What the Pickup "sees": its Aperture

Manfred Zollner

The aperture, that is the window though which the pickup "looks" at the string and samples it. A magnetic pickup is most sensitive to those string vibrations that happen immediately ahead of the pole-plate of its magnet(s). The further the string movements occur away from the pole-plate, the smaller the voltage generated by the pickup is. Accordingly, a position-dependent sensitivity-function can be derived that can in turn be recalculated into a spectral sensitivity function. The latter generally features a low-pass characteristic: high-frequency components are attenuated – and this happens increasingly as the local aperture function becomes wider. In the following, measurement-results regarding the aperture damping, taken from several magnetic pickups, are presented.

The treble-damping caused by the aperture can be easily explained using the example of the sound-on-film process: the (optical) audio track of a film with sound is comprised of different blackening of the corresponding area on the film. Sampling it with a narrow band of light will illuminate the sensor (a photo-diode, or the like) to a different degree depending on the blackening. In **Fig. 1** the film runs horizontally, while the (sound-) sampling is done with an optical slit oriented transversely to the flow of the film. The slit averages the light intensity. If the width of the slit corresponds exactly to one wavelength (or multiple integers), a zero in the transmission will occur. This is because the intensity of the light in the slit will not change as the film moves. The resulting mapping-error is part of a filtering that may be easiest illustrated with an impulse response.

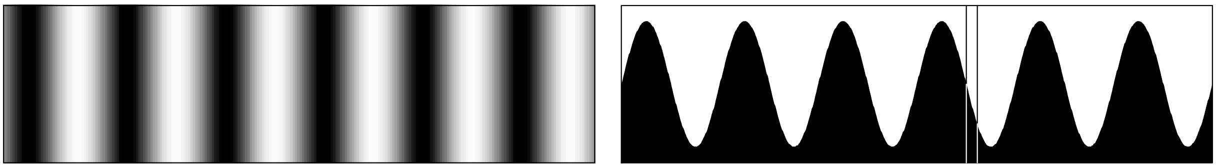

Fig. 1: Sine-shaped transparency in the film; intensity print (left) and transversal print (right). On the right, a narrow sampling-fissure is indicated.

In impulse-analysis, a short impulse excites the system under investigation. The system "responds" with an **impulse response**. Systems theory [2] uses a Dirac-impulse for the excitation – but since this cannot be realized in practice, a short impulse of finite duration τ will be used here. The sampling-slit has a relatively longer duration w. The result of the sampling is a trapeze-shaped impulse elongated to $\tau + w$ (**Fig. 2**); it is mathematically described as convolution of excitation- and sampling-signals.

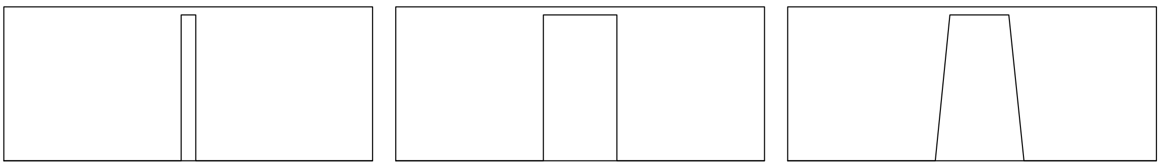

Fig. 2: Excitation impulse, sampling-slit, result of sampling. For more specifics, see [2, 3].

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For linear system the following holds: the time-function of the output signal results from convoluting the time-function of the input signal with the impulse-response of the system; the spectrum of the output signal results from the multiplication of the (complex) input-signal spectrum with the (complex) transfer function of the system [2]. Fig. 2 shows a short signal-impulse receiving a trapezoid lengthening as it runs through a broad sampling slit. Swapping the time-functions of excitation impulse and sampling slit yields the same result: the convolution is commutative. If the signal sampled by the slit is to receive the smallest distortion in its shape, the slit should be as narrow as possible: convolution with a Dirac leaves the signal unchanged: $x(t) * \delta(t) = x(t)$. The corresponding counter-productive issue here is that given an all-too-narrow slit, too little light-energy will be received by the sensor. The S/N-ratio becomes prohibitively small. We cannot count on infinite light-energy, either … i.e. a compromise is required.

