Alnico-magnets for guitar-pickups

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Usual guitar pickups may be distinguished on the one hand by the number of their coils (single-coil vs. humbucker), and on the other hand by the material used for their magnets (ferrite vs. alnico). Advertisements will have the alnico alloys of various strengths (Alnico-2, -3, -5) feature certain sound characteristics - however, the corresponding statements are often contradictory and in fact incorrect. The following concise analysis delivers measurement data for the magnetic materials.

In a magnetic pickup, a permanent magnet generates a steady magnetic flux the strength of which is varied by the vibrating string [1]. The variation over time of the magnetic flux induces a voltage into a coil that – strongly amplified – drives a loudspeaker. In internet fora and especially in promotional material, there are very different descriptions of how the magnetic material influences the sound.

Alnico-2:
"For a vintage-oriented, warm sound. Since the magnetic field is a little weaker than with a regular Strat-pickup, the string oscillates more freely and naturally. The result is improved sustain.."
On the other hand, also: *"Given the rather weak Alnico-2, the tone literally collapses."*
Or: *"Pickups with Alnico-2-magnets are softer in their tonal character, have less treble, are less loud, rounder and somewhat less dynamic."*
But then also:: *"Thanks to its Alnico-2-magnet, the pickup does not loose any treble."*
Or: *"Alnico-2 corresponds rather exactly to an aged Alnico-5 magnet."*

Alnico-5:
"Alnico-5 = a clear, strong sound with steely twang and a firm bass."
However also: *"Alnico-5 = a bluesy basic character with a pleasant, round delivery."*
Moreover we see: *"Alnico-5 = quick response and a slightly undifferentiated reproduction"*
Or: *"Stronger magnets give less treble."*
But then again: *"The stronger Alnico-5 magnet gives a more brilliant sound."*

What is indeed correct is that Alnico-5 is stronger than Alnico-2. What else is correct in this listing? To answer this question we investigated individual Alnico-cylinder-magnets in a cylindrical coil, and also modified and measured complete pickups. Alnico alloys belong to the group of magnetically hard substances i.e. their magnetization cannot be changed easily. However, with a sufficiently strong magnetic field, Alnico-magnets may be demagnetized completely, and re-magnetized to a well-defined degree. For the experiments, an electro-magnet with u-shaped iron core was used (**Fig.1**).

Both legs of the electromagnet carry equal coils with 600 turns each. Both these coils may be serially connected to a variable transformer♣ (0 – 140 $V_{eff,}$; also known as a variac) or a DC power supply (0 – 5 A). The length of the air-gap of the electromagnet is adjustable; a typical value is e.g. 16 mm. In a magnetic circuit including an air gap, the simplest approximation is based on the assumption that the magnetic resistance in total is concentrated in the air gap. Given 1 A DC and 1200 turns of the coils, the magnetomotive force is calculated to 1.2 kA, and the values in the air gap result in H = 75 kA/m and B = 94 mT. **Fig. 1** shows on the right the ideal values calculated using this approximation (blue), as well as the measured values (black). The differences can be traced to stray flux and the (magnetic) resistance of the iron that cannot be neglected entirely. The differences are in any case insignificant since in the following no connection needs to be made to the current generating the field.

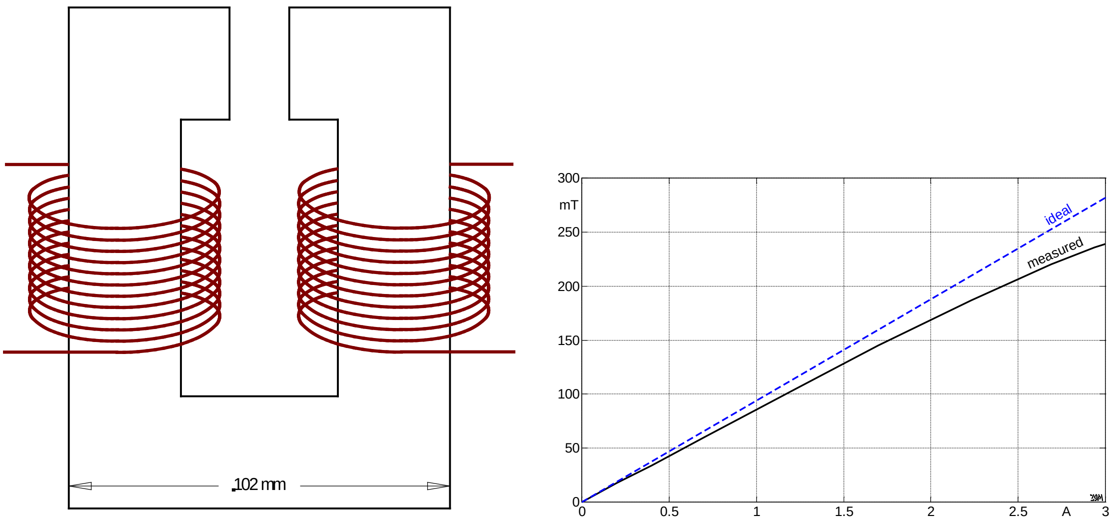

Fig. 1: The electromagnet used in the experiments (left), and the flux density measured in the air gap (right). The iron core consists of layered electrical sheets of 3 cm x 3 cm = 9 cm^2 cross-sectional area.

