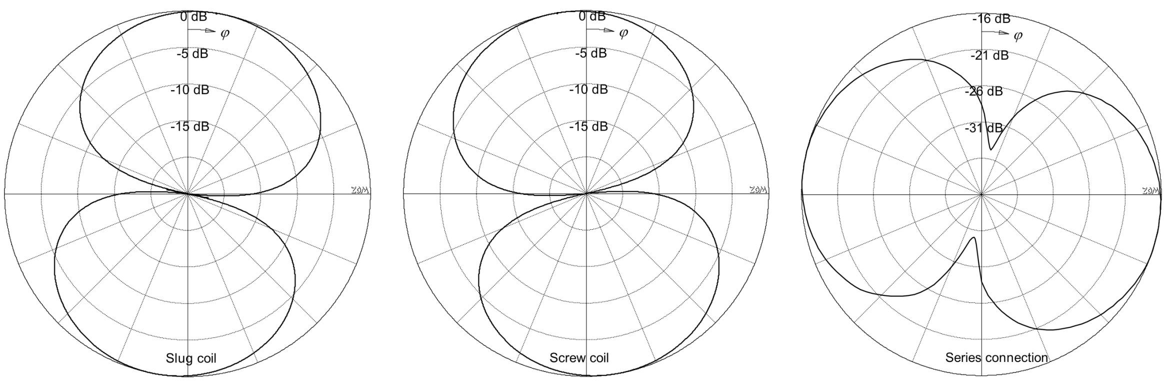


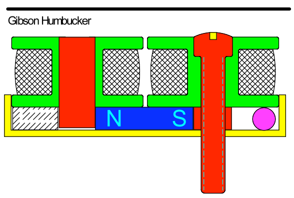
Fig. 5.7.1: Time function (left) and spectrum (right) of interfering signals. The upper two graphs relate to noise due to a CRT screen, the lower graphs show the interference by a transformer. The left graph for the CRT is scaled in Volts; the maximum value is 12 mV. The time function for the transformer is scaled in mV with the maxima being at 0,9 mV. Both level spectra are scaled in dBµ, i.e. relative to 1 µV.

In order to obtain quantitative data on the hum-sensitivity of typical guitar pickups, **measurements** were taken in an artificial interference field created via a pair of **Helmholtz coils** (B_{eff} = 6,5 µT). For singlecoil pickups, the axis of the coil was oriented in parallel to the direction of the field while humbuckers could be rotated. The interfering voltage (measured at 500 Hz) was 0,1 – 0,2 V for singlecoils; for humbuckers the maximum was 30 mV. Taken by themselves, these numbers are not very meaningful – however, in combination with the transfer coefficient of the pickup it is possible to give a **signal-to-noise ratio** (level of the useful signal minus the level of the interference). Of course, a pickup boasting 10000 turns on its coil will reproduce the interfering field more strongly (i.e. louder) compared to a pickup having 5000 turns, but the former will also generate a louder useful signal than the latter. Consequently, the individual relation between voltage of the useful signal and the voltage of the interferer (or the difference between the levels of these signals in dB) is the purposeful measure.

It was striking during most humbucker trials that – in contrast to the euphoric slogans in advertisement – the hum-rejection is rather modest. Seth Lover's statement that *"the 2 coil pickup eliminates the hum"* should not be taken literally. Indeed, the very plausible basic principle of interference compensation using two inverse wound coils requires a design which is symmetric relative to a single central point; this is not there for your typical humbucker. The magnet positioned below the coils bends the magnetic field and downgrades the hum-suppression substantially.

In **Fig. 5.7.2** we see the directional patterns gathered with a Gibson 490R pickup. If only a single coil (without ferromagnetic materials) were rotated in the magnetic field, a cosine-shaped directional pattern would be seen (direction of field, rotation axis and coil axis all being perpendicular to each other). Due to the ferromagnetic being positioned like a "u" the field is bent such that both coils "squint" inwards; the highest sensitivity is found to be off by 9°, directed inward from the coil axis. Interfering fields directed through the pickup in parallel to the axis of the coils can be compensated to good effect. However, if the direction of the field is perpendicular to the coil axis, the compensation effect is only rather moderate.





$$D_1 = \cos(\varphi - 0.16); \qquad D_2 = \cos(\varphi + 0{,}16);$$

$$D = 0{,}935 \cdot \cos(\varphi - 0{,}16) \; - \; \cos(\varphi + 0{,}16)$$

The coil with the slugs is less sensitive by 0,6 dB.