In the frequency domain, the sampling via a slit has the effect of a **low-pass filter**. The broader the slit, the lower the cutoff frequency of the low-pass. The geometric width of the slit is recalculated via the speed into a time-function, the Fourier-transform of which yields frequency response of the transmission. For a movie with sound (and for a tape-recorder), 'speed' indicates the speed at which the film (or the magnetic tape) progresses. To – at last – shift our focus now to the **magnetic pickup**: here 'speed' means to indicate the velocity with which the transversal waves propagate on the string. Given a simplified consideration, this speed is about 100 m/s in the low E-string (E2). If the magnetic aperture were 1 cm wide, the corresponding travel time would be 0.1 ms. Let us first assume (as a simplification) that the aperture window is to be of rectangular shape: outside of the 1-cm-broad range the sensitivity of the pickup would be zero, and inside it would be constant (unequal to zero). In this case the corresponding Fourier-transform is the sin(x)/x-function – also termed si-function or (with a slightly deviating definition) sinc-function♣.

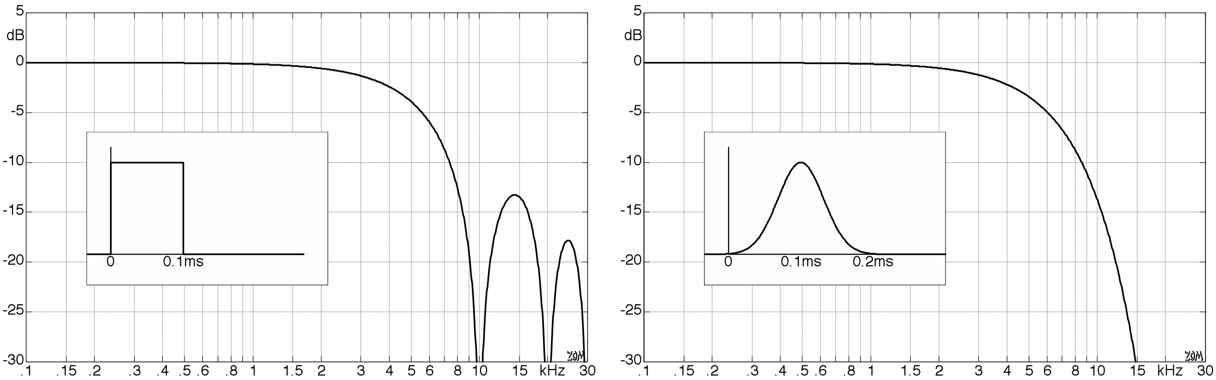

Fig. 3: Time-function and spectrum of two slit-functions: rectangular impulse and Gaussian impulse [3].

In its left-hand graph, **Fig. 3** shows the frequency response of the filter using level-scaling. There's 5 dB damping at 5,6 kHz – that would already be audible. However, several of our assumptions are speculative: the propagation speed, the width of the aperture, and the shape of the aperture. A rectangle-shaped sensitivity is not realistic; rather, we need to consider that the sensitivity will decrease gradually as the location of the string movement moves away from the magnet's pole plate. Thus, a better approximation is given by the Gaussian function as it is shown on the right in Fig. 3. Re-thinking is also required for the propagation speed of the transversal wave, because it is not constant but frequency-dependent (dispersive [1]). The higher the frequency, the faster the wave propagates. This reduces the wavelength at high frequencies … and that in turn reduces the aperture-damping.

♣ sinc(x) = sin(πx)/πx

The model-based considerations presented in Figs. 1 – 3 are well suited to illustrate the fundamentals behind aperture-damping. However, quantitative data for particular pickups would be of interest, as well. In order to obtain to those, an FEM-calculation would in principle be predestined – alas, the installed software♣ included too many errors which made for a 'mission impossible'. As long as the programmer is not aware of the difference between reversible and differential permeability, calculations regarding dynamic processes will have their limitations.

Measurements regarding the width of the aperture have already been presented in [1]; the results shall be quickly reiterated here. In order to measure the size of the window of the magnetic field with a reasonable effort, the following **experimental setup** was developed: a steel string (diameter 0.7 mm) of 12 cm length was bent in its middle to show a crank of about 2 mm length (**Fig. 4**). The string was then clamped to the shaft of an electric motor such that it could rotate around its longitudinal axis. Fixed to a carriage, the pickup under investigation could be slid back and forth along the string. The rotating crank in the string represented a place-discrete, time-periodic excitation i.e. a local impulse. The speed of the motor was not of relevance; it merely needed to be kept constant during the experiment. Sliding the pickup along the axis z of the string yields the local response function $a(z)$.