First, a **Telecaster**-pickup made by S. Duncan was analyzed. With its Alnico-2-magnets it generates 35 mT at a distance of 2 mm (all following pickup flux densities are given for a **distance of 2mm**). Initial concerns whether the electromagnet described above would be strong enough to demagnetize the pickup magnets proved to be unfounded: this worked out very nicely. You position half of the pickup within the air gap, crank up the variac, turn it down again, repeat this for the other half of the pickup – and the magnets are demagnetized. To re-magnetized them, 3 A taken from the DC power supply are sufficient. The most important question here is: does the permeability (and with it the inductance) change as the magnetic field strength is varied? Answer: yes, indeed, there are differences – but they are very small. Compared to the original state, the inductance of the coil drops by 7% after demagnetization and due to this the pickup resonance rises by 3.5%. This can be measured but is (spectrally) too little to be audible. After re-magnetization the original inductance is exactly restored and there are no measurable differences to the original condition.

The same procedure was repeated for a **Stratocaster** pickup (made by Fender). With its Alnico-5-magnet, the effects are more pronounced: the inductance for the magnetized state is larger by 13% compared to the demagnetized condition. The shape of the inductance-curve between demagnetization and magnetization remains totally unspectacular: a monotonous change without any local maxima or minima.

♣ This is a transformer with a continuously variable output voltage (0 – 140 V).

Fig. 2 depicts in its upper section the impedance frequency response of a singlecoil pickup fitted with six Alnico-2-magnets (Tele, neck). Demagnetizing reduces the inductance by 7%. For the transfer function (lower section of Fig. 2) this indicates (theoretically) a minimally improved treble response – however, of course a pickup with demagnetized magnet and demagnetized string would not generate any voltage at all.

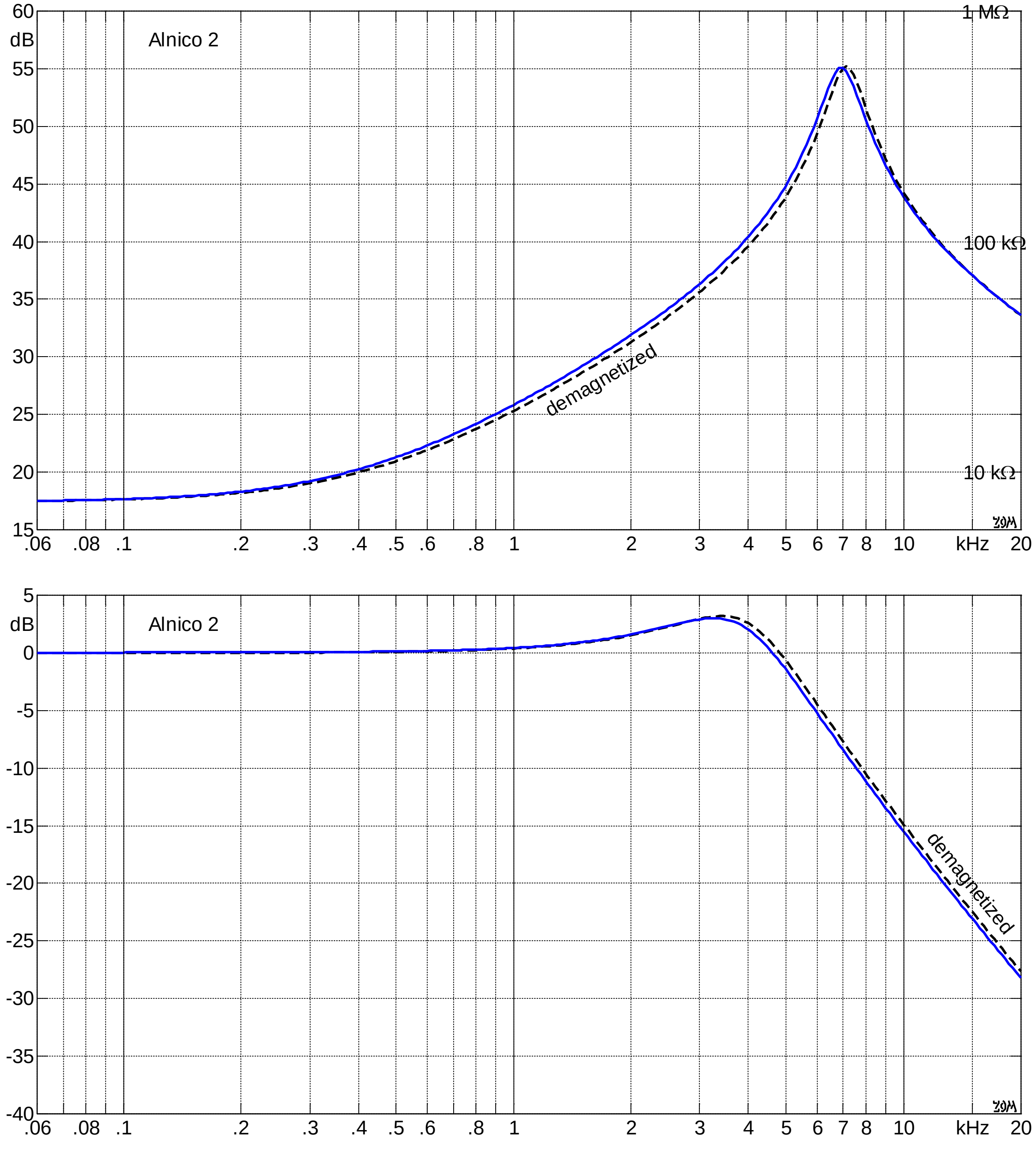

Fig. 2: Top: pickup impedance with magnetized (—) and demagnetized (---) magnets, respectively.
Bottom: transfer function for both conditions; load = 450 pF // 111 kΩ (cable, potentiometers, amplifier).
The transfer functions are referenced to 0 dB at low frequencies (demagnetization → loss of functionality).