Fig. 5.7.2: Normalized directivities *D* of the humbucker coils: 1 = coil with slugs, 2 = coil with screws. The pickup (Gibson 490R) subjected to a parallel AC-field of 500 Hz with both coils disconnected and measured separately. The right-hand directional diagram shows the directivity with both coils connected on series. φ = rotational angle of the pickup relative to the magnetic field.

In Fig. 5.7.2 the minimum for the series connection does not occur at φ = 0° (i.e. axial direction of field). This is not due to the magnet but to the differences between the coils which are created on part by differences in the coil winding and in part by differences in the coil core (i.e. the screws and slugs). In practice it is rather irrelevant for which interference direction the pickup is least sensitive since interference can come from any direction. The player's performance will not improve if he/she needs to hold the guitar horizontally to minimize the hum♣. Therefore, it is best to concentrate on **worst-case-**scenarios and consider those interferer directions which create the strongest hum. Magnetic fields with a direction running in parallel to the coil axis are most disturbing for singlecoil pickups. Gibson-type humbuckers are most sensitive to hum-fields running in parallel to the strings (i.e. axis-normal). In coaxial humbuckers (see chapter 5.3) the coil-symmetry is the decisive factor for the direction of strongest interference – normally these pickups hum the most for axis-parallel fields.

♣ Come to think of: that may depend on the guitar player, as well, …

 Translation into English by Tilmann Zwicker

Fig. 5.7.3 schematically shows the field distributions for a humbucker. The magnetic flux in both coils is opposed if the direction of the field runs in parallel to the coil axis. This shows that a direction-independent compensation is **in principle not possible**. For the Gibson 490R and axis-normal field direction (i.e. the worst case), the anti-phase connection of the coils reduces the interfering signal merely to one third – referenced to the interfering voltage which would be generated in one coil by the axis-parallel field. Since the coils are connected in series and the useful signals are summed up, we could add another 6 dB and specify the **worst-case hum-suppression to 16 dB**. On the other hand, it should not be forgotten that not all useful signal components are in fact added up: a number of partials of the string vibration are even cancelled out completely due to the sampling of the string at two points.

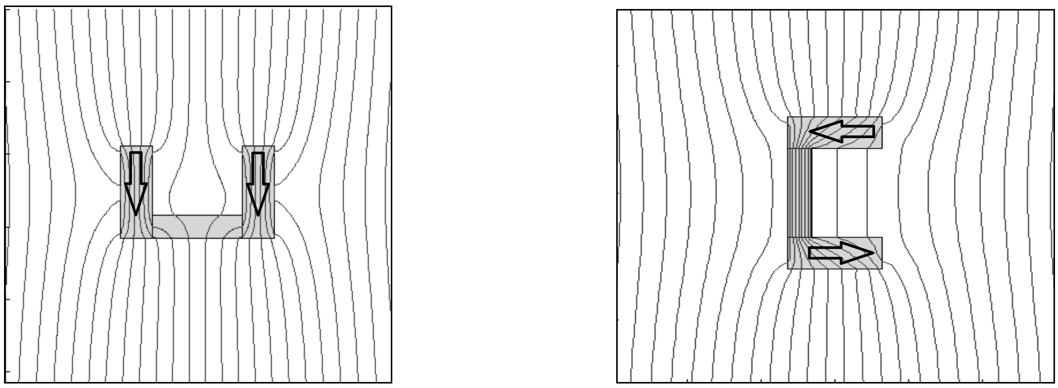


Fig. 5.7.3: Shape of magnetic field running through a Gibson-type humbucker. If the field runs in parallel to the coil axis (left), in-phase voltages are induced. However, for an axis-normal magnetic field (right) anti-phase interference signals are created (just like the signals induced by the strings).

The directionality of the interference suppression could be described in simple formulas in Fig. 5.7.2. For the **frequency dependency** we get more complex relations, however. On the one hand, this is due to the skin-effect but also due to the capacitive coupling between the two coils at higher frequencies. **Fig. 5.7.4** depicts the frequency responses of the transmission with an excitation in the parallel Helmholtz-field. Compared to the single-coil operation the Gibson 490R reduces the interference by merely 10 dB (or 16 dB considering the doubling of the useful signal with both coils in operation). For Fender's coaxial humbucker the gain is **24 dB**, after all.