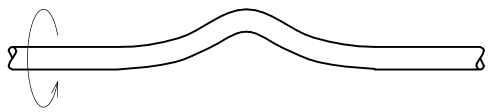

Fig. 4: Rotating steel string with crank.

If the pickup were a linear system, and if the crank would be limited to a very short range along the string, $a(z)$ could be interpreted as local impulse response. However, since the excitation impulse (the crank) has a length clearly different from zero, $a(z)$ represents a convolution of crank $k(z)$ and local impulse response $h(z)$. As a consequence, the measurement of the length of the window of the magnetic field has a tendency to give results that are a bit too large.

Of course, this measurement method clearly deviates from the excitation as it occurs in reality: in a plucked string, a transversal wave runs along the string while in the process described above a crank rotates. However, it is impossible to generate a singular impulse excitation on a freely vibrating string because the place of the deflection z (axial coordinate) and the time t are tied together via the propagation speed. Once generated, every transversal impulse runs along the string with high speed and therefore will not generate a stationary excitation. The rotating crank, however, allows for setting aside the place-time link that is obligatory in the transversal-wave equation, and for changing the place at will as slowly as desired (i.e. sliding the carriage to different positions).

For the following measurements, a Stratocaster-type coil was fitted with a cylinder-magnet (∅ 5mm, length 15mm; choice of Alnico-2, Alnico-3, and Alnico-5). The resulting pickup was now first brought to zero distance to the cranked wire (∅ 0.7mm), and then set to a distance of 3 mm. Subsequently, it was slid along the string while the induced voltage was measured at the same time. It makes a difference whether the pickup is brought to the measuring distance from far away, or whether it first fully approaches the string and is only then set to the measuring distance. This is due to the difference between differential and reversible permeability; increase and decrease of the magnetic field run on different HB-curves [1].

♣ Regular price just shy of € 20000.-, no less.

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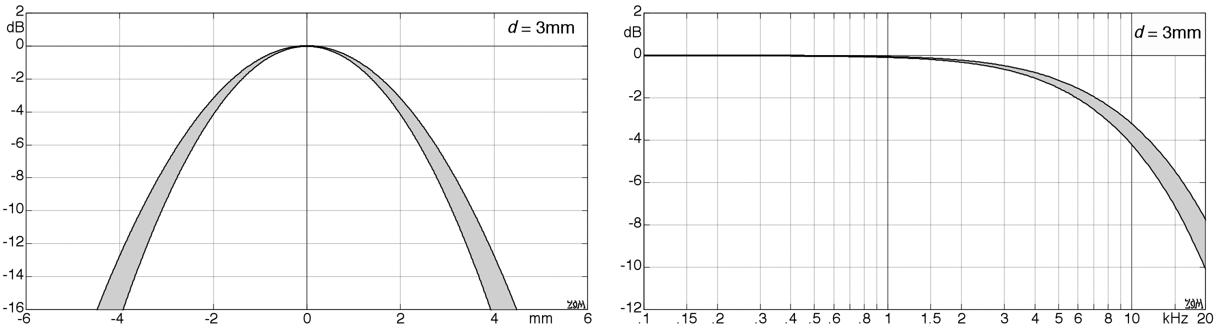

Fig. 5: Measured aperture-function referenced to the maximum value; in space (left) and spectrally (right). The dispersion of the E2-string (b = 1/8000) has been considered for the transfer function [1].

Fig. 5 depicts the measurement results for a clearance of 3 mm between the pole-plate of the magnet and the string. If the crank rotates directly above the pole-plate, the voltage is at its maximum. As the crank is shifted by 4 mm, the voltage level drops already by 13 – 16 dB (with 14 dB representing a decrease to one fifth). The variance marked as grey area shows the differences between Alnico-2, Alnico-3 and Alnico-5. The somewhat stronger Alnico-5 magnet yields the inner curve, the other two yield the outer one. The Fourier-transform of the grey area is shown in the right-hand graph. Here, the frequency axis has been stretched to string-typical values in order to account for the **dispersive** wave propagation (for higher precision see [1]). Result: relative to Fig. 3, the treble-attenuation is reduced. As the distance between magnet and string increases, the aperture-window broadens (**Fig. 6**), and the treble-attenuation grows.

