5.10 Determining the transfer behavior

In Chapter 5.9 the purpose of an equivalent circuit diagram has already been explained; it is supposed to represent the transmission characteristics of a pickup in a form easily understandable to the electronics expert. How far this is successful shall now be examined for some selected pickups via control measurements. First, we have to specify which **transmission** is meant. The generated *effective quantity* is the electrical voltage created at the pickup terminals for a defined electrical load, and the *source quantity* generating this effective quantity is the string velocity perpendicular to the fretboard. These two quantities give the **transmission coefficient** H_{Uv}. We could, in addition, also use the string velocity in parallel to the fretboard, or the strain-wave velocity running along the string – but for the following, let us limit ourselves to the string velocity oriented perpendicular to the fretboard (fretboard-normal velocity).

To model the transmission behavior the string-plucking guitarist is advantageously replaced by a source which can be described more precisely. Such a source could be a generator coil creating the magnetic field, positioned coaxially with the pickup coil or orthogonally to it, or it could be a short string moved by a shaker, or an impulse-excited, laser-monitored long string. It may be noted already in advance that all control measurements confirm the suitability of most of the equivalent circuit diagrams – modifications are required merely for pickups with strong eddy-current dampening.

5.10.1 Measurements using a shaker

For the shaker-measurements, a string of 10 cm length is driven by a B&K-Shaker (Type 4810) such that it vibrates – along a sinusoidal curve – orthogonally to its longitudinal axis while keeping its shape (no string bending). The string acceleration is frequency-selectively monitored via a PCB-impedance-measuring head (Type U-288) connected to a DFT-analyzer. In most cases a D'Addario PL-026 string of 0,66 mm diameter was used; the measurement frequency was in the range of 50 – 100 Hz with a deflection amplitude of 0,2 – 0,5 mm. Any non-linearity of the drive-system was suitable compensated for if necessary.

Shaker-measurements allow for a relatively precise determination of the absolute pickup-sensitivity, but can only be carried out in the low-frequency range due to structural resonances. While the **passive** two-terminal networks of an equivalent circuit diagram (*R, L, C*) may be identified via measurement of the pickup impedance, the shaker-measurement enables us to calibrate the **active** source contained in the ECD. Indeed, pickup excitations via alternating magnetic fields (Chapter 5.10.2 – 5.10.4) merely allow for determination of the magneto-electric transmission coefficient; conversely, the shaker-measurements described here make possible the identification of the mechano-electric transmission coefficient H_{Uv} - though limited to the low frequency range where H_{Uv} is independent of frequency. Typically, we find H_{Uv} to be about 0,1 – 0,3 Vs/m for the Stratocaster pickup. The precise value is of course dependent on the individual pickup and on the distance between string and magnet; moreover the string diameter needs to be considered.

From the point of view of systems theory we could state: the impedance-measurement allows for the specification of poles and zeros in the transmission-function; the shaker measurement adds the basic amplification. Or we could say: with the impedance measurement the shape of the transmission frequency response can be determined while the shaker-measurement yields its absolute position.

The string velocity is not only applicable as source quantity at low frequencies but also across a broad frequency range. Proof is found in **Fig. 5.10.1** comparing the time-function of the string velocity (left-hand section) to the voltage generated by a Telecaster-Bridge-pickup (right-hand section). The pickup was mounted at a distance of 2,5 mm below the string, and loaded with 110 kΩ and 330 pF. The ray of the laser-vibrometer struck the string on the (extended) axis of the magnet with the string vibrating in the direction of the axis of the magnet, and thus also in the direction of the laser beam. The velocity-signal generated by the laser-vibrometer was filtered with a 2nd-order low-pass in order to model the filtering happening within the pickup. The sameness of the two plots is impressive proof that the pickup indeed does detect the string velocity, and allows for an absolute scaling of the transmission coefficient of **0,29 Vs/m** in the low-frequency part of the oscillation.

As a comparison, shaker measurements were available which, however, were taken with 2,00 mm string/magnet-distance and with a 0,66-mm-string. They had yielded a transmission coefficient of 0,31 Vs/m. Matching the string diameter (0,66 mm → 0,70 mm) increases this value to $0{,}31 \cdot (0{,}70/0{,}66)^2$ Vs/m = 0,35 Vs/m, and matching the string/magnet-distance (2,0 mm → 2,5 mm) decreases it to **0,30 Vs/m** (Chapter 5.4.5). Consequently, the absolute sensitivity determined with little effort via the shaker is a very good match to the value obtained from the laser-vibrometer-setup.