Fig. 3 shows corresponding measurements for a singlecoil pickup fitted with 6 Alnico-5 magnets (Strat). This is, however, not the same pickup as the one for which Fig. 2 was drawn up, and consequently we may only compare the effects of the magnetization and NOT the difference of the magnet materials. The difference between magnetized and demagnetized for Alnico-5 amounts to 13% and is thus larger than for Alnico-2 (7%) – for these two specific pickups, that is, since the individual geometry impacts on the result, as well. In Figs. 2 and 3 , the colored curves refer to fully magnetized magnets. Magnets with weaker magnetization give results between the two curves, with a slight progression: the curves for half-magnetized magnets tend to be closer to the curve of the demagnetized magnets although the difference is not big. Independently of the absolute pickup sensitivity which will be discussed subsequently, the result of our investigation is: **the stronger a magnet is magnetized, the lower the resonance Q-factor and the lower the resonance frequency; both these effects are slightly more pronounced in Alnico-5-magnets compared to Alnico-2-magnets.**

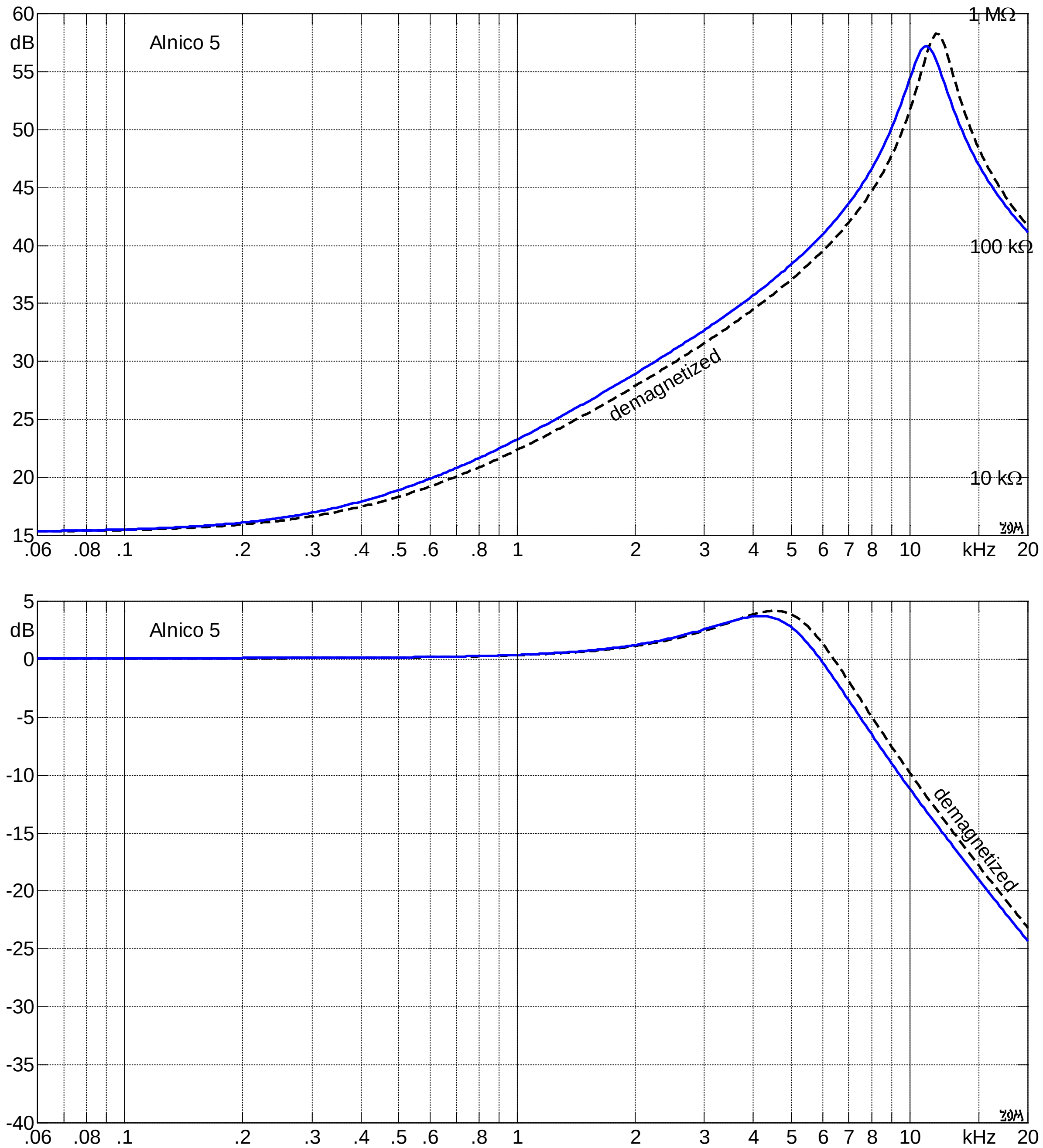

Fig. 3: Top: pickup impedance with magnetized (—) and demagnetized (---) magnets, respectively.
Bottom: transfer function for both conditions, load = 450 pF // 111 kΩ (cable, potentiometers, amplifier).
The transfer functions are referenced to 0 dB at low frequencies (demagnetization → loss of functionality).