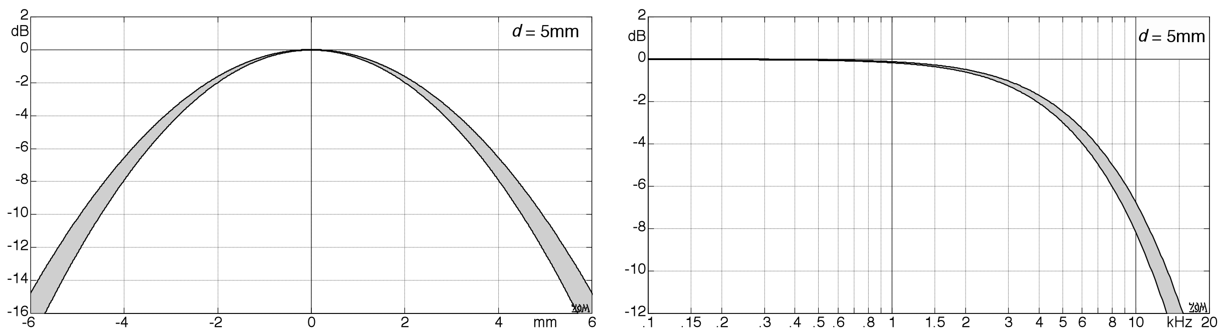

Fig. 6: As in Fig. 5, but for 5 mm clearance between pole plate and string.

In the book "Physics of the Electric Guitar", the aperture-damping was calculated also for other strings – assuming that the width of the aperture is the same for all 6 strings. Whether this assumption is correct would have to be verified with a modified test-bench; however, this will not be possible during this lifetime since in the meantime the lab has been dissolved and shut down. Still, a few models can help to show at least qualitative relationships. Three-dimensional FEM-calculations form the corresponding basis in the steady-state case (for the dynamic case, unacceptable FEM-errors occur♣). The calculations were done for a pickup fitted with an Alnico-5-magnet (∅ 5 mm, length 15 mm), and a clearance between magnet and string defined to be 4 mm. In the first place, the winding of the coils does not play any role because only the static magnetic field – which is independent of the winding – was calculated. The diameter of the string was assumed to be 0.2 mm and 0.7 mm. 0.2 mm – equiv. to 8 mil – is in fact already very thin. For both diameters, solid strings were assumed. The lower guitar strings actually are wound; the effective cross-section thus is smaller than the geometric cross-section; 0.7 mm is a reasonably compromise here.

♣ Again, the manufacturer of the software used was not aware of the difference between reversible and differential permeability.

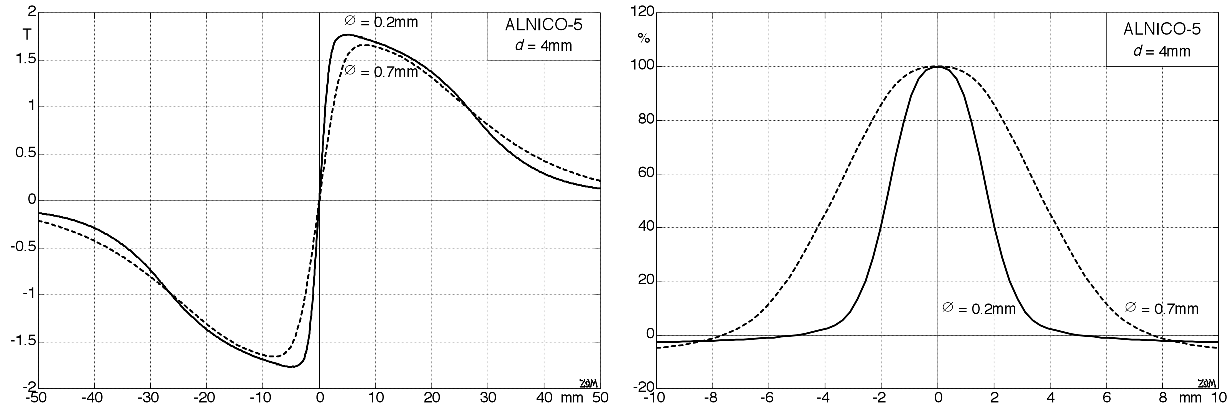

Fig. 7: Axial flux density in the string for different string diameters (left). On the right: radial flux density in the string referenced to the max. value (flux density in the mantle). For both: steady-state magnetic fluxes (DC-field).