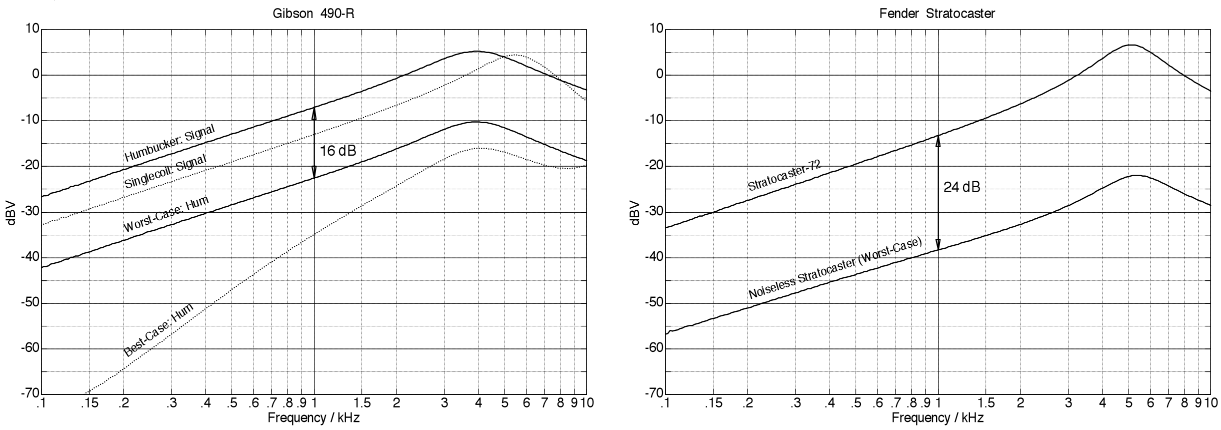


Fig. 5.7.4: Frequency dependency in the parallel Helmholtz field (6,5 μT_{eff}). The pickups were loaded each with 200kΩ // 330pF. For comparison, the right-hand section shows Stratocaster pickups with comparable sensitivity.

The transmission factors shown in Fig. 5.7.4 are not quite applicable to the real-world operation: for the interference generation, the Helmholtz coils are a good standard; however, this does not hold for the generation of the useful signal, because the air-gap changes caused by the string vibration have a locally very limited effect. To achieve a comparable assessment, the following **measurement method** was used. For each pickup, the interference voltage level was measured at 520 Hz and an effective flux density of 6,5 μT (worst case). To determine the sensitivity to the useful signal, a 0,66-mm-string was moved in front of the magnet poles in axial direction at 84 Hz and an amplitude of 0,4 mm. The S/N-ratio (level of the useful signal minus level of the interfering signal) derived from these readings was arbitrarily increased by 11,5 dB such that for the Stratocaster pickup – which was used as reference – a **standardized hum rejection of 0 dB** resulted. Using this definition, pickups with positive hum rejection are less interference-prone that the reference pickup. The best results were achieved by the Joe-Barden Strat pickup and the Gretsch FilterTron – due to their symmetric construction.

The following **table** lists the data taken during the measurements done according to the above approach. The double-digit representation for the hum-rejection of the singlecoils does not imply that indeed an accuracy of 0,2 dB was achieved. Such a high accuracy is actually not required, anyway, since differences of e.g. 1 dB are normally not detectable. However, the low hum-sensitivity of the Gretsch **HiLo-Tron** is noticed. This pickup shows that one level alone does not have much informative value: the hum level of the SDS1 is actually 2 dB higher – the SDS1 delivers a much higher useful signal level. On the other hand, the DP172 is even less sensitive that the HiLo-Tron – its hum-level is however lower by almost 8 dB. We must moreover also not forget that factors other than these pickup-parameters do play a role: the HiLo-Tron is known for its brilliant (i.e. bright) sound and will presumably be used by most guitar players for a more "clean" sound using little distortion in the amplifier. This is rather different for the SDS1: with its high output and mid-range emphasis, it is predestined for "crunch" i.e. a distorted reproduction. Distortion, however, implies high gain, and thus relatively loud hum.

Tonabnehmer §)	**Hum-level /dBV**	**Signal-level / dBV**	**S/N-ratio / dB**
"Telecaster"-Fake (Neck)			
Fender Jazzmaster-62 (Bridge)			
Fender Jazzmaster-62 (Neck)			
Duncan APTR-1 (Telecaster-Type, Neck)			
Fender Telecaster-52 (Neck)			
Duncan SSL-1 (Strat-Type)			
Schaller			
Fender Stratocaster (bar magnet)			
Fender Stratocaster-72 (G-Magnet)			
DiMarzio DP172 (Telecaster-Type Neck)			
Fender Telecaster-73 (Bridge, D-Magnet)			
Rockinger P-90			
Fender Telecaster-70 (Bridge), w/out plate			
Rockinger Strat-Type (bar-magnet)			
Rickenbacker (Toaster-Pickup)			
DiMarzio SDS-1			
Fender Texas-Tele (Bridge, D-Magnet)			
Fender Telecaster-70 (Bridge)			
Fender Stratocaster (USA Standard)			
Ibanez Blazer			
Gibson P-90			
"Telecaster"-Fake (Bridge)			
Fender Telecaster-52 (Bridge)			
Duncan APTL-1 (Telecaster-Type, Bridge)			
Gretsch HiLoTron			
Fender Jaguar (Neck)			
Lace-Sensor gold			
Squier Humbucker			
Gibson 490R			
Gibson Burstbucker #2			
Gibson ES 335 (Neck, 1968)			
Gibson 57 classic			
Fender Noiseless Stratocaster (Neck)			
DiMarzio DP184			
Gibson Tony Iommi			
Gretsch FilterTron			
Joe Barden (Strat-Type, Bridge)			

