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 $a(z)$.

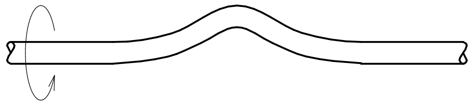


Fig. 5.4.19: Rotating steel string with crank.

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.

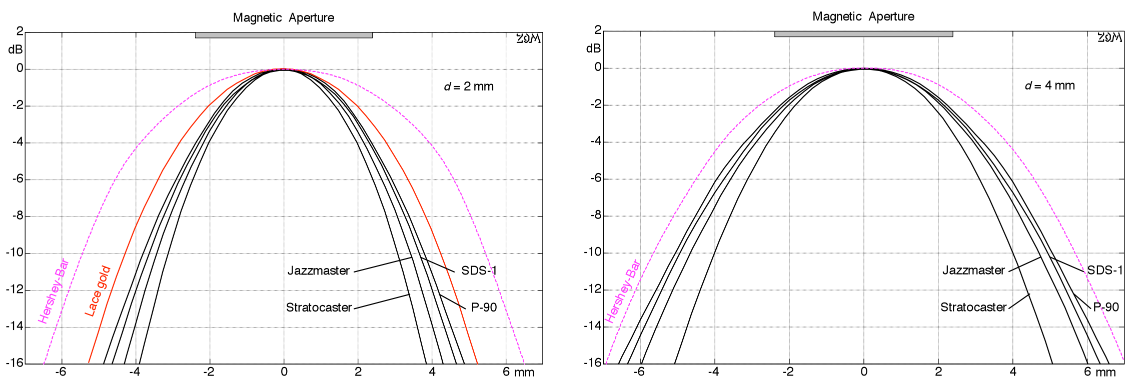


Fig. 5.4.20: local window-functions normalized to the same maximum. The width of the Jazzmaster's cylindrical magnet is included as a bar at the upper border of the figure. Pickups: P-90, SDS-1, Jazzmaster, Stratocaster. Lace: cf. Ch. 5.4.7, Hershey-Bar cf. Ch. 5.4.8.

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.

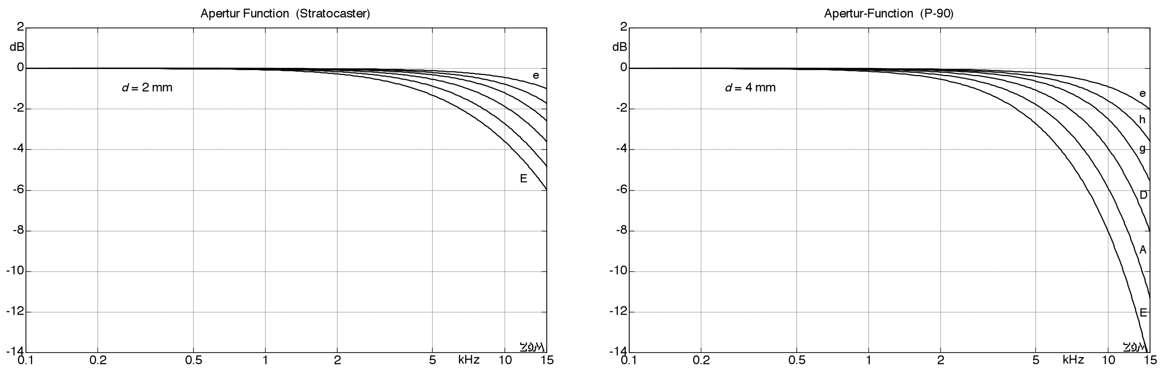


Fig. 5.4.21: frequency response (real part) of the magnetic aperture function; dispersion is considered.
Left: Stratocaster; distance magnet/string d = 2mm. Right: P-90; d = 4mm.

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).