Demagnetizing pickups in hope that the treble response will improve does not really work. In practice, the proviso will be: whether pickup magnets are magnetized to 100% or 80% will make for a measurable difference, but not for an audible one.

The results depicted in Figs. 2 and 3 were obtained from two different pickups. The question which differences exist between Alnico-2- and Alnico-5-magnets can only be answered using *one and the same coil* (**Fig. 4**). This coil was measured without magnets (= air coil), and again with six Alnico-2- and Alnico-5-magnets, respectively. The magnets were fully magnetized. We can clearly see a difference between the situations with and without magnets. The difference between Alnico-2- and Alnico-5-magnets, however, is – at **0.8 dB** – so small that the *spectral* effects remain inaudible (effects on loudness will be discussed below).

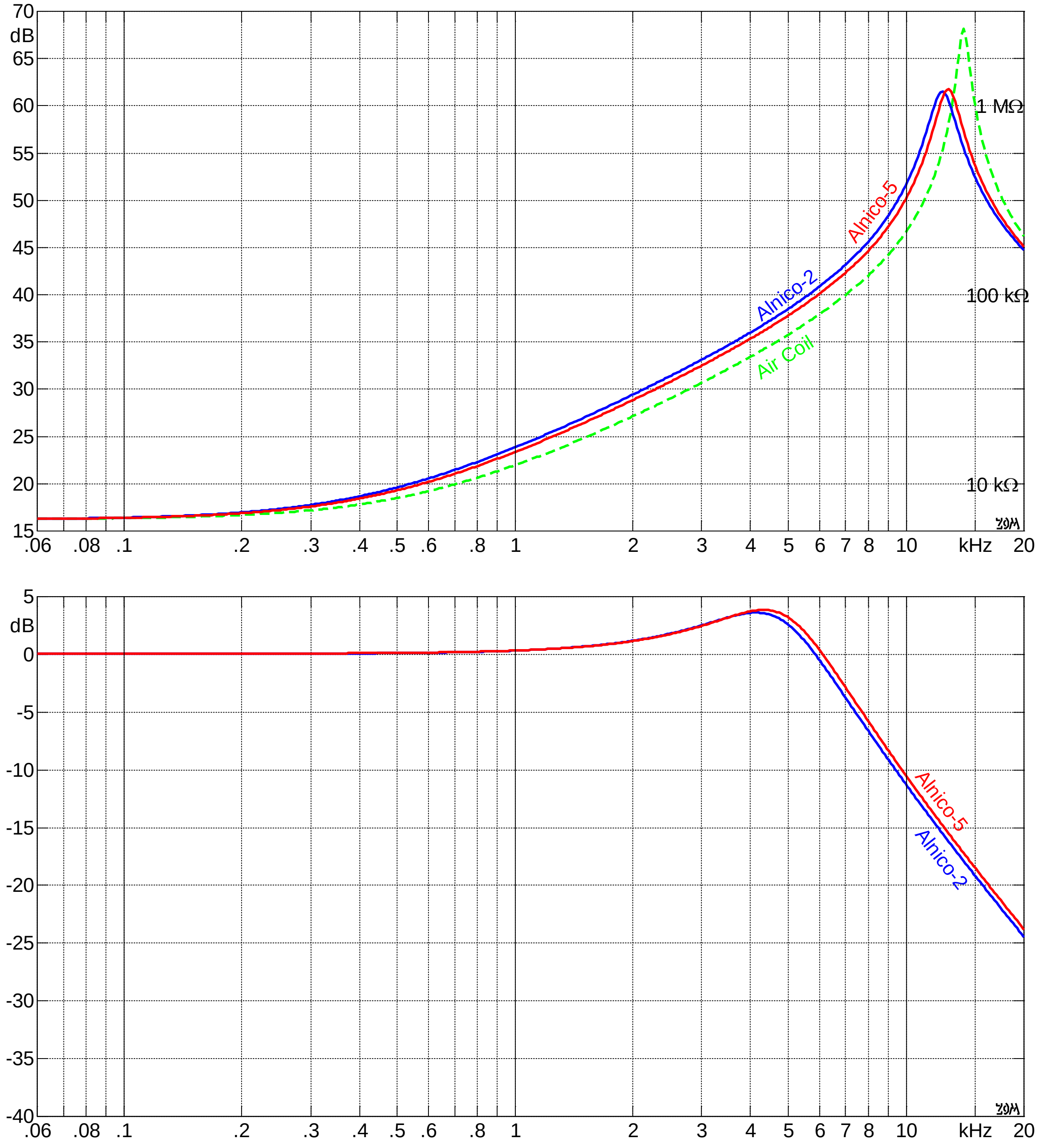

Fig. 4: Top: pickup impedance without magnets (air coil), and with various Alnico-magnets, respectively. Bottom: transfer function for Alnico-2 and Alnico-5, load = 450 pF // 111 kΩ (cables, potentiometers, amplifier).