Table: hum-rejection. Interfering field: parallel single-frequency magnetic field, f = 520 Hz, B_{eff} = 6,5 µT. String vibration: f = 84 Hz, amplitude 0,4 mm, distance of string to magnet = 2mm, D'Addario PL-026. The pickup was loaded with 50 kΩ fro this measurement.

§) The actual values are reserved for the printed version of the book

The levels of hum in the **Jazzmaster**- and the Stratocaster-pickups differ by 7 and 8 dB, respectively. This difference matches the ratio of the surfaces (2:1) and the assumed number of turns (ca. 1:0,9). The stronger hum-sensitivity of the Jazzmaster-pickup would be compensated if the useful signal level would also be stronger by 7 – 8 dB. However, the gain relative to the Stratocaster pickup is only about 5 dB i.e. the Jazzmaster-pickup "hums more". The difference of barely 3 dB is however not dramatic, plus the spectrum of the interference plays a role, as well. Connected to the typical circuitry, the Jazzmaster pickup has a stronger resonance peak than the Stratocaster pickup: in case of a broadband interference (e.g. fluorescent lights, or phase angle control) the Jazzmaster carries both the useful signal and the interference equally. However, if the interference has its emphasis at low frequencies (incandescent light, or power transformers), the Jazzmaster wins out because the useful signal is emphasized. As long as the differences in the signal-to-noise ratios (measured at 84 Hz / 520 Hz) are merely a few dB there will be no big effect noticeable in practice.

Humbuckers do play in another league: relative to a singlecoil they show a significant S/N-gain of 19 to more than 40 dB as long as they are subject to interferers generating parallel magnetic field lines (as generated by distant hum sources or by Helmholtz coils). A power transformer operating close to a humbucker will generate a strong field with bent field lines and may cause strong disturbance despite the hum-rejection effect. Moreover, the two coils of a humbucker may not have the same sensitivity: if the number of turns or the core materials are different, the compensation effect may be incomplete.

Many singlecoil-guitars fitted with more than one pickup feature a **hum compensation** via different direction (cw or ccw) of the winding and opposed magnet polarity of the pickups. As two pickups are selected in combination, a humbucking-effect happens. Occasionally a **compensation coil** is built into the guitar – it includes no magnet and reacts only to the interference. Connected in series with the pickups coil, and given correct dimensioning, it reduces the interference. Since the useful signal has to travel through an enlarged inductance, the resonance frequency decreases, as well. Changes in sound are possible. Connecting the compensation coil in parallel (as it was tried with moderate success e.g. in the P100) increases the resonance frequency.

In closing it should be mentioned that **magnetic shielding** is possible but is inefficient and impractical. Fully encapsulating the pickup would be pointless since it could not sense the string vibration anymore. Shielding covers around both the pickup *and* the string do exists, but the musicians see them as obstacle (or best as transport safety) and remove them (sometimes to use them as ashtrays ....) . However, shielding against **electrical fields** which are capacitively coupled to the pickups from voltage-carrying lines, is possible and purposeful. Shielding foils and conductive paint serve well for this. Still, it should be considered that the magnetic fields will induce an **eddy current** into any conductive surface which may dampen the pickup resonance. For this reason, high quality shielding covers are made from nickel silver (German silver) and possibly in addition can include slots (see chapter 5.9).

5.8 Non-linear Distortion

Both the measurements with the motorized test bench (chapter 5.4.4) and the measurements with the shaker (Fig. 5.4.23) make us surmise that the functions of distance relationships are in fact (non-linear) power functions – in the framework of a diverging magnetic field this would not be surprising. However, sinusoidal excitations fed into non-linear functions will lead to non-linear distortion i.e. to the generation of new frequencies. Such a system can be seen as linear only for very small (string) excursions; the amplitudes occurring in the practical musical application are rather strong such that the large-signal-behavior needs to be investigated, as well.