The FEM-results are shown in **Fig. 7**. If we take the magnetic north pole as the pole plate, then the magnetic flux penetrates into the string directly above but leaves the string again after just a few millimeters. Since the magnetic flux extends in two directions within the string, the flux density depicted in the left-hand graph has two different signs. Its derivative *dB/dz* along the axial coordinate of the string is shown in the right-hand graph. The axial change of the axial flux is the section which penetrates the mantle-area, entering the string at the first few millimeters and leaving it again at a larger distance. Clearly visible: the thinner the string, the shorter the range in which the flux enters. While this is not yet the width of the AC-field-aperture, it provides a hint that should be taken seriously. The tendency is: the thinner the string, the narrower the aperture, and the smaller the treble-attenuation.

The above hypothesis received confirmation via an **AC-calculation**: the AC-field generated by a short coil encompassing the string decays more quickly the thinner the string is (**Fig. 8**). The permeability of the string μ_{rev} was assumed to be constant for this calculation – the FEM-software can then do the math.

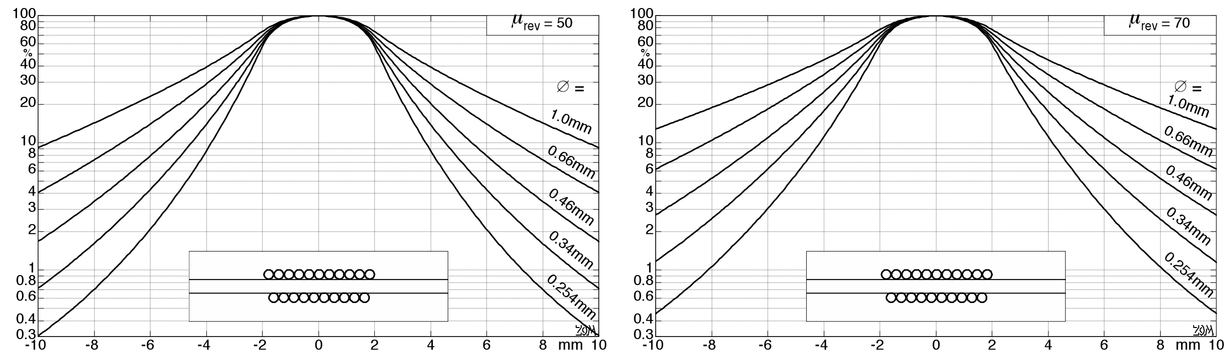

Fig. 8: Standardized axial flux density. AC-field-excitation with a string-encompassing coil of 4 mm length.

Figs. 7 and 8 give hints regarding the string-internal magnetic field but do not show the aperture-window. Comparing the measurement results (Figs. 5 and 6) with the DC-field generated by the magnet, the differences are unacceptably large (**Fig. 9**). This is despite the fact that there must be a relationship between the radial flux density in the string (flux density through the mantle) and the induced voltage: in those ranges where the radial flux density is zero, transversal movements of the string cannot change the magnetic resistance, and thus no voltage can be induced into the pickup coil. The DC-field therefore appears to be a necessary requirement for the transfer function but not a sufficient one.