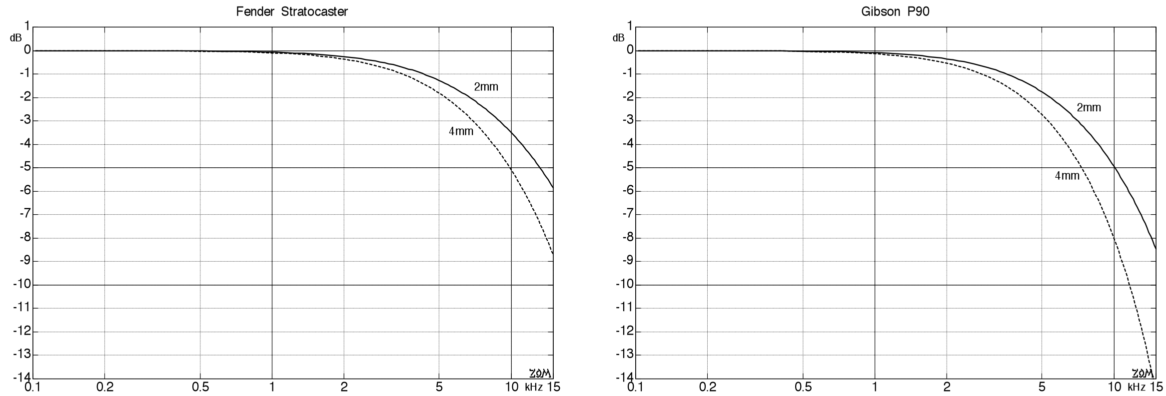


Fig. 5.4.22: Aperture-low-pass (E2-Saite) for 2mm and 4mm magnet/string distance. Normalized, dispersion is considered.

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.

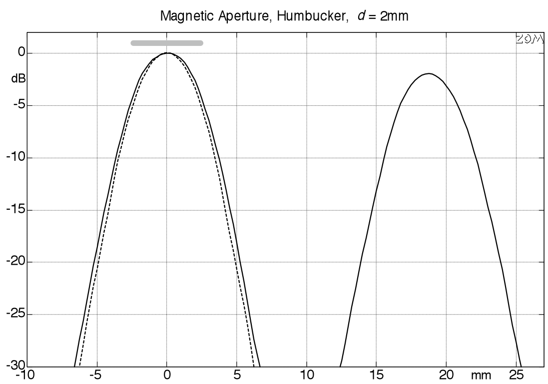
Using a logarithmic division of the abscissa (as it is done in the right-hand section of Fig. 5,4,23) and adding a fixed value *A* to the distance *d*, we obtain straight lines with good approximation. The distance function therefore is a power-function of the type:

$$L_U = 20 \cdot \log\left((d+\Delta)^{-\psi}\right) \mathrm{dB}$$ 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.



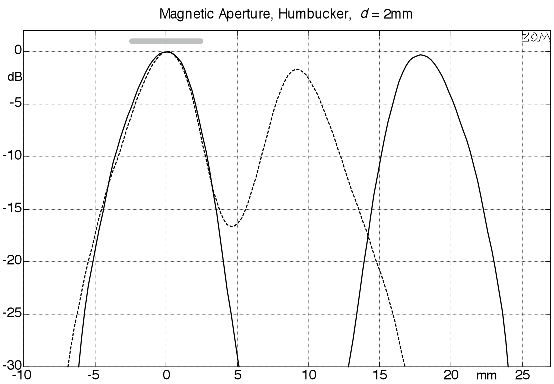


Fig. 5.4.24: local aperture functions normalized to the same main maximum (coils in series).
Left: typical Gibson-Humbucker, e.g. 490R; to compare: Fender Jazzmaster (----).
Right: Gretsch Filtertron (18mm pole distance), DiMarzio DP184 (7,6 mm pole-distance, ----);

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.

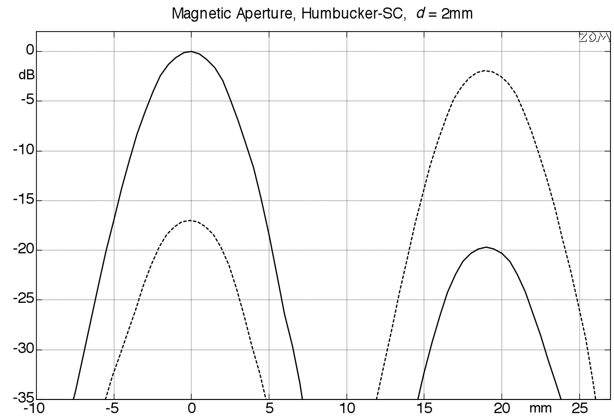
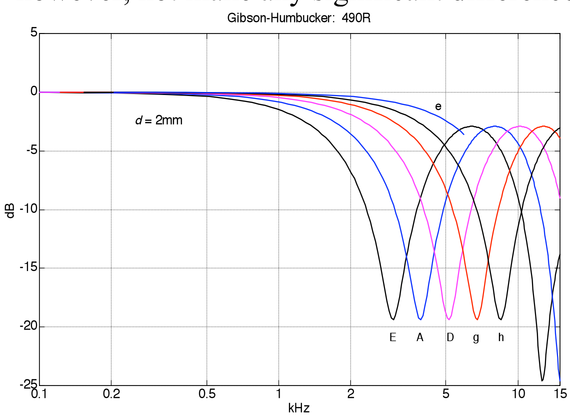


Fig. 5.4.25: same as in Fig. 5.4.24 but with the humbucker in single coil (split) mode. The result for the secondary maximum needs to be interpreted as 'in principle'; the measurement accuracy is mediocre at best here. Typically the secondary maximum is about 14 – 20 dB below the main maximum.