In order to explain the basic relations, let us first look at a system with a transfer characteristic including a linear term and a square term:

$$y(t) = a \cdot x(t) + b \cdot x^2(t); \qquad x(t) = \hat{x} \cdot \sin(\omega t)$$ Transfer characteristic; signal

The squared sine-function can be seen as a superposition of a (constant) DC-component and an oscillation at double the frequency:

$$y(t) = a \cdot \hat{x} \cdot \sin(\omega t) + b \cdot \hat{x}^2 \cdot \tfrac{1}{2}\left(1 - \cos(2\omega t)\right)$$ Nonlinear distorted signal

The spectral representation of $y(t)$ shows three components: the DC-part at 0 Hz, the first harmonic at ω and the second harmonic at 2ω. Form this we obtain the 2nd-order harmonic distortion k_2 at:

$$k_2 = \frac{b \cdot \hat{x}^2}{\hat{x} \cdot \sqrt{4a^2 + b^2 \cdot \hat{x}^2}} \approx \frac{b \cdot \hat{x}}{2a}$$ 2nd-order harmonic distortion

A value used often instead of harmonic distortion is the (2nd-order) **harmonic distortion attenuation**:

$$a_{k2} = 20 \cdot \lg\left(1/k_2\right)\text{dB} \approx L_1 - L_2$$ Harmonic distortion attenuation

L_1 is the level of the 1st harmonic and L_2 the level of the 2nd harmonic. The approximation holds, strictly speaking, only for small signal levels but will be used without constraints in the following.

In the **general case** the transmission curve does not only include a 2nd-order distortion component but further series components of higher order:

$$y(t) = a \cdot x(t) + b \cdot x^2(t) + c \cdot x^3(t) + \ldots$$ General transmission characteristic

Any continuous function can be expanded into such a series (Taylor-MacLaurin). The corresponding spectral representation includes not only the additional 2nd order harmonic but also further lines (higher harmonics) at integer multiples of the fundamental frequency. The distortion components in power function decrease with the order and therefore we will regard only the dominating 2nd-order distortion as a simplification.

If a nonlinear system is excited not with a mono-frequency signal but with a **mixture of frequencies**, not only multiples of the fundamental frequencies result but also summation and difference frequencies. For the ideal, **dispersion-free** string, exactly harmonic partial tones are assumed, i.e. for example 100, 200, 300, 400 Hz. The difference tones generated by the non-linearity (as described above) correspond exactly to already existing frequencies. The flexural rigidity of real strings, however, generates dispersion and a frequency-spreading resulting in complicated spectra. For every primary tone (e.g. 100, 201, 302.3, 404 Hz), neighboring lines come into being which lead to additional beat-like **modulations**.

The typical transmission curve shown in **Fig. 5.8.1** describes the correspondence between the distance of string to magnetic pole and the magnetic flux. With the string in the still position, the distance between magnetic pole and string is d = 2 mm in this example (operating point). A sinusoid movement of the string with an amplitude of 1,5 mm leads to a non-linear flux change, in which the negative half-waves have smaller value that than the positive half-waves. The induced voltage is proportional to the flux *change* over time (law of induction, $d\Phi / dt$), and a saw-tooth like curve results for the voltage. In this example the square harmonic distortion attenuation is about 12 dB, corresponding to a 2nd harmonic distortion of about 25%. The 3rd-order harmonic distortion attenuation amounts to about 26 dB (k_3 = 0,5 %).

The square harmonic distortion is approximately proportional to the amplitude of the string vibration. For the above example and an excursion of 0,5 mm, k_2 decreases to about 8 %, and k_3 to about 0,055 %.