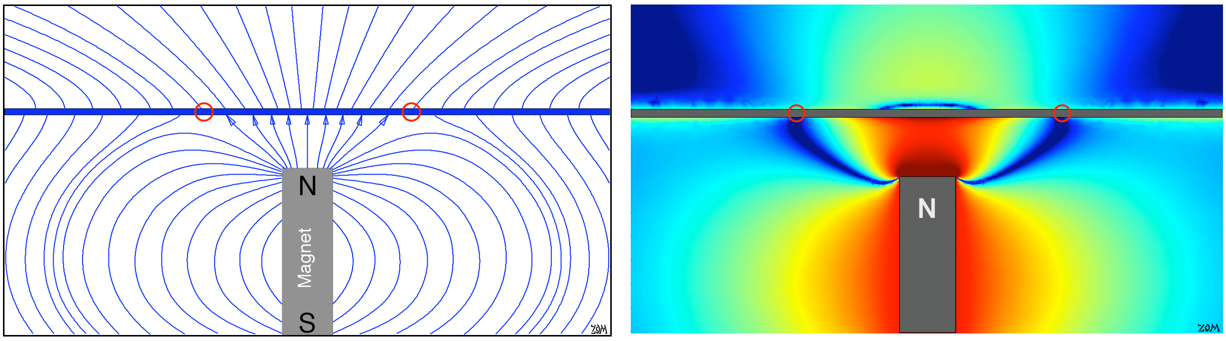

Fig. 9a: Steady-state magnetic field, flux lines (left). On the right the absolute value of the vertical component is depicted on a log scale; the color-dynamic is 45 dB. Alnico-5-magnet (5mm x 18mm), string diameter 0.66mm.

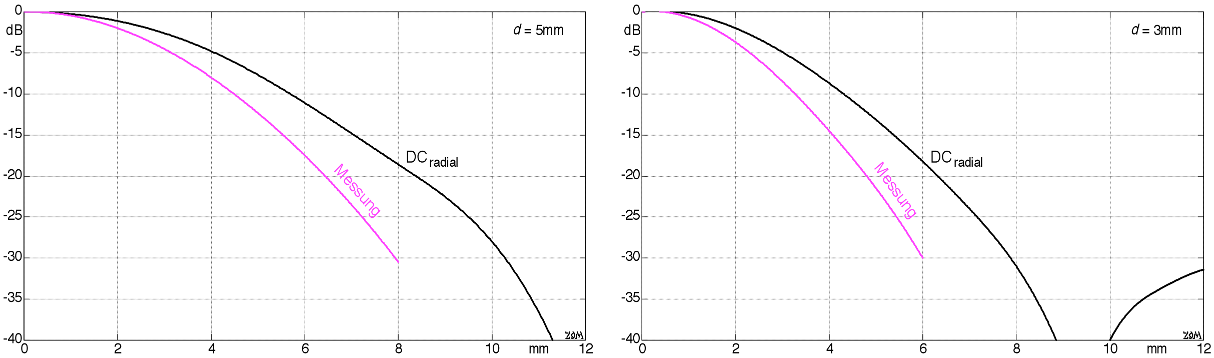

Fig. 9b: Calculated radial DC-flux density in comparison to the measured AC-level of the induced voltage; for two different string/magnet distances. Abscissa = horizontal distance to the axis of the magnet.

In **Fig. 9a**, in the left-hand graph, the magnetic DC flux is schematically presented. The field enters the string up to the range marked by a red circle; it leaves the string at larger distances. The right-hand graph shows – using color-coding – the absolute value of the radial flux density. This latter is small in the dark blue range, and large directly above the pole plate. If the string moves within a range of large radial flux density, a relatively large induced voltage results, and a small voltage occurs if the string moves within the small ranges marked with a red circle each. Of interest is the range beyond the marking: the radial flux density creeps back up to somewhat larger values but – by far – does not reach the values found directly above the pole plate. Still, completely gone it is not, either, and for this reason a secondary maximum exists, i.e. a kind-of "secondary aperture". In Fig. 3, a Gaussian curve was chosen as an approximation of the shape of the aperture; this is purposeful in close range to the pole plate. However, within the range marked by the red circle, at a distance of 9 – 12 mm, we find a zero. In this region, experimental proof cannot be achieved, though, because the string would have to rotate with a precision of 1 µm - that's not doable with justifiable effort. It's not categorically necessary, either, because the difference in the transfer function is insignificant. On the other hand, the discrepancy between the measured curve (compare Figs. 5 and 6) and the radial flux density (**Fig. 9b**) … that is significant. Something is still missing!

The multitude of different measurements and calculations finally developed into the following **function model**: The first term of the aperture function results from the radial component of the DC-field, modulated at the place of the string movement. The modulation (i.e. the change in the DC-field) is a local AC-excitation that propagates along the string – this is the second term. Finally, the strength (and the direction) of the AC-field generates the voltage induced in the pickup coil. Thus, two place-dependent damping processes are at the basis of the local aperture function: the decrease of the DC-field (source = magnet), and the decrease of the AC-field (source = string movement).

