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.

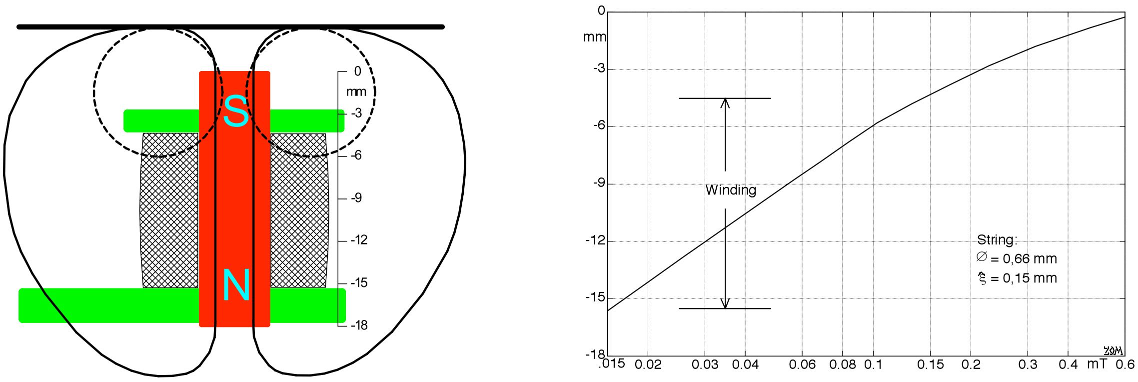


Fig. 5.4.13: magnetic flux for a Stratocaster-pickup (left, schematically). The static flux runs through the whole cylindrical magnet (——), the alternating flux mainly circles close to the strings (----). On the right the decrease of the density of the alternating flux along the axis of the magnet is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

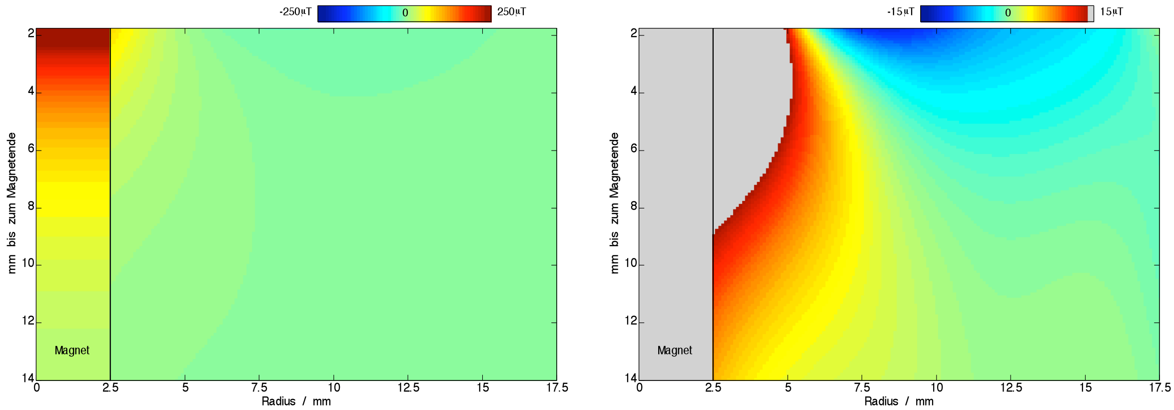


Fig. 5.4.14: Alternating magnetic flux density around an alnico-V magnet. The color-coding exemplifies the distribution of the flux density: the scale for the left section is such that the flux-density distribution within the magnet becomes visible; the scaling on the right clarifies the flux density 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.

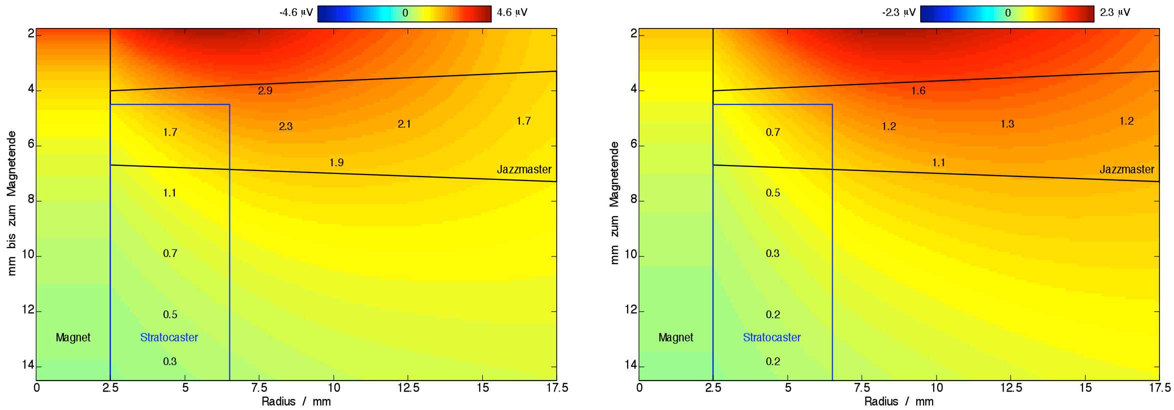


Fig. 5.4.15: alternating voltage in the winding dependent on the number of turns and the distance to the pole plate. The coil cross-sections marked are those for Stratocaster- and Jazzmaster-pickups. On the left, the distance between string and magnet is 2 mm, on the right it is 4 mm. The numbers entered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