Fig. 5 shows corresponding experiments with double the coil length of the pickup. Again, the differenced are very small and comparable to those found in Fig. 4. A cross-section of the pickups may be seen in **Fig. 6**.

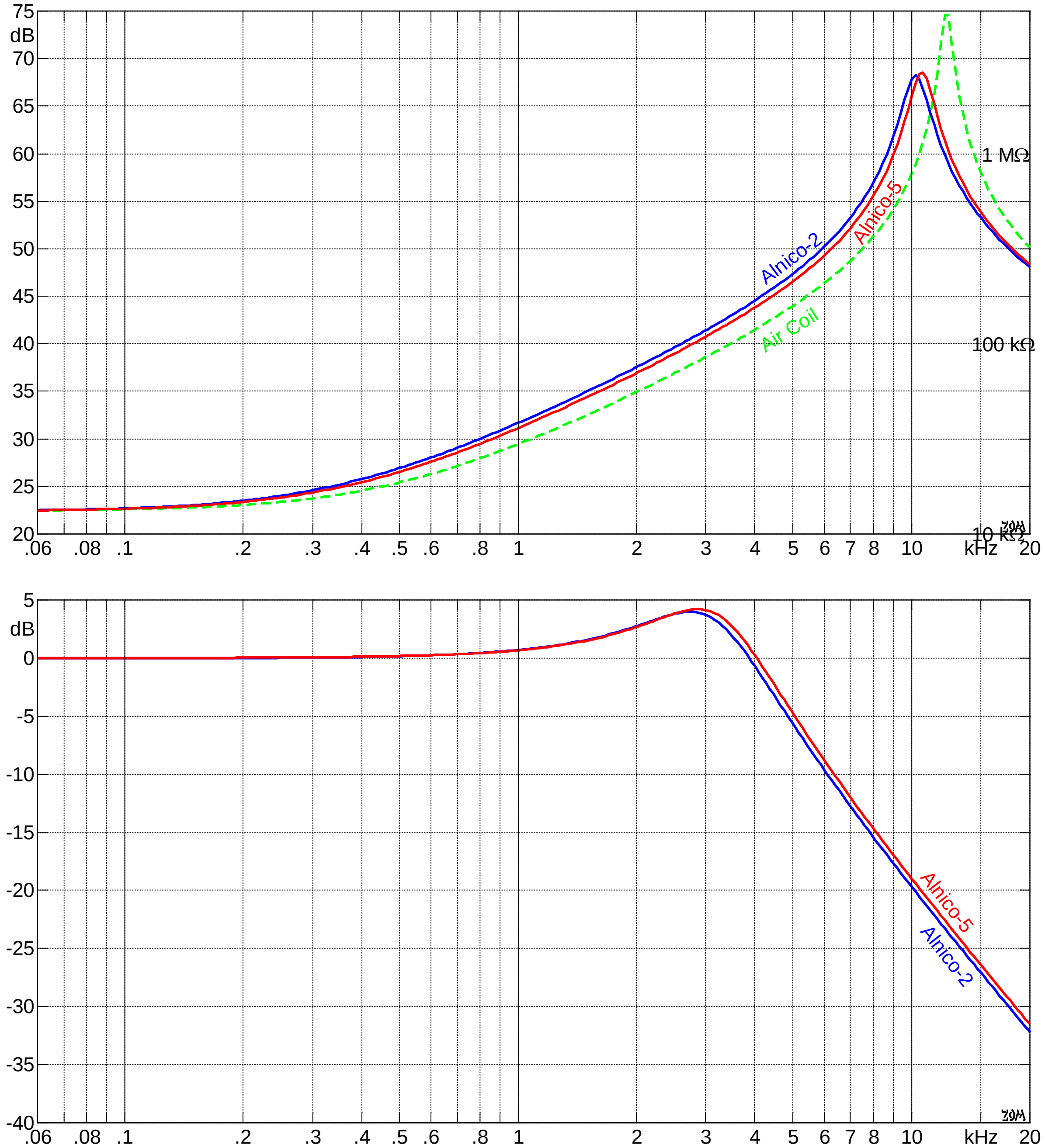

Fig. 5: Top: pickup impedance without magnets (air coil), and with various Alnico-magnets, respectively. Bottom: transfer function for Alnico-2 and Alnico-5, load = 450 pF // 111 kΩ (cables, potentiometers, amplifier).

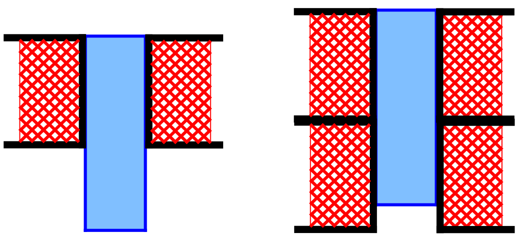

Fig. 6: Coil with magnet (left), two coils with magnets connected (in phase) in series (right).