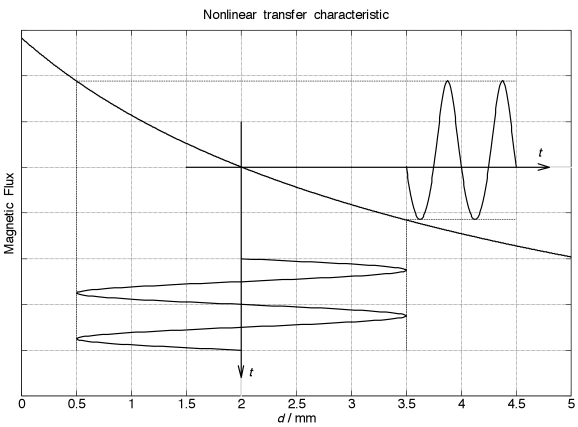
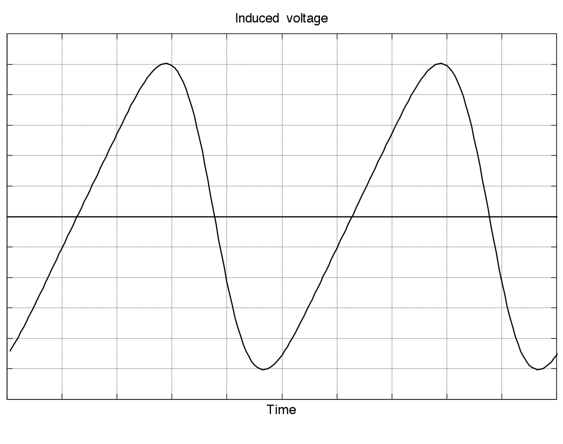
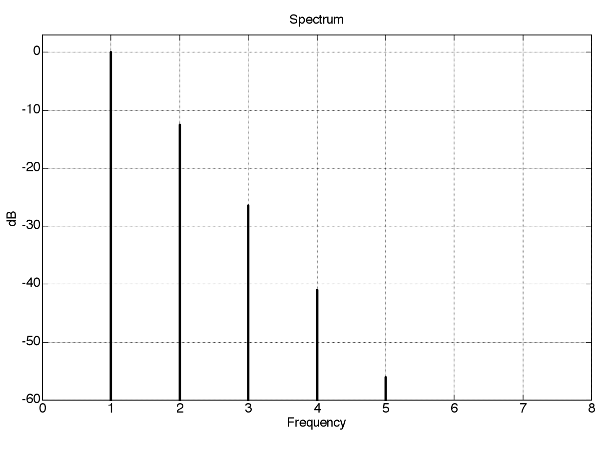


Fig. 5.8.1: Curved transmission characteristic and sinusoid excitation (left). The time-derivative of the distorted magnetic flux has a saw-tooth shape (lower left, the spectrum contains all whole-numbered harmonics (below).





The following measurements were taken on the shaker test bench at 84 Hz. As was established with an acceleration sensor, initially the shaker itself had a harmonic distortion of k_2 = 2%. This value could be improved to 0,1% via compensation – a base line which is more than adequate in view of the much higher pickup distortions. In Fig. 5.8.2 the results for singlecoil and humbucking pickups are shown. The string excursion was 0,4 mm for all measurements, the clear span (distance *d*) between the (still) string and the magnetic pole was varied between 0,5 mm and 5 mm.

Fig 5.8.2: Harm. distortion attenuation a_{k2}, f = 84 Hz, excursion amplit. = 0,4 mm. String diameter = 0,66 mm. Abscissa: distance string/magnetic pole *d*. For the T-Iommi-pickup, the distance string/cover is used, the distance to the magnetic pole is thus larger, and the curve needs to be shifter right for comparison.

For all pickups the distortion decreases with increasing distance; within the relevant range of *d* the 2nd order harmonic distortion amounts to 4 – 5% for 0,4 mm string excursion. Considering that with strong picking 2 mm excursion can easily be reached, a harmonic distortion of above 10% is possible. This is, however, not a characteristic of a special pickup but occurs similarly in all investigated pickups. As with comb-filter responses, it is necessary to take into account that every pickup is part of a musical instrument: one can objectively describe its transmission characteristic but an evaluation remains a subjective affair. Since the vibration of each string is distorted individually (without interaction with neighboring strings, see below), the effect of the distortion is much less spectacular than the numbers would appear to indicate. Clearly audible distortion is generated mainly in the electronics to which the pickup is connected but not in the pickup itself.

Fig. 5.8.3 compares measurements and calculations. As a good approximation, the field transmission characteristic of a **Stratocaster** pickup follows a simple **power function**:

$$\Phi = K_0 + K_1 \cdot \left(\Delta + d + x(t)\right)^{-1} \qquad \Delta = 4{,}3\,\text{mm} \qquad \text{Field-transmission characteristic}$$

The levels of the first and second harmonics dependent on the distance *d* (left) and the excursion amplitude $\hat{x}$ (right) agree very well with the measurements. The static magnetic flux (no string excursion) can be defined via the constant K_0; for AC-considerations its value is without importance since it disappears in the process of differentiation. The constant K_1 determines the transmission coefficient. For small string excursions it is (for 7600 turns on the coil) $K_1 = 1{,}1 \cdot 10^{-9}\,\text{Vsm}$. Taking the magnet cross-section as the area through which the field penetrates yields – with d = 2 mm and $\hat{x} = 0{,}4\,\text{mm}$ – a flux-density amplitude of 0,5 mT.