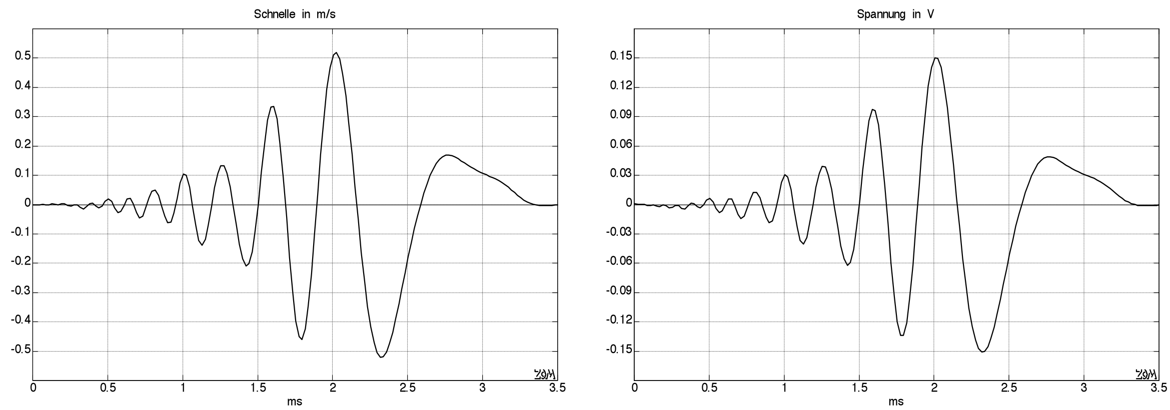


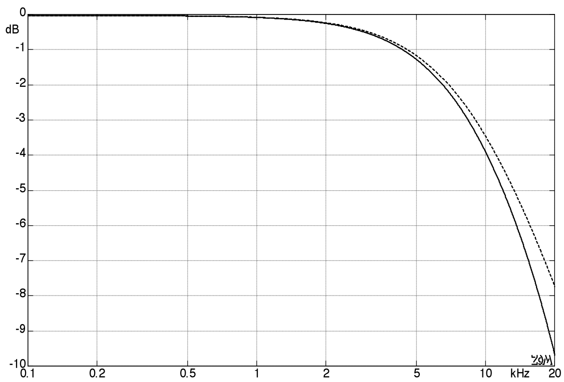
Fig. 5.10.1: String velocity obtained via the laser-vibrometer (left); corresponding pickup voltage (right). For string diameter and string/magnet distance see the text. Pure transversal wave.

Measurements using the shaker make possible a relatively effortless determination of the transmission coefficient. The following hints are helpful to limit measurement errors to an acceptable level:
- the pickup needs to have sufficient distance to the shaker to avoid direct magnetic coupling;
- the string needs to vibrate with a constant shape and must not develop any “life of its own”;
- the pickup needs to be mounted with non-magnetic materials to avoid any eddy-currents;
- the “magnetic history” of the string influences the result and should be recorded exactly;
- a DFT-window with small level-error (picket-fence-effect) may be dispensable for transmission measurements because the resulting error compensates itself (it shows in both channels in the same way), but it is still strongly recommended to make comparisons with other measurement approaches;
- the pickup should be mounted as rigidly as possible since, with a string-excursion of e.g. merely 0,5 mm, a vibration of the pickup of as little as 50 μm in amplitude can already cause ugly measurement errors.

5.10.2 Measurements with the Helmholtz-coil

Using a pair of Helmholtz-coils, it is possible with only little effort to generate a parallel magnetic field the strength and flux density of which can be precisely calculated. We need to consider, however, that magnetic fields around strings are everything but parallel – it is therefore easily possible that measurements employing the Helmholtz-coil yield other results compared to measurements where the pickup is excited by a vibrating string.

For the following measurements two oval Helmholtz-coils were wound; they had a size of 33 cm x 27 cm and 175 turns. The resistance of both (in parallel connection) is 7 Ω, they were driven by the AF-100 frontend of a Cortex workstation at L_U = 18 dBV for 600 Ω source-resistance. With these values a flux density of 6,5 μT_{eff} resulted in the low frequency range at the measuring position. Since the (inductive) coil impedance could not be expected to remain small relative to the source impedance across the whole measurement range (which would have resulted in perfect current impression), the actual current was monitored (**Fig. 5.10.2**) and any deviations were **compensated for** arithmetically. Still, we are confronted with differences compared to the results obtained with other measuring methods. A more in-depth analysis of the coil impedance showed a **resonance** at 44 kHz, i.e. capacitive currents having a field-amplifying effect♣. Given this situation, the share of the inductive current was now determined for a coil-equivalent circuit (Fig. 5.10.2, ----), and only the deviation of this share was arithmetically compensated for the subsequent pickup measurements.



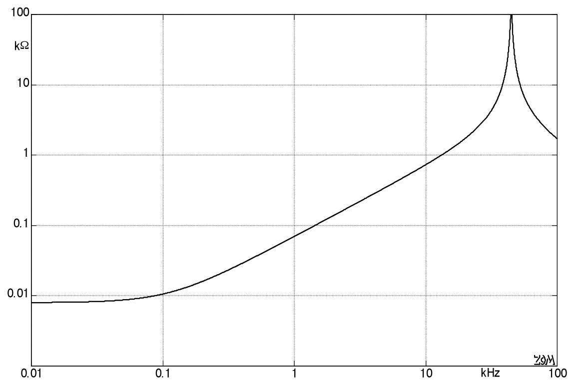


Fig. 5.10.2: Current flowing into the terminals (600 Ω source impedance, ——), inductive current (----). The right-hand graph shows the frequency response of the amount of the Helmholtz-coil impedance.

Measurement and calculation are compared in **Fig. 5.10.3**. The measurements took place within the parallel field of the Helmholtz-coils; the axis of the Helmholtz coils and that of the pickup coil coincided. The compensation mentioned above resulted in operating conditions which were equivalent to the operation with impressed magnetic flux density. The results of the calculations were obtained using a quadripole equivalent circuit diagram. The component values of this ECD were derived from the impedance frequency responses, as they were determined in Chapter 5.9.2. The basic correspondence of the curves shows that the transfer behavior of the magnetic pickup, from magnetic field to voltage, can approximately be derived from a simple measurement of the impedance frequency response. The absolute scaling cannot be determined that way but can be achieved at a single low frequency using the shaker (Chapter 5.10.1).

♣ For a parallel-resonance-circuit, the current in the terminals is smaller (!) than the current in the res. circuit.