 Translation by Tilmann Zwicker

The results in numbers: the difference in inductance between fully magnetized magnets and fully demagnetized magnets amounts to 7% for Alnico-2-magnets (Fig. 2), and to 13% for Alnico-5-magnets (Fig. 3). The difference in inductivity between the coil fitted with six Alnico-2-magnets and the coil fitted with six Alnico-5-magnets is 7,5% (Figs. 4 to 6).

We need to remind ourselves that there is not one single magnetic material designated Alnico-2 and Alnico-5, respectively [1]. Rather, these designations stand for a group of magnetic materials with similar but by no means identical characteristics. When ordering e.g. Alnico-2-magnets, it may even be questionable whether in fact a material from that group will be delivered – or possibly Alnico-3 having very similar characteristics. These materials cannot be distinguished by their look. The results given above were taken using magnet-cylinders sourced from a US-manufacturer supplying pickup parts – hoping that indeed they were of “the” typical material…

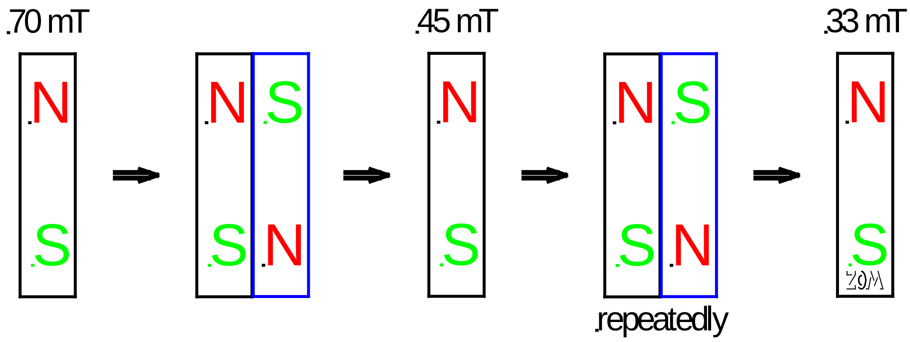

Fig. 7: Demagnetization of an Alnico-5-magnet due to inappropriate handling.

It is purposeful that these magnets were shipped from the U.S. in a demagnetized state. Actually, the bad habit to ship pre-magnetized slugs stuck together in a ball has the consequence of partial demagnetization. **Fig. 7** shows (on the left) a fully magnetized Alnico-5-magnet with a flux density of about 70 mT. Just sticking it on its side to a similar magnet makes both magnets loose about one third of their magnetization. Repeating this process several times on different sides of the magnet even creates a loss of as big as about 50%. For that reason do take note: if you handle pre-magnetized magnets, stick them together exclusively on their end face, and remove them from each other via purely axial movement!

In addition to the singlecoil-measurements discussed above we investigated the question whether the results found with cylindrical magnets also hold for bar-magnets. Different bar-magnets were inserted into a Gibson humbucker (60’s vintage, T-top coils): the old original magnet, Alnico-2 rough and smooth, Alnico-3 rough, Alnico-4 rough, and Alnico-5 rough and smooth. A rough surface of the magnet indicates a cast magnet while sintered magnets (or such having been sanded down) feature a smooth surface. To cut a long story short: the spectral differences are even (much) smaller than those found for singlecoil pickups. This is not really surprising since the magnet is positioned <u>below</u> the coils, and therefore is permeated by next to no alternating flux [1]. The impedance-frequency-responses differ by less than 0.4 dB; this difference is inaudible. **Fig. 8** shows merely the borders of the range in which all seven bar magnets were measured. The results for Alnico-2 and Alnico-3 are close to the upper impedance curve, those for Alnico-5 close to the lower curve. The original magnet and the Alnico-4 are positioned in between. There were no significant differences found between rough and smooth magnets.