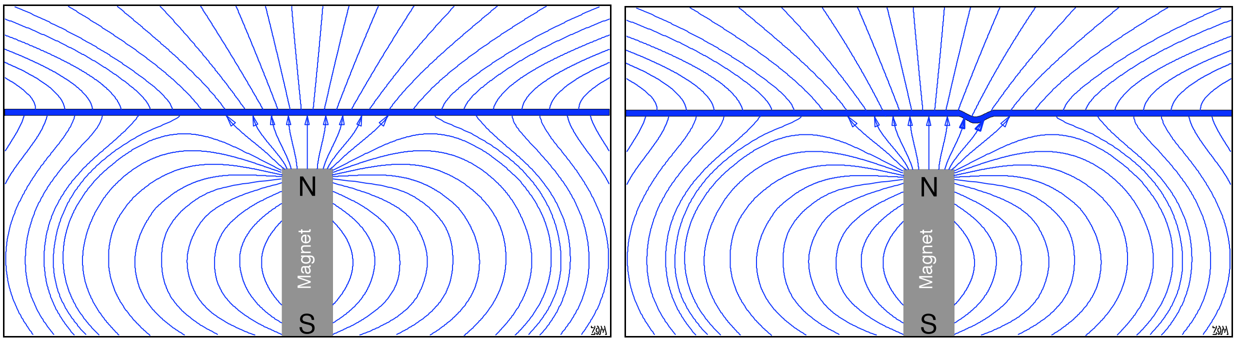

Fig. 10: Steady state magnetic DC-field; string without and with local crank.

Again, in more detail: an impulse excites the system (string, magnet, coil), and the transfer function is formed from the impulse response via Fourier-transform. This process is in fact only defined for linear systems – but corresponding linearizations are possible in the small-signal-range as approximation. The "impulse" is a small indentation running along the string and "bending" the magnetic field in the process. This makes for a change in the magnetic flux within the coil, resulting in an induced voltage. The left-hand section of **Fig. 10** shows the system without excitation, while on the right the excitation impulse is visible in the form of a crank (compare to Fig. 4). The FEM-software used here does correctly calculate the magnetic steady-state flux; still, it would be incorrect to derive the change in the field from the difference of two steady-state calculations (left-hand vs. right-hand graphs) – such modulations around an operating point are known not to run along the tangent of the curve (differential permeability), but along the considerably flatter recoil-line (reversible permeability [1]). Because it is exactly here that the FEM-software includes incorrect calculations, a model-consideration needs to take over. **Hypothesis**: the change in the field is largest in the vicinity of the crank; it is approximated by a small coil (operated with AC). The excitation coil is placed at a variable distance below the string, and for this setup the voltage induced into the pickup coil is calculated.

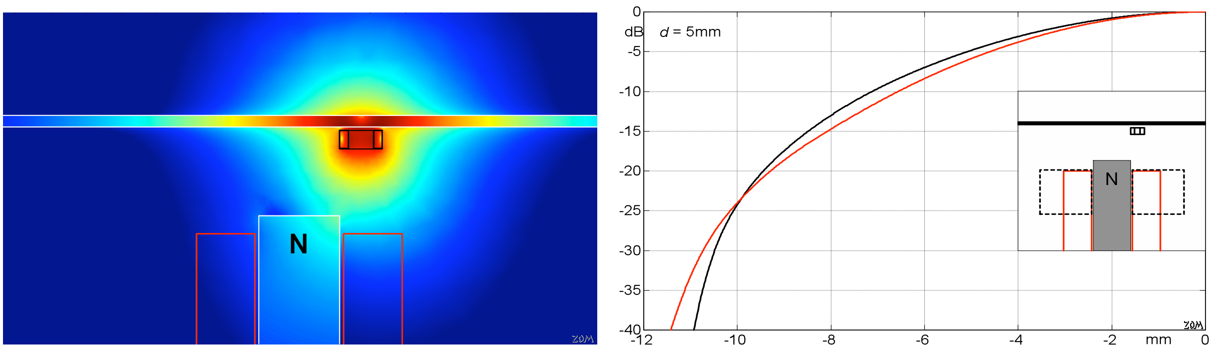

Fig. 11: The AC-field generated by an excitation coil placed below a string. On the right the voltage level.