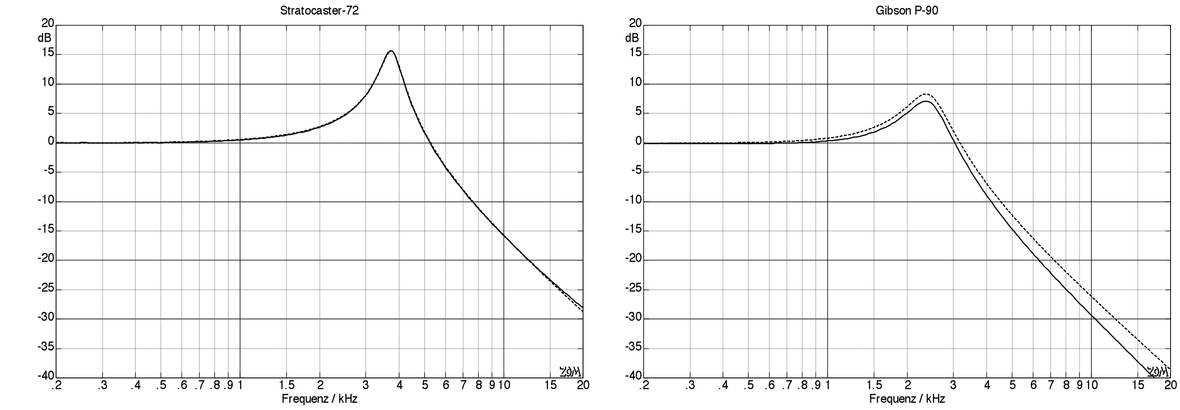


Fig. 5.10.3: Pickup transmission factor G_{Uv}: measured with Helmholtz-excitation (——), calculated with ECD (---). Fender Stratocaster (left), Gibson P-90 (right), each loaded with 700 pF.

The **Stratocaster**-pickup has little eddy-currents and for it we find a very good correspondence between measurement and calculation, while significant differences are observed for the **P-90**. Other than the capacitive coupling which could be the reason for small differences in the highest octave, it is in particular the different field geometry that is responsible for the discrepancies. The **brass plate** used as mounting base below the P90-coil influences the coupling factor stronger for the parallel Helmholtz-field incident than for the focused string-field. As one removes the brass plate from the P-90, the Q-factor increases, and measurement and calculation correspond (left-hand section of **Fig. 5.10.4**).

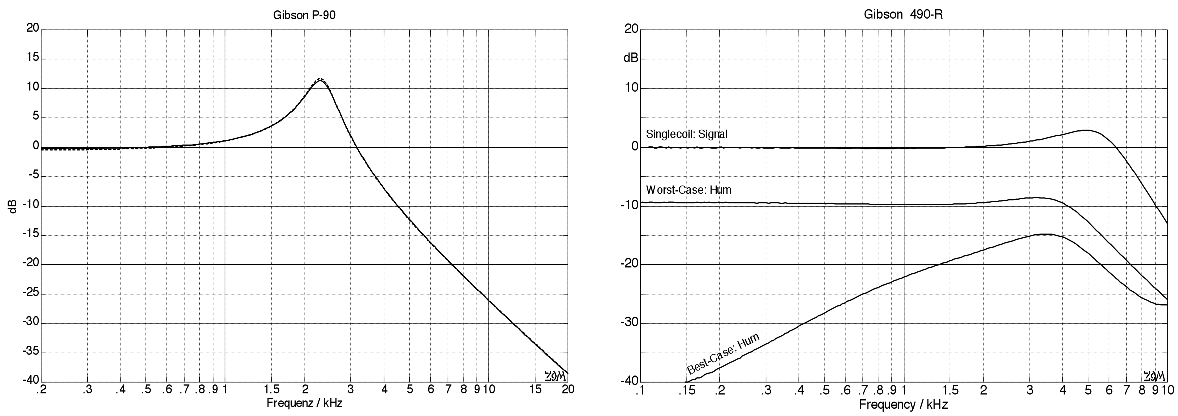


Fig. 5.10.4: Pickup transmission factor G_{Uv}: Helmholtz-measurement (——), ECD-Calculation (---). Gibson P-90 w/out brass plate, 700-pF-load (left). Gibson 490-R, 330 pF // 200 kΩ load (right).

The Helmholtz-field turns out to be totally unsuitable to measure the velocity/voltage-transmission coefficient of a **humbucker**: the out-of-phase connection between its two coils is designed to render such parallel fields ineffective. **Fig. 5.10.4** shows how well or how badly the design succeeds in that respect. The upper curve was taken in single coil mode, the lower in humbucking mode with an axis-parallel field (the direction of the magnetic field was in parallel with the coil axis). At least in the lower-frequency range the compensation works well. However, as the pickup is turned by 90°, barely 9 db of compensation dampening remain. This appears somewhat weak, especially since the pickup is manufactured by *the inventor of the humbucker* (Gibson advertisement). More details regarding hum suppression are explained in Chapter 5.7.

5.10.3 Measurements with a coaxial coil

For these measurements the pickup is excited by a generator coil the axis of which coincides with the axis of the pickup (thus the designation coaxial coil). **Fig. 5.10.5** shows a cross-section through the setup: a small coil (e.g. 6 mm ∅) carrying a sinusoidal current is positioned over the magnet of a singlecoil-pickup (e.g. Fender Stratocaster). The magnetic field of the small coil is – as a contrast to the Helmholtz-field - focused and thus more similar to the magnetic-field of the string. For the Stratocaster pickup already the Helmholtz-measurement was useable – the coaxial excitation works similarly well. We do get effects of capacitive coupling above 10 kHz but these are negligible. For the P-90 the Helmholtz-excitation gives clearer divergences re. the ECD-model; the coaxial excitation results in a better agreement because the magnetic AC-flux is mainly concentrated on the upper side of the winding und therefore the brass plate located below the pickup has merely a weak effect.