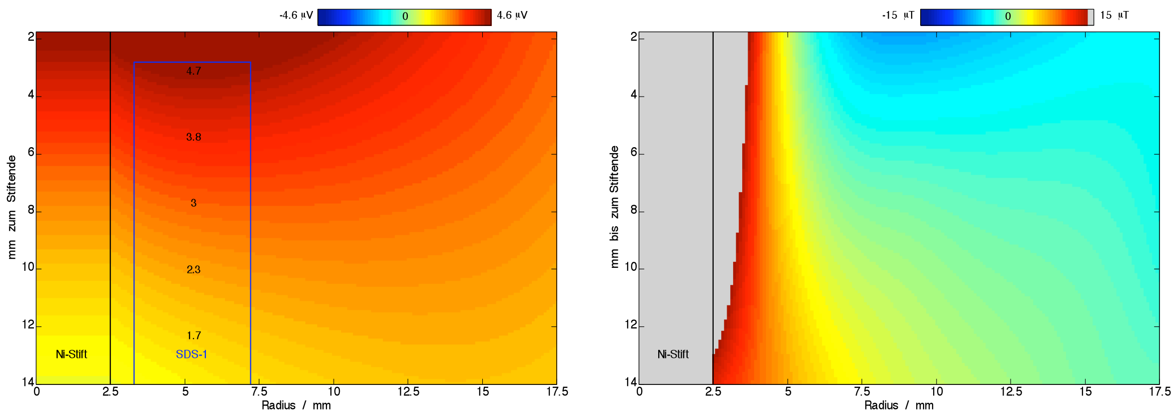


Fig. 5.4.16: for a nickel cylinder (5 mm x18 mm) with two bar magnets (3 mm x13 mm); voltage in the winding (left) and magnetic flow density (right). d = 2mm.

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).

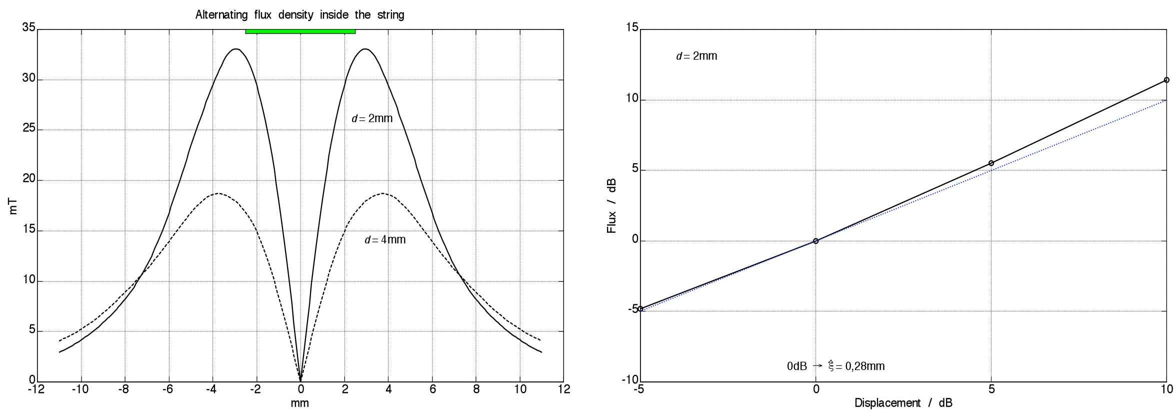
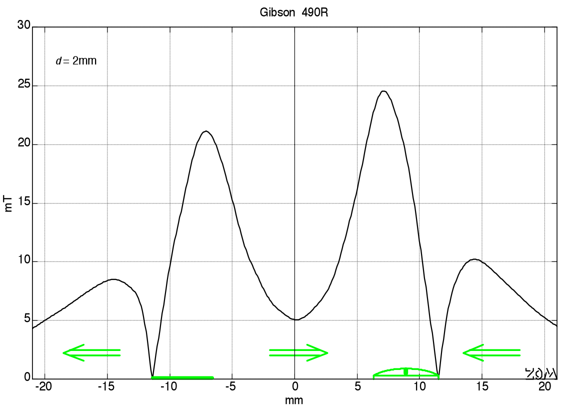


Fig. 5.4.17: String-internal axial alternating flux-density (RMS value). The diameter of the cylindrical magnet is marked in grey. On the right the normalized drive-dependency of the alternating flux density.

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.



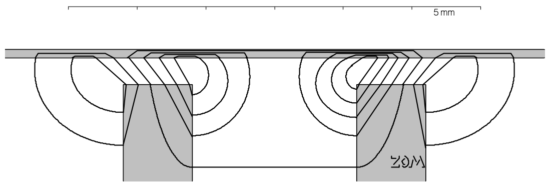


Fig. 5.4.18: left: string-internal axial alternating flux density for a humbucker (measured RMS values); above: approximate course of flux.

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).

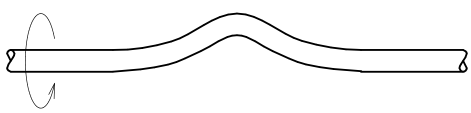


Fig. 5.4.19: Rotating steel string with crank.