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.



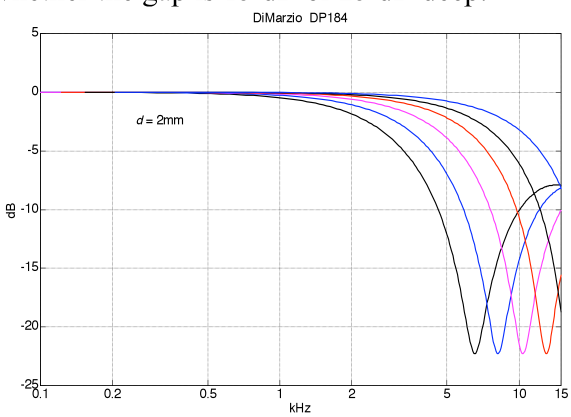


Fig**. 5.4.26:** calculated frequency response (real part) of the magnetic transmission function, with dispersion considered. Left: Gibson 490R, both coils in series. Right: DiMarzio DP-184, series connection.

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.

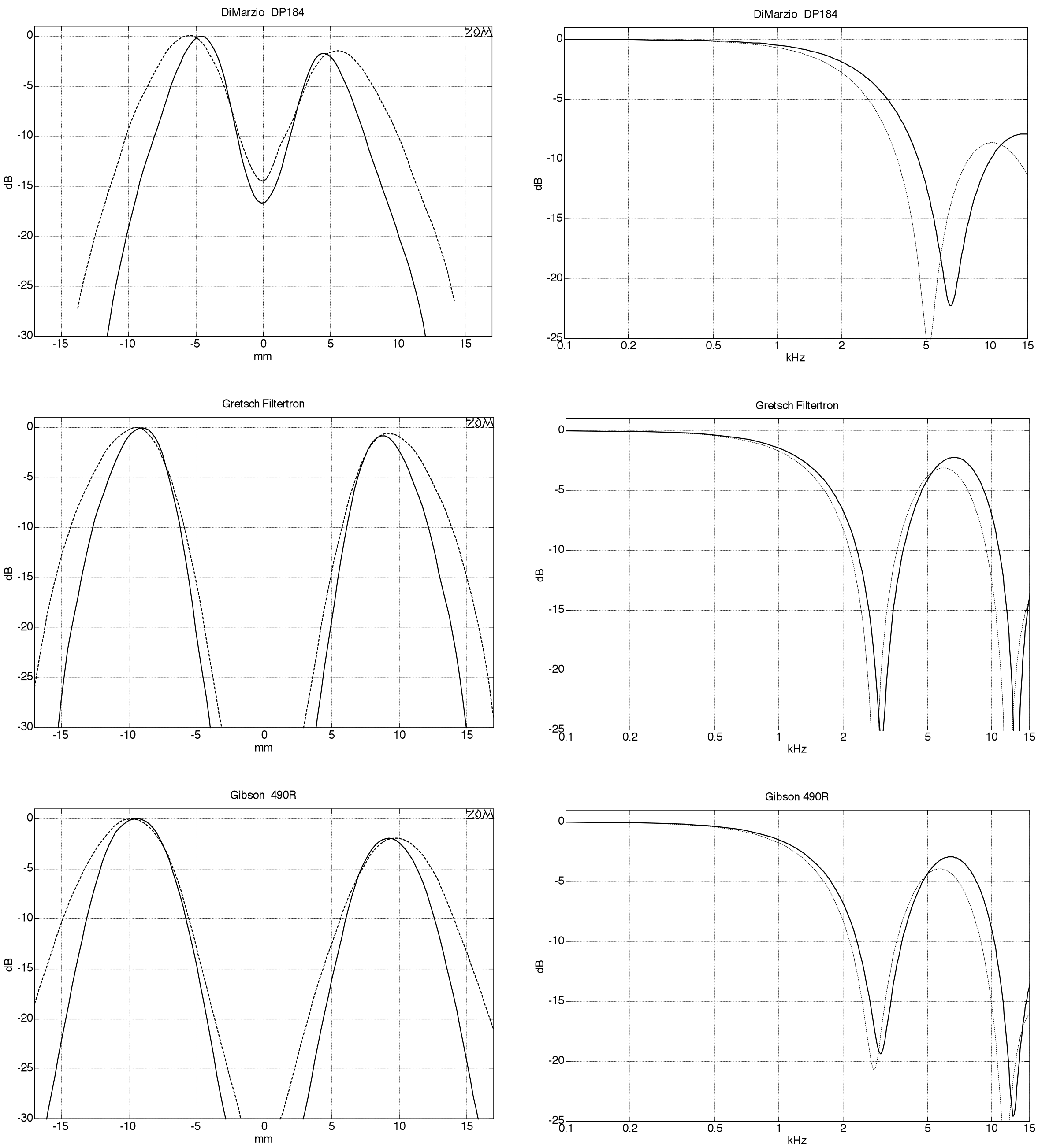


Fig. 5.4.27: left: normalized aperture window, string/magnetic-pole distance —— 2mm, ------ 4mm.
DP-184 (top), Gretsch Filtertron (middle), Gibson 490R (bottom).
Transmission behavior for the E2-string (right column).

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.

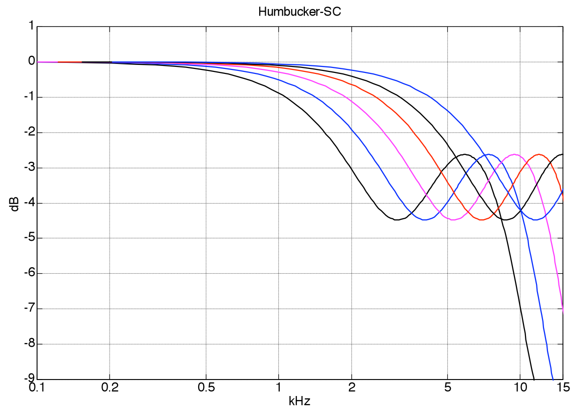