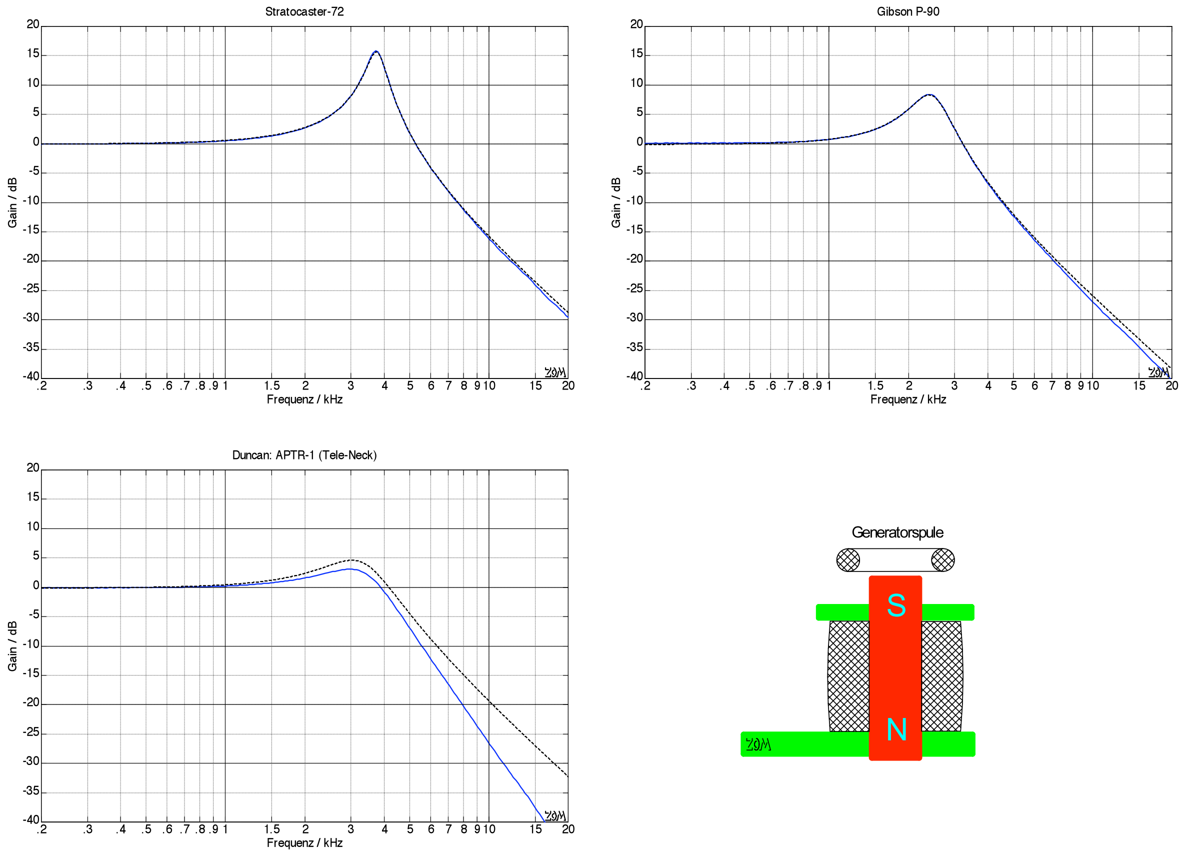


Fig. 5.10.5: Pickup with coaxial generator coil (cross-sectional drawing for a Stratocaster pickup).

For the Telecaster neck pickup, we see clear differences between the measured curve and the transmission function derived from the two-terminal equivalent circuit diagram. These differences are due to the eddy-current dampening of the metallic pickup cover. Apparently one does arrive at a limit regarding modeling for pickups when confronted with such strong dampening, and a modification of the simple quadripole-equivalent-circuit-diagrams introduced in Chapter 5.9.3 is required (see Chapter 5.10.5).

5.10.4 Measurements with the tripole coil

The coaxial coil introduced in the previous chapter generates an alternating magnetic field which is a much more locally effective field than the field of the Helmholtz-coils. However, there are still differences compared to the field distribution of an oscillating string. A further optimized approximation of the field geometry of the string can be achieved with a tripole-coil, i.e. a layout …..

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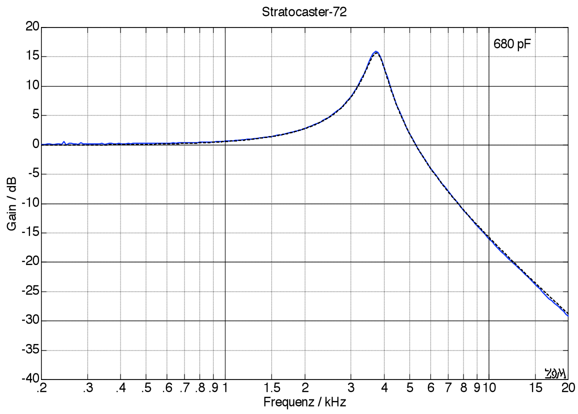
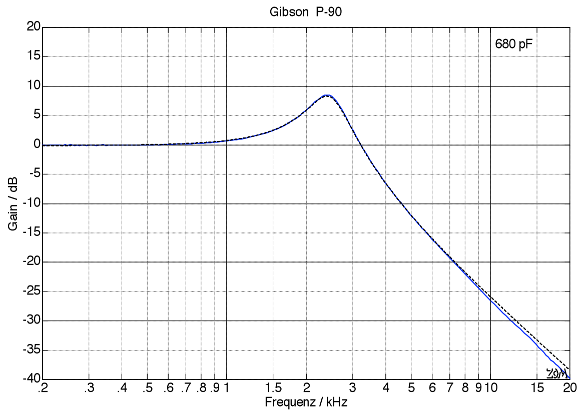