This is only a coarse estimate since the magnetic flux is not concentrated on the magnet cross-section but spreads into neighboring areas. The area is therefore larger than assumed. At the same time, it is necessary to consider that not all turns of the winding are penetrated by this magnetic flux. The number of turns therefore is smaller than assumed. These two errors are conveniently opposed and the overall estimate should not be too far off. Compared to the DC-component of the flux density (which amounts to about 100 mT at the end face of the magnet) the AC component is very small for the parameters as given above, and a linearization for the calculation of the fundamental oscillation is possible without large errors. The nonlinear behavior is described by the given characteristic with sufficient accuracy.

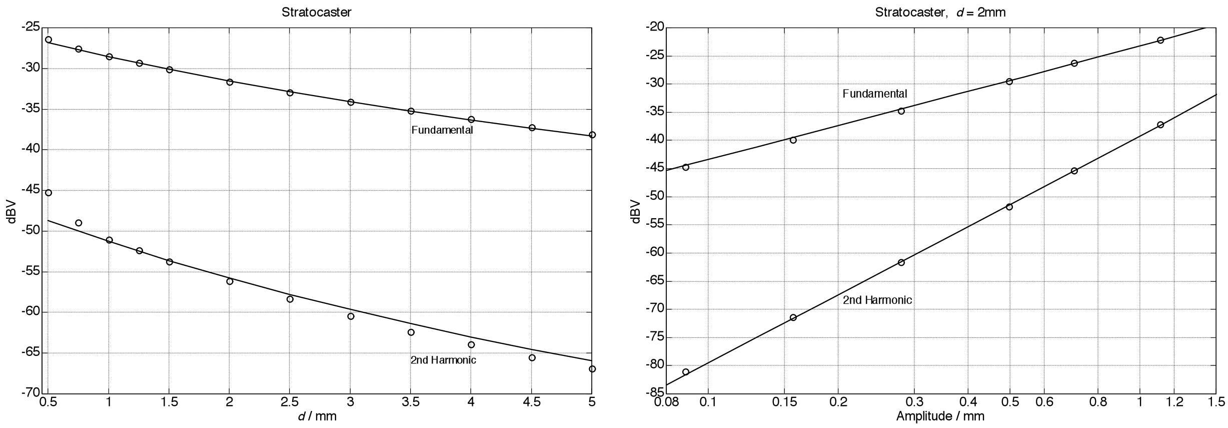


Fig. 5.8.3: Dependency of the level of the 1st and 2nd harmonic on the distance (left) and the amplitude (right). The dots are measured values, the lines result from a calculation of the power function as discussed in the text.

The real string vibration does not include only a single frequency but is a **frequency mixture** from many partials. If all these frequencies were exact multiples of the fundamental, the non-linearities of the pickup would create new components exclusively at the already present frequencies. For example, the 3rd-order distortion of the fundamental generates (amongst other components) a tone at three times the fundamental frequency – i.e. exactly at the frequency of the 3rd partial (3rd harmonic). However, the partials of the string are **not exactly harmonic**: flexural rigidity, magnetic filed of the pickups and frequency-dependent bearing impedances lead to a spreading of the frequencies of the partials. An E_2-string tuned to exactly 82 Hz could e.g. have a 3rd harmonic which is shifted from 246,0 Hz to 246,3 Hz. A 3rd-order distortion of the fundamental will create (amongst other components) a distortion product at 3 · 82 Hz = 246,0 Hz which creates a beat-like amplitude change with the 3rd harmonic (246,3 Hz). Since, however, every string vibration in reality includes modulation of the partials anyway, the additional modulation generated by the pickup is insignificant.

Completely immaterial are **nonlinear string interactions**. The primary tones (f_1, f_2) generated by two strings interact and produce sum- and difference-tones ($n \cdot f_1 \pm m \cdot f_2$) due to the nonlinear characteristics. To measure this effect quantitatively, 2 neighboring strings were strongly plucked and the pickup output voltage was analyzed. This was done for the following pickups: Gibson '57-Classic, Gibson Tony Iommi, DiMarzio DP184, Fender Texas-Special-Telecaster. Even with a mere 1-mm-distance between string and magnet, the intermodulation remained below 0,1%. The main reason for pickup distortion is the magnetic resistance of the field in air between string and magnet – this resistance being nonlinearly dependent on the string position. The neighboring string vibrating at a distance of about 1 cm has practically no influence on this process.

The magnetic flux changes generated by individual strings do superimpose in the magnet (or in the field-shaping pole pieces) – but the relative flux changes are so small that the – in principle non-linear – hysteresis may be linearized, after all. String interactions and string intermodulation starts to play a role only as non-linear distortions appear in the amplifier.