Fig. 5.4.28: Humbucker in single-coil configuration. The window-side-lobe is 14 dB below the main maximum in this example.

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).

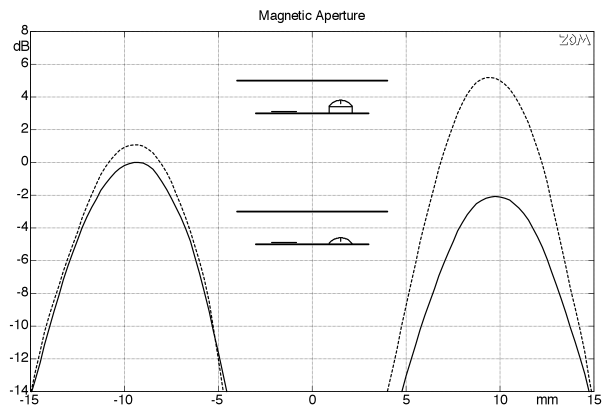


Fig. 5.4.29: change of the aperture-function dependent on the position of the screw. The left-hand maxima relate to the slug, the ones on the right to the screw.

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).

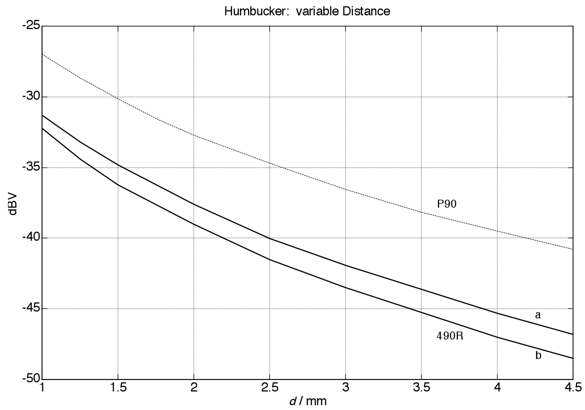


Fig. 5.4.30: voltage level dependency on variable distance; Gibson 490R (motorized test bench)
a = level of coil with slugs, offset over this coil.
b = level of coil with screws, offset over this coil.
To compare the distance dependency of the P-90 pickup is taken from Fig. 5.4.23 (dashed line)

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).