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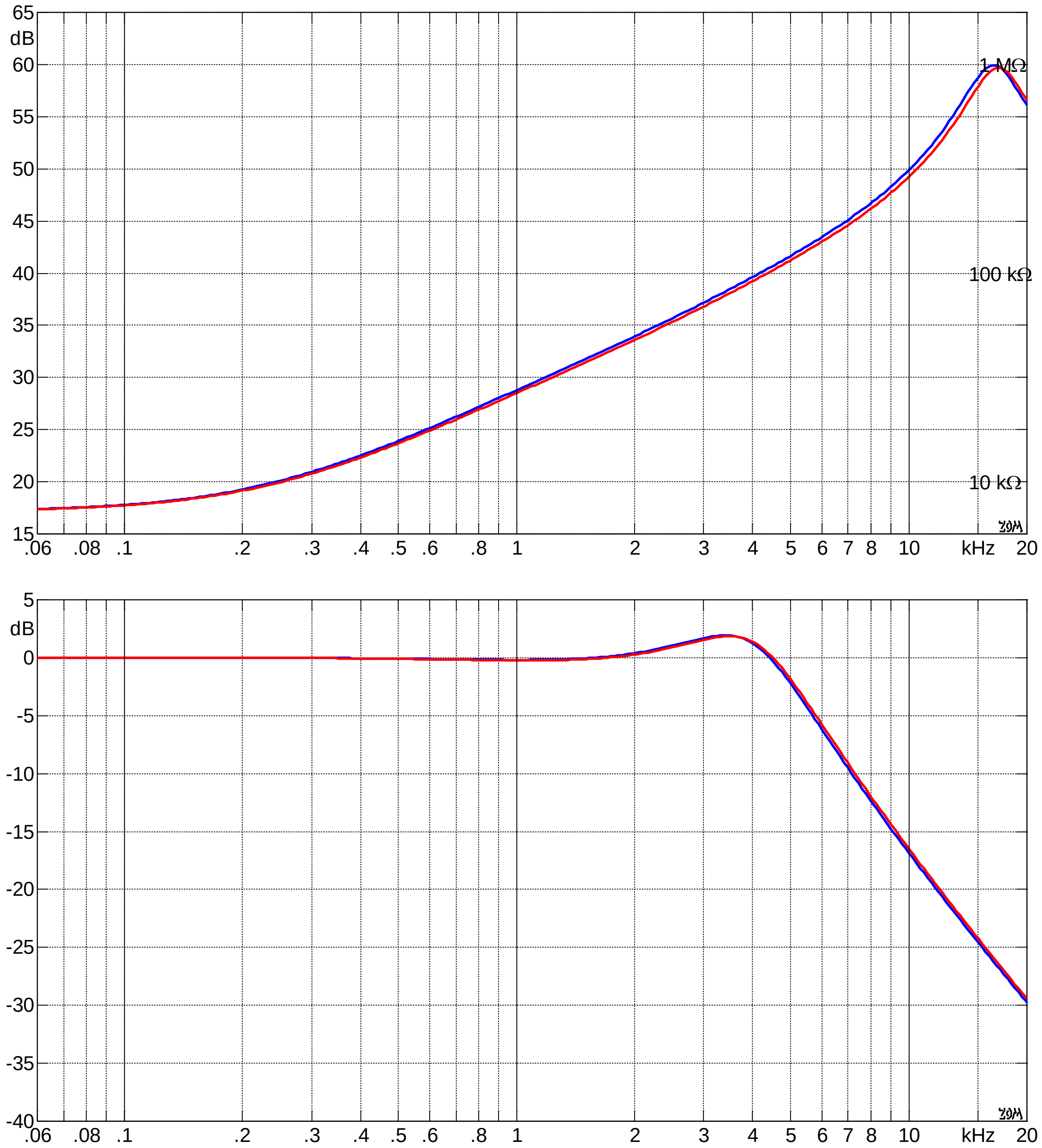

Fig. 8: Maximum differences in impedance and transmission, seven different bar magnets.

It was already mentioned several times that the *spectral* differences are too small to be audible. Now, however, we do arrive at the salvation for all those who find it impossible to believe that all magnets generate the same sound: the sensitivity (**loudness**) of pickups with different magnets and otherwise equal build is of course different, after all! All transfer functions shown here were referenced to 0 dB at low frequencies to enable the reader to compare the *relative* shape of the curves. The absolute (vertical) position of the curves is, however, different: the stronger a magnet is, the more sensitive the pickup is and the higher the transmission coefficient. To determine the "strength" of a magnet, its magnetic flux density was measured with a precision gauss-meter at a distance of 2 mm. Cylindrical Alnico-2-magnets yield about 35 mT and Alnico-5's yield about 60 mT – if they are fully magnetized (not often the case for commercially available magnets).

Checking the absolute transmission coefficient showed proportionality in good approximation: double the magnetic flux density gives double the voltage. The voltage output of a pickup can therefore double (or drop to half its value) if the magnet(s) is (are) exchanged. With the same setting on the amplifier, the pickup will sound louder or softer, and distort more or less easily. Since in almost all tube amps (we're using only that kind, aren't we?) the volume control is located after the first tube stage, there will be differences in the **distortion–behavior** even if we change the volume setting to compensate for the loudness change of the pickup (in order to obtain a fair comparison). On the other hand, changing the volume setting, however, may very well introduce changes in the sound – but those are due to the amp (!) because the operation of volume potentiometer will include a dependency on frequency (at least in most tube amps). The pot will have e.g. 1 MΩ, and the Miller capacitance in the following tube stage will generate a treble loss depending on the setting of the pot. It gets (far) worse if the compensation for equal loudness is done at the guitar – for passive guitar circuits, anyway. Changing the setting of the guitar-volume-control will introduce sound changes due to the guitar circuit [1, Chapter. 9], not due to the magnet. For active guitar circuits, this issue may be dropped – but here we need to check whether the preamp (often merely a single FET) is operating still in its linear range.

Another parameter that may change as magnets are swapped is the **width of the aperture** [1]. For Alnico-5 a somewhat narrower aperture window was found. This gives the bass strings a little more treble.

In summary: swapping magnets (e.g. Alnico-5 for Alnico-2) reduces the inductance of the coil and at the same time the aperture window becomes narrower. Both effects manifest themselves weakly. Under laboratory conditions, one may find a slight treble gain for singlecoil pickups. For humbuckers, the differences are insignificant. Important, however, is the difference in sensitivity which can easily amount to 6 dB and lead to differences in the transmission behavior of the amplifier. When using after-market magnets, one should be mindful of professional storage and handling. For example, two magnets bought from the electronics supplier Conrad had lost half of their magnetization. It is easy to imagine what happens if a guitar player installs such magnets and then posts the results on the world-wide-web …

