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.

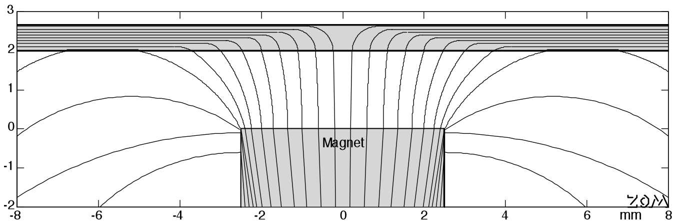

Fig. 5.4.8: Magnet, string, flux lines. The shape of the field is not calculated exactly but shown as a simplification

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.

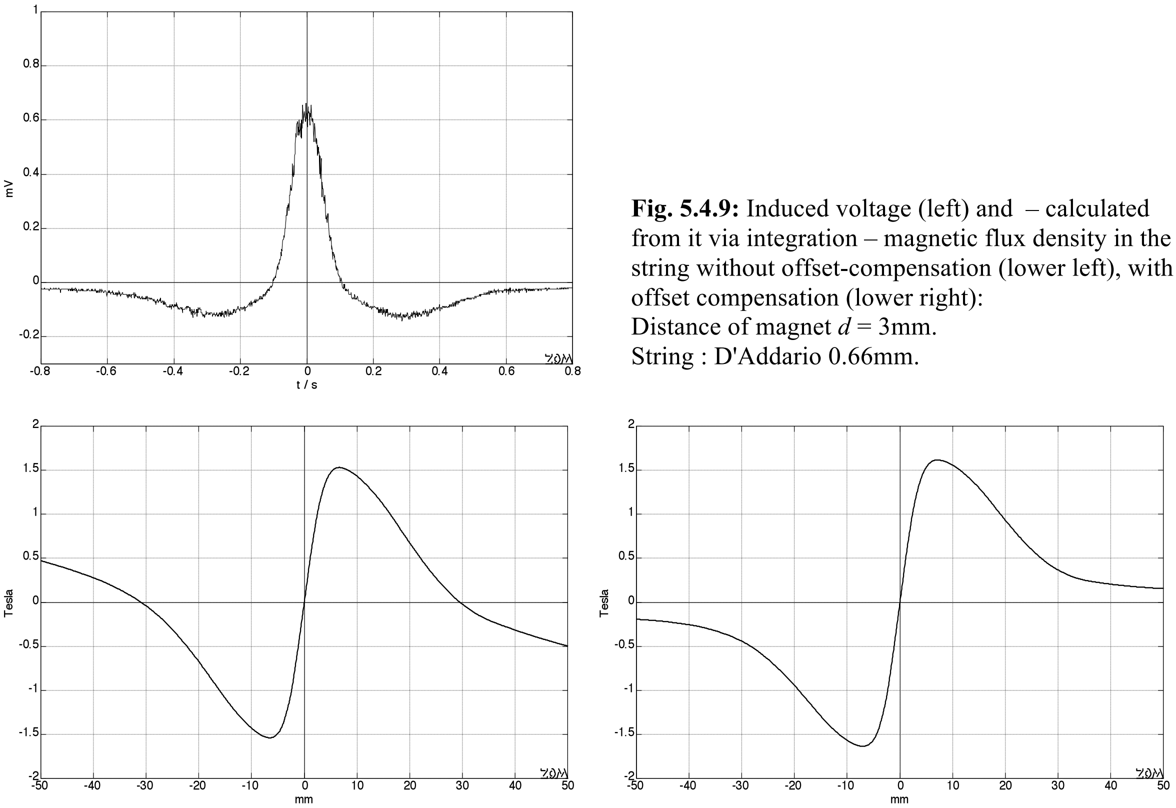

Fig. 5.4.9: Induced voltage (left) and – calculated from it via integration – magnetic flux density in the string without offset-compensation (lower left), with offset compensation (lower right):
Distance of magnet d = 3mm.
String : D'Addario 0.66mm.

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.