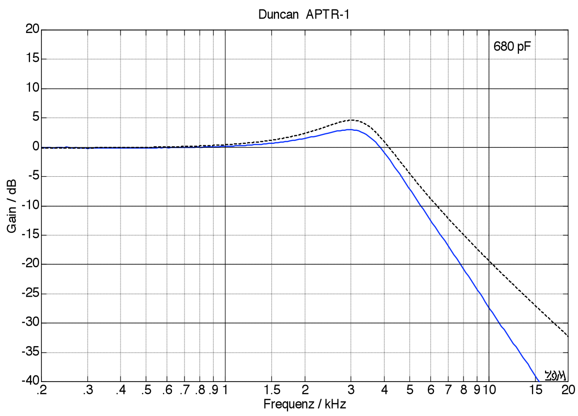


Fig. 5.10.6: Tripole coil excited by alternating current, measurement (——), ECD-model (---).

While the correspondence between measurement and model-calculation is again good for the Stratocaster- and P90-pickups, significant divergences appear for the Telecaster-neck-pickup. The cause is found in the metal **shielding cover**. Although it is made of non-magnetic material, this cover introduces a dampening due to the eddy currents induced into it. The effect is mainly felt in the treble range. The equivalent circuit diagram (ECD) derived from the impedance obviously requires modifications in order to account for eddy-currents close to the strings, and to better model the frequency dependence of the mechano-electric coupling. At this point we can also look into the question whether the tripole-excitation always yields results which are equivalent to normal operation (string oscillation). It may be as well that the ECD-model given above is closer to reality. Measurements with the laser-vibrometer give clarifications regarding these issues (Chapter 5.10.5).

5.10.5 Measurements with the laser-vibrometer

The measurement methods presented in the previous three chapters (5.10.2 – 5.10.4) deliver nicely agreeing results for pickups that feature a small level of eddy-currents. However, as soon as pickups with eddy-current-dampening (e.g. P-90) are the subject of the measurements, we see differences at higher frequencies. We could ignore these differences because the transfer behavior at 10 – 20 kHz is not really that important due to the lowpass filtering. On the other hand, we could consider the divergences as an indicator that an extension of the overhead towards the limits of our models might be in order and that decreasing the differences would be worth the effort. Still, none of the measurement approaches proves that the velocity/voltage-transfer-function indeed shows the identified frequency response. In the end, all three methods yield merely the magnetic-field-to-voltage-transfer-function, or – to put it even more radically – the current/voltage-transfer-function. Considerably more insight is offered by measurements with the laser-vibrometer which do require a higher effort regarding instrumentation but directly capture the desired source quantity (the string velocity).

Laser-vibrometers take advantage of the **Doppler-Effect**: the frequency of a reflected wave changes if source and reflector move relative to each other. If source and reflector get closer, the reflected beam of light has a higher frequency than the ray emitted by the source (laser). If source and reflector move away from each other, the frequency is lower. Given v = speed difference between source and reflector, the relative frequency change corresponds approximately to $\Delta f / f_0 \approx v/c_{\text{light}}$. As one points the laser-beam at the oscillating string, the voltage generated by the laser-vibrometer corresponds to the string velocity in the direction of the beam. String movements along the string (i.e. perpendicular to the laser beam) are not detected. This means that strain-waves (if we discount a minimal transversal contraction) are not detected by the laser-vibrometer – but they are by the pickup. When performing laser-based control measurements on a pickup, we need to ascertain as a consequence that either exclusively transversal waves are generated, or that the two wave-types clearly happen separately. For the following experiments using a string of a length of 28 m could ensure a sufficient mode decoupling. This string is deflected on one end by a short transversal impulse. Below the string the pickup is positioned at the regular distance (2 – 5 mm), and above the string we have the laser-vibrometer. Fig. 5.10.1 could already drive home the point that a magnetic pickup indeed samples the transversal string velocity at the given point – this is the same with a laser-point. Transforming the voltage given by the pickup as well as that given by the laser-vibrometer into the frequency domain puts us in the position to determine the **transmission function** of the pickup. In principle, that is ……

Unfortunately, we may not conclude from the fact that the laser-vibrometer can carry out highly precise measurements that the pickup measurement automatically is also free of measurement artifacts. It is necessary that exclusively a transversal wave of plane polarization propagates in the string – but this is not easily accomplished. Structural resonances in the string bearing continuously lead to undesired strain-waves which falsify the measuring result. After carrying out extensive pre-experiments, an experimental setup could be developed which includes strain-waves artifacts only at very high frequencies. Since the pickup operates as a low pass, the remaining interferences are tolerable or insignificant. A similar situation exists for the inevitable offsets in the circuits, which cause voltage drifts at low frequencies. The offset compensation chosen for the experiments was sufficiently potent, and the remaining error was insignificant (Cortex-Workstation CF-90, CF-100). The T_{Uv}-values given in the figures belong to individual measurements which were not always carried out with a string-to-magnet distance of 2 mm.

Fig. 5.10.7 compares the results of the laser-measurements with the ECD-model-calculations. During the measurement the pickup was loaded with an RC-circuit; this was considered correspondingly in the calculations. While the resonance-emphasis is, generally speaking, correctly reflected, all measurements give relative to the calculations a characteristical **treble-loss** amounting to about 1 dB at 10 kHz.