In its left-hand section, **Fig. 11** shows the color-coded AC flux density; on the right we see the level of the induced voltage, referenced to its maximum. The abscissa is the distance of the axes of the two coils. The shape of the pickup coil has a slight influence on the run of the curve but for typical dimensions the differences are small. In Fig. 11, the same excitation current was used for every location of the excitation coil – however, the "impulse" (the crank) runs through ranges of radial fields of different strengths. For this reason the location dependency of the radial field (shown on Fig. 9) needs to be included in the calculation. The aperture function thus depends on two terms: on the radial DC-field that becomes weaker as the distance to the magnet axis grows (Fig. 9), and on the AC-field that becomes weaker with growing distance to the excitation coil (Fig. 11).

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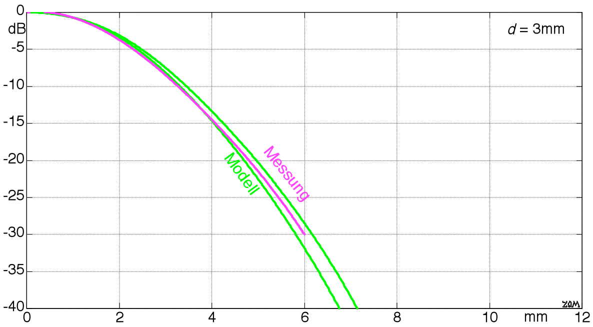

Fig. 12: Spatial aperture-function, model ("Modell") and measured values ("Messung").

The results are summarized in **Fig. 12** showing the measurement results taken with the rotating crank (Figs. 5 and 6) and with the curves calculated using the function model. Given that the material parameters are not know in detail, the correspondence can be seen as being very good. The excitation impulse depicted in Fig. 10 does not maintain its shape on a real string but becomes broader – however, this does not represent any problem: the dispersion is a linear operation that is considered in its own separate system.

The following is what we take from the above measurements, calculations and hypotheses: the magnetic aperture has the result of a treble damping on the low E-string (E2) which increases as the distance between the magnetic pole and the string becomes wider. In HiFi-circles, any enthusiast would find this effect (shown in Figs. 5 and 6) devastating … however, this is the guitar world: since a magnetic pickup acts as a low-pass filter [1], the frequency range above 5 kHz is insignificant, and the treble damping is barely noticeable. Moreover, the effect quickly drops further as we move to the higher strings (A, D, …) where it becomes completely irrelevant. To achieve a guitar sound that includes many harmonics, it is purposeful to place a single-coil-pickup fitted with an Alnico-5-magnet as close to the strings as possible, avoiding any metal parts that could carry eddy-currents. If – with such a setting – beats caused by the magnetic field become overly dominant, a compromise between trebly sound and beats needs to be sought (and found).

Translator's note: *it should be explicitly mentioned the above is particularly relevant for the classic Fender-type pickups with the magnets placed within the coils directly under and close to the strings. Single coils pickups and humbuckers with bar magnets placed under the coil and thus away from the strings have a more distributed magnetic field and a wider aperture to begin with –for these latter pickup types, bringing the pickup close to the strings will have a smaller impact on the sound itself (output volume is another topic not considered here).*

The model presented here (a combination of DC- and AC-field) is a simplification that makes the qualitative interrelations become visible. We should not expect precise quantitative results – the system is too complex for that. We are dealing with place-dependent (or flux-density-dependent) reversible permeability in the string, with anisotropic magnets (at least for Alnico-5), with non-linearities as the string is moving more strongly, and we would need availability of a particularly excellent FEM-software for the calculations. Well, that day may come … time will tell.

Further literature:

[1] Zollner M.: Physik der Elektrogitarre, www.gitarrenphysik.de;
Physics of the Electric Guitar, https://www.gitec-forum-eng.de/the-book/
[2] Marko H.: Methoden der Systemtheorie. Springer, 1986.
[3] Zollner M.: Signalverarbeitung, 2009. Bibliothek der OTH Regensburg (circulating).
[4] Zollner M.: Frequenzanalyse, 2009. Bibliothek der OTH Regensburg (circulating).