On top of the interactions resulting from two strings, the term **intermodulation** could however also be considered regarding the combination tones generated by individual partials of one string. Strong low-frequency string excursions shift the operating point on the non-linear transmission characteristic (Fig. 5.8.1), and as a consequence the amplitude of the higher frequency partial changes. Again, the shaker test bench delivers quantitative data: a D'Addario string (0,66 mm diameter, PL026) was adjusted to 2 mm distance to the magnetic pole. A low-frequency vibration (20 Hz, 0,55 mm amplitude) was added to a higher-frequency vibration (80 Hz, 0,23 mm amplitude), with the vibrations oriented in parallel to axis of the magnet. As a result of the non-linearity, new spectral components appear with the 60-Hz- and 100 Hz-lines being of particular interest. In the idealized **model**, the two-tone-mixture $x(t) = \cos(\omega t) + k \cdot \cos(\Omega t)$ receives a 2nd-order distortion: $y(t) = \kappa \cdot x(t) + x^2(t)$.

$$y(t) = \kappa \cdot x(t) + \cos^2(\omega t) + k^2 \cdot \cos^2(\Omega t) + 2k \cdot \cos(\omega t) \cdot \cos(\Omega t). \qquad \text{Non-linearity}$$

With $\cos^2 \alpha = (1 + \cos 2\alpha)/2$ and $\cos\alpha \cdot \cos\beta = [\cos(\alpha + \beta) + \cos(\alpha - \beta)]/2$, the new frequencies resulting from the non-linearity can be easily calculated: next to the DC component (0 Hz, unimportant in this context), the double primary frequencies (2ω, 2Ω) and the sum- and difference-frequencies ($\Omega + \omega$, $\Omega - \omega$) occur. The 3-tone-mixture of $\Omega - \omega$, Ω and $\Omega + \omega$ can be interpreted as classical amplitude modulation [e.g. 3]. A more descriptive approach: the low-frequency primary tone (20 Hz in the example) shifts the operating point back and forth along on the curved (non-linear) characteristic, and the additionally present higher-frequency signal (80Hz) finds a time-dependent steepness of the characteristic curve. In the ranges of higher steepness, the output signal is stronger, and for lower steepness correspondingly weak (**Fig. 5.8.4**). For the measurement, the 20-Hz-amplitude was 0,55 mm, and the 80-Hz-amplitude amounted to 0,23 mm. For the calculation to be compared to the measurement, the same characteristic as in Fig. 5.8.3 was used, and the correspondence is acceptable (Fig. 8.5.4, left). The harmonic-distortion model therefore fits also well for describing intermodulation distortions.

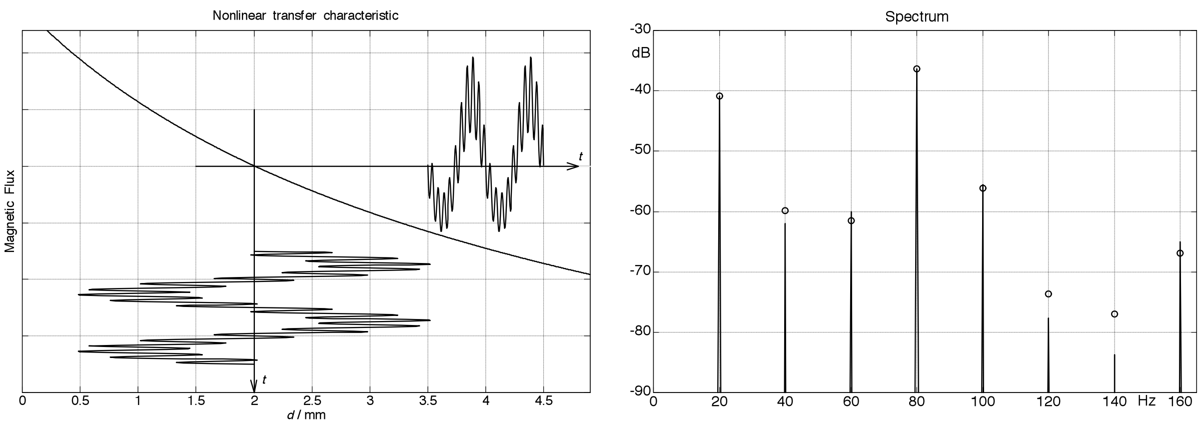


Fig. 5.8.4: curved characteristic with two-tone signal (left). The right-hand section shows measurements (o) and the correspondingly calculated string-velocity-spectrum; characteristic as in Fig. 5.8.3. The shape of the curve in the left section shows the basic relations but does not correspond to the data of the right-hand figure.