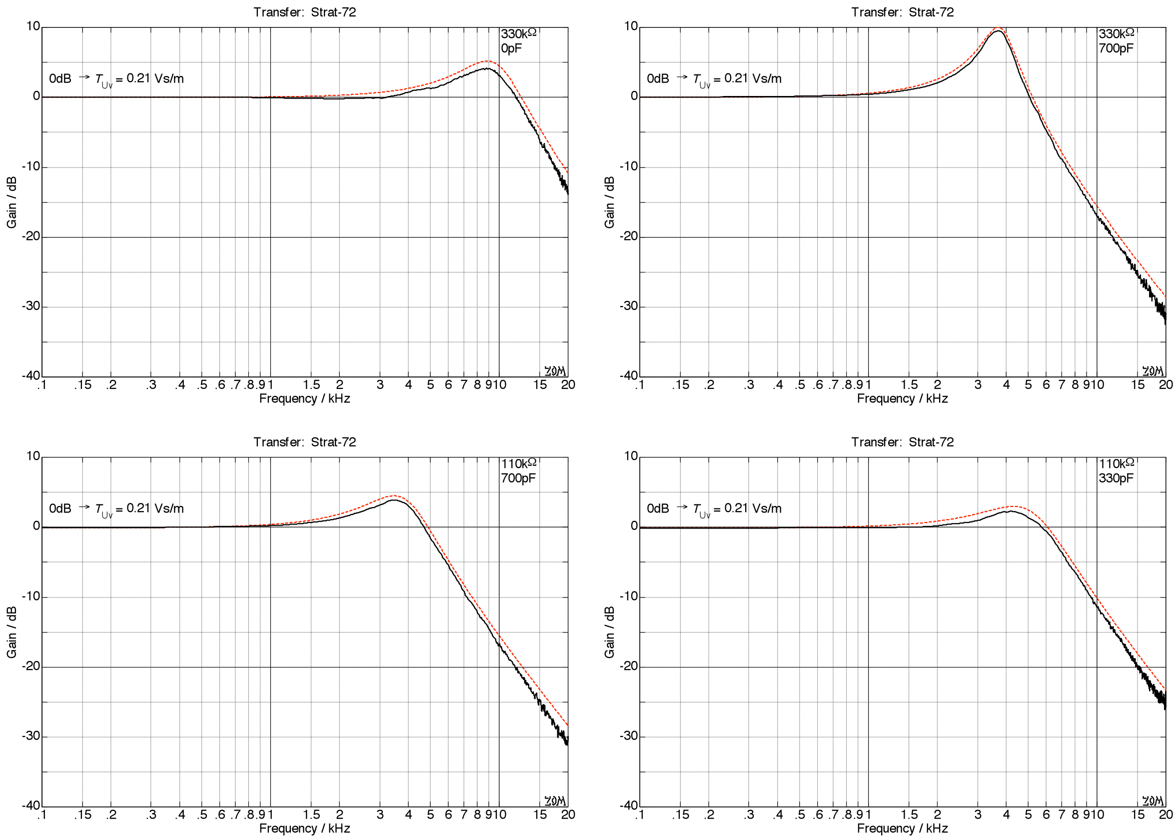


Fig. 5.10.7: Transversal-wave transmission-factor: laser-vibrometer (——), ECD-model-calculation (----).

In **Fig. 5.10.8** corresponding measurements and calculations are depicted for a coaxial humbucker (Fender Noiseless Stratocaster). Despite the different construction and the so-called "beveled magnets" (Chapter 5.4.6), the level differences in the treble range turn out to be analog those in Fig. 5.10.7.

Fig. 5.10.8: Transversal-wave transmission-factor: laser-vibrometer (——), ECD-model-calculation (----). This figure remains reserved for the print version of this book.

Further measurement results are shown in **Fig. 5.10.9**; they feature similar divergences between measurement and model-calculation in spite of different pickup build. The Duncan APTL-1 and the Fender Telecaster bridge pickup are seated on a ferromagnetic assembly plate; their cheapo-counterpart uses a ferrite bar-magnet instead of 6 alnico magnets; the Jazzmaster pickup sports a relatively large winding-surface and short magnets; for the P-90 two bar-magnets are located beneath the coil – the differences between measurement and calculation still amount merely about 1dB in the relevant frequency range (only slightly more for the P-90). Consequently, it is possible to derive the transmission-behavior of all pickups of this simple singlecoil-type from the impedance frequency response. It may be – if necessary – supplemented by a slight treble attenuation the cause of which can be found for the most part in the aperture window (Chapter 5.4.4).