Instead of Alnico alloys, hard ferrites (**ceramic magnets**) are also common for use in pickups – next to never within coils, but certainly below the coil(s), both in singlecoil and humbucker configurations. Pioneer Leo Fender started building pickups with cylindrical Alnico-magnets with a length-to-diameter ratio of about 3 – 4. This is ideal for most Alnico alloys but not for ceramic magnets. To fit a singlecoil pickup with a ceramic magnet, it is not sufficient to simply swap the Alnico cylinder for a hard-ferrite cylinder (you may do that but the result will not be satisfactory). Rather, the six Alnico-cylinders are replaced by six iron-cylinders, and a ceramic bar-magnet is installed below the coil. We will not look at this approach any further in the present context since additional parameters come into play (e.g. the permeability of iron). What is worth the while here is taking a look at humbuckers: their Alnico-bar-magnet may easily be exchanged for a ceramic bar-magnet. Except for the resulting change in magnetic field strength, the coil inductance will also change – but does this have a noticeable effect? It is known that the reversible permeability of ceramic magnets is almost equal to that of air [1], i.e. it is smaller that that of any Alnico-magnet. Consequently, the inductance will drop. **Fig. 9** shows how much. There's nothing more to add.

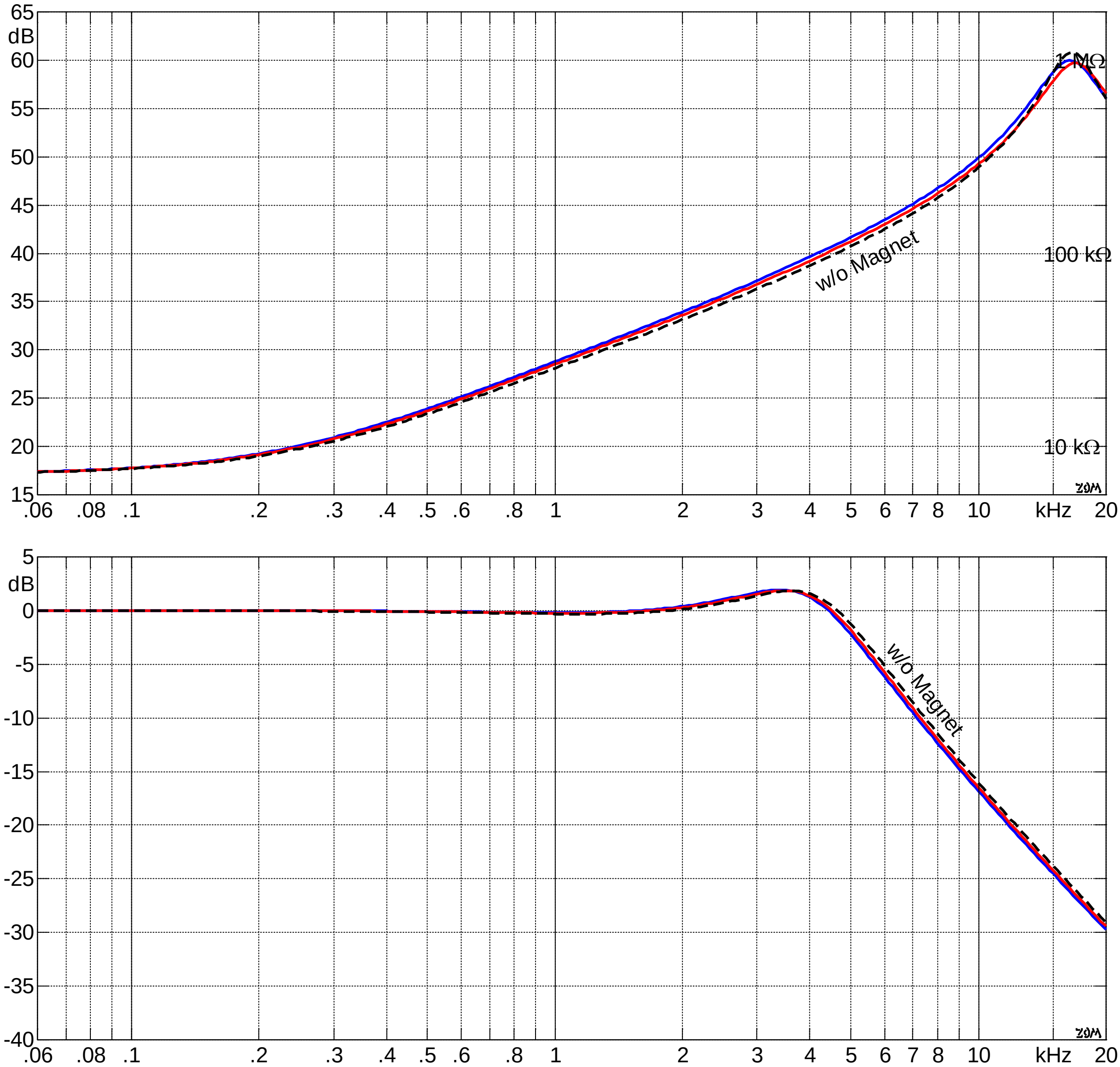

Fig. 9: Differences in impedance and transmission. As a supplement to Fig. 8, the measurement "*entirely without magnet*" is included (---), in the lower part of the figure as theoretical result, and for the operation with ceramic magnet, respectively.

Literature: [1] Zollner M.: **Physik der Elektrogitarre** (Physics of the Electric Guitar), www.gitec-forum.de.

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