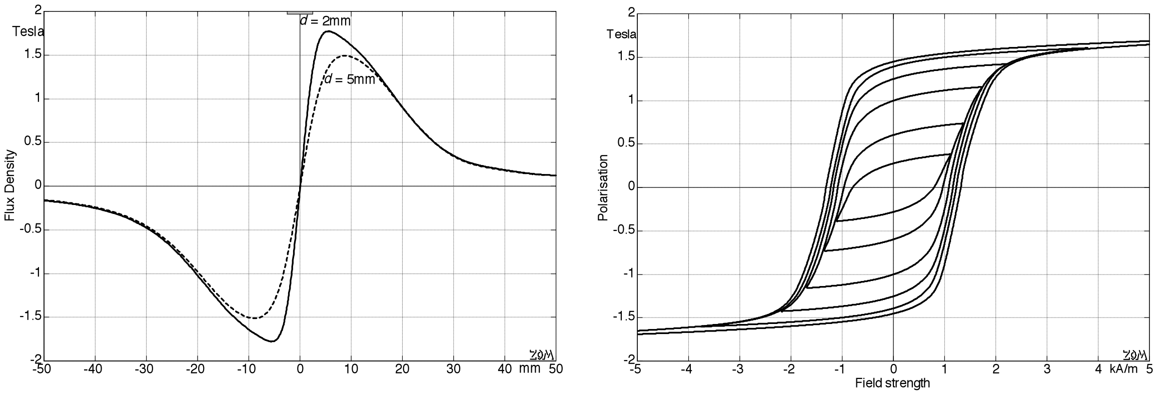

Fig. 5.4.10: Axial magnetic flux through the string for *d* = 2mm / 5mm (left); string-hysteresis (right).

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).

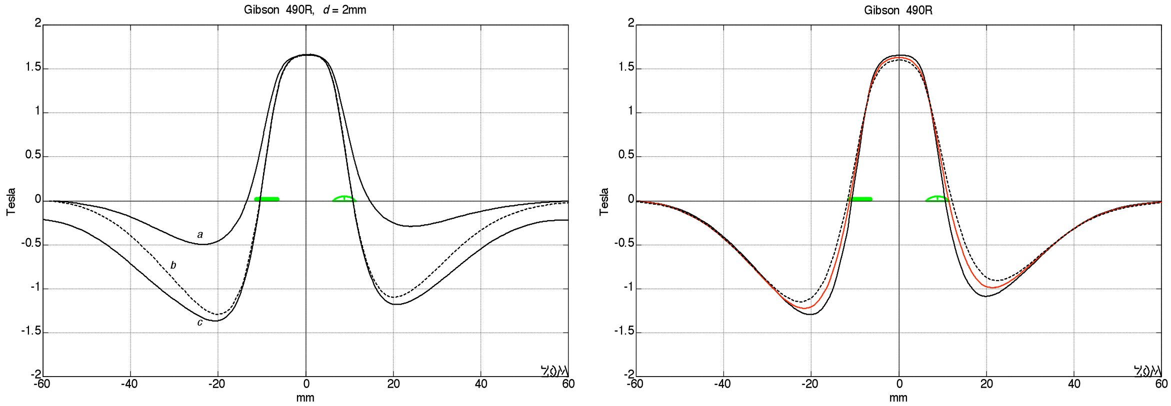

Fig. 5.4.11: Axial flux density through the string for a Gibson-Humbucker 490R. **Left**: *a* = un-magnetized string. *b* = magnetic poles at 2 mm after touching (*d* = 0) the string, *c* = after magnetization of an extended part of the string. **Right**: magnet/string-distance = 2, 3, 4mm, each after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

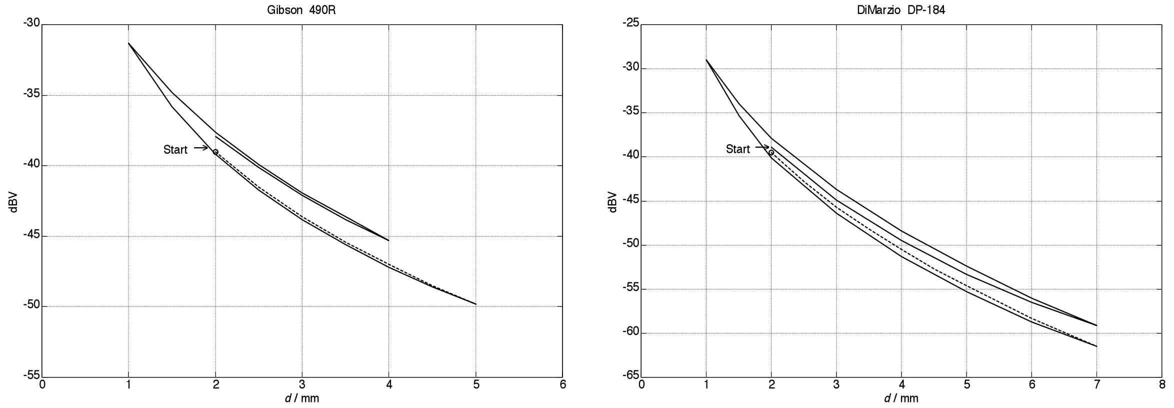

Fig. 5.4.12: Dependency of the induced voltage level on distance. Engine bench testing, rotating crank .

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.