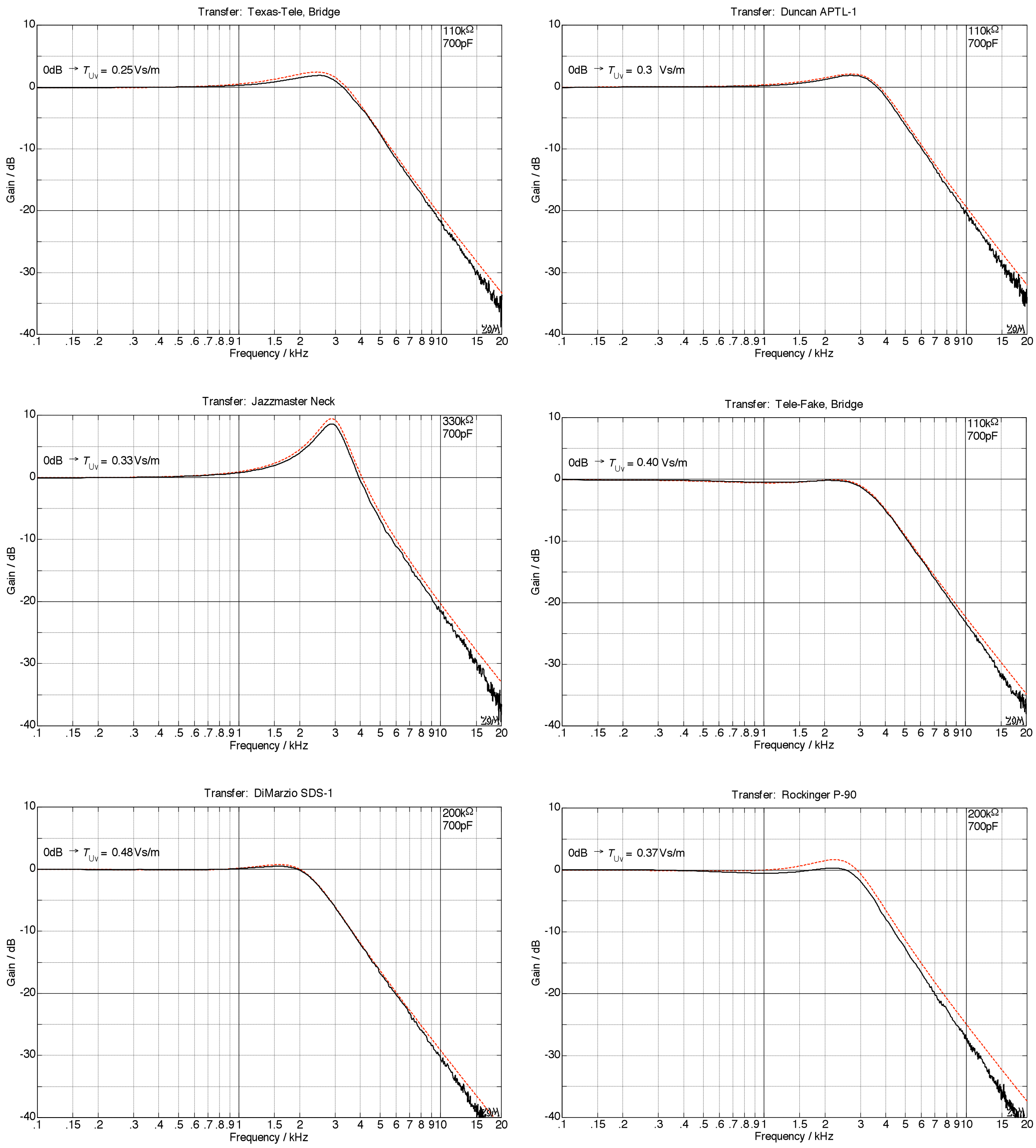
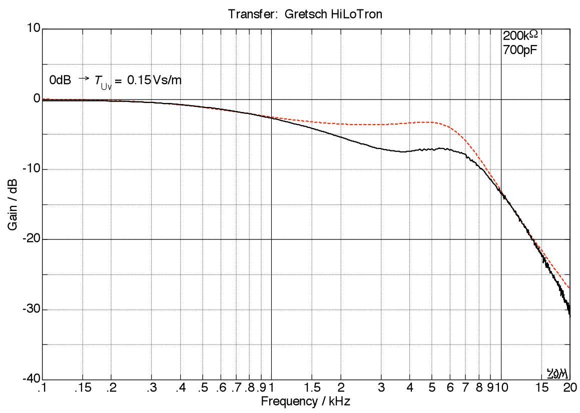


Fig. 5.10.9: Transversal-wave transmission-factor: laser-vibrometer (——), ECD-model-calculation (----).

But not all singlecoil-pickups show the aperture-induced differences between measurement and model-calculation as depicted on Fig. 5.10.9. The Gretsch HiLoTron has a striking comb-filter-like interference curve, and the Telecaster-neck-pickup gives serious discrepancies at high frequencies – in these cases it is not possible to draw conclusions regarding the transmission behavior from the impedance-equivalent-circuit-diagram. The reasons are found in the magnetic field – but they are highly individual.

Let us first take a look at the HiLoTron-pickup which first entered service in the late 1950s in Gretsch guitars (e.g. Tennessean). Tom Wheeler writes in his book “American Guitars” that the pickup was developed by “fulltime Gretsch personnel”. However, with No. 2683388 there was a patent already in 1954 which shows the exact same construction. Inventor is Ralph Keller who is designated as “assignor to Valco Manufacturing Co.”. Valco (the successor to National and Dobro) manufactured guitars for other companies in the 50s, including Gretsch. Maybe somebody among the “fulltime Gretsch personnel” took off the vinyl-cover and checked out the pickup? Or – as it does happen now and again – the time was ripe and two inventors had the same idea at the same time without knowing from each other (they were both from Chicago, though ….).

Anyway, it’s all **Ralph Keller’s** glory, who on the other hand also has to take the rap for the justifications he gives in his patent: *The most important advantage stems (...) from the generally parallel relation of the magnetic lines of force with the instrument strings as compared with the perpendicular relation between the magnetic field and the strings which is common in many currently used pickup devices. (...) As a result, a wide area of the magnetic pattern is efficiently activated by the moving strings whereby to produce substantially greater and more effective variations in the reluctance of the magnetic field. (...) Consequently, (...) the pickup produces substantial improvements in the tone color of the instrument due to the capturing of additional overtones or harmonics which are not ordinarily reproduced when the pickup point is limited to a single point or relatively restricted area on the strings*. In short: according to Ralph K. the aperture-window should be as long as possible in order to capture as many harmonics as possible. This assumption (which was also taken up by Leo Fender♣ at the beginning of the 1960s when he designed the Jazzmaster pickup) is however not in agreement with systems theory: the longer the (actually effective) impulse response, the more the system has a narrow-band character. This is a fundamental aspect of the reciprocity of time and frequency as elaborated e.g. by Marko or Küpfmüller. In the case of the HiLoTron-pickup, the measurement of the transmission function shows – compared to the curve derived from the impedance ECD – a string specific interference gap at 5 kHz (**Fig. 5.10.10**).



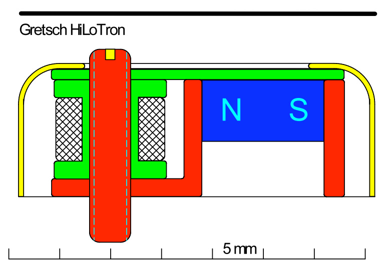


Fig. 5.10.10: Gretsch HiLoTron. Laser-vibrometer (——), ECD-model (----).

♣ Compare to Chapter 5.1

The horizontal position of the bar-magnet indeed lets the string be sampled “across a wide range”, or more precisely at two relatively distant points – this leads to comb-filter-like superpositions (**Fig. 5.10.11**). As the string vibrates perpendicular to the fretboard, **two air-gaps** change: one (as usual) over the pole-screw, and a second one over the south pole of the bar magnet. The air gap bordering the pole-screw is the smaller one and therefore the transversal wave occurring here causes a larger *relative* distance change. In other words: at this position the pickup is more sensitive. Increasing the string-to-pickup-distance makes the pickup become less sensitive, as is to be expected; the interference effect becomes stronger, however (due to the air gaps becoming more similar).

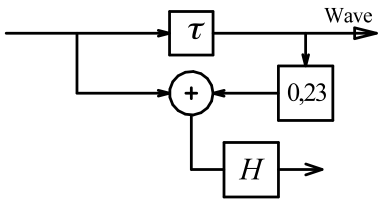


Fig. 5.10.11: Block diargam (above). Difference between laser measurement and ECD-model (——), frequency response of interference filter (----, right).

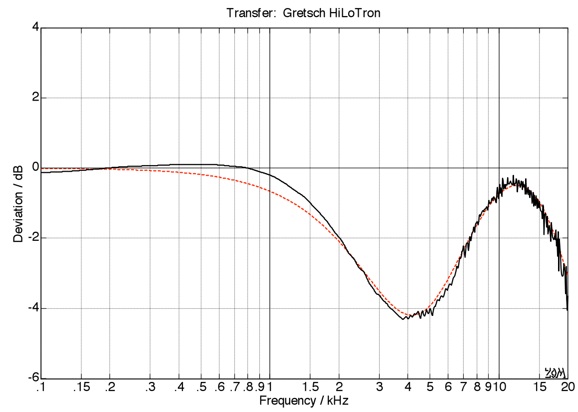


Fig. 5.10.11 models the delay-time between the two air-gaps with $\tau(\omega)$ (due to the dispersive wave-propagation τ is frequency-dependent). Optimization of the parameters resulted in an effective distance of the two sampling points of 23 mm which is in good agreement with the dimensions. A real factor takes care of the smaller sensitivity of the second “channel”; it amounts to 0,23 in the example. Although the magnetic polarity at the two sampling points is opposite, the two channels need to be *added* (constructive interference): bringing the string closer to the pickup decreases the magnetic air-gap resistance in both cases and thus increases the magnetic flux. Of course, in reality the sampling does not happen at two ideally small points but in two areas with finite dimensions each. Model and measurement will therefore not match exactly. That for the chosen example the differences are nevertheless as small as a few tenths of a dB (Fig, 5.10.11) is a nice confirmation of the model. **Fig. 5.10.12** shows the measurement results compared to the complete model, and also the dependency on the string.

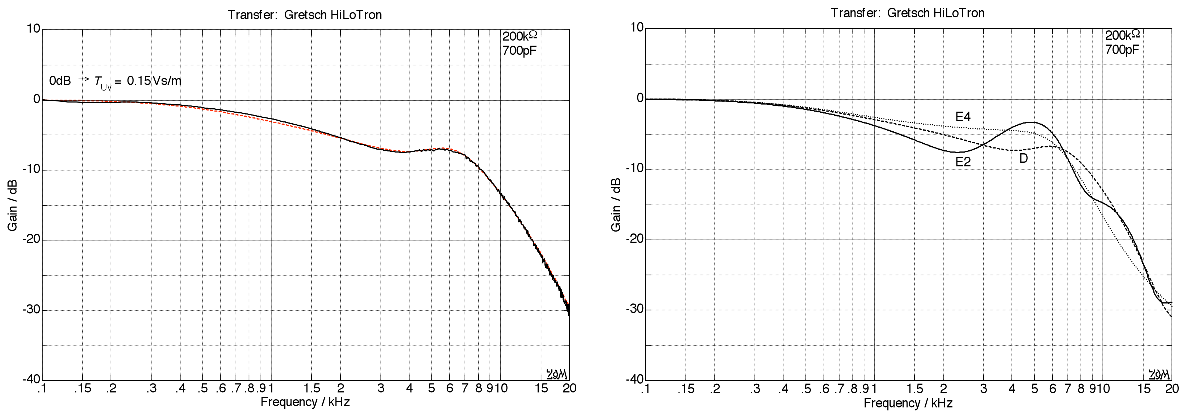


Fig. 5.10.12: Comparison measurement/model (left), string-specific transmission function H_{Uv} (right).

The “two-location-sampling” gives the HiLoTron-pickup its very own transmission characteristic which is unique in this form. Compared to a humbucker, the interference gap is much less pronounced, and the low coil inductance results in a brilliant, treble-rich sound. We find an entirely different situation for the **Telecaster** pickup. While here, as well, the measurement results differ from the model-calculations based on the impedance equivalent circuit diagram, they do so in a different way and due to different causes (**Fig. 5.10.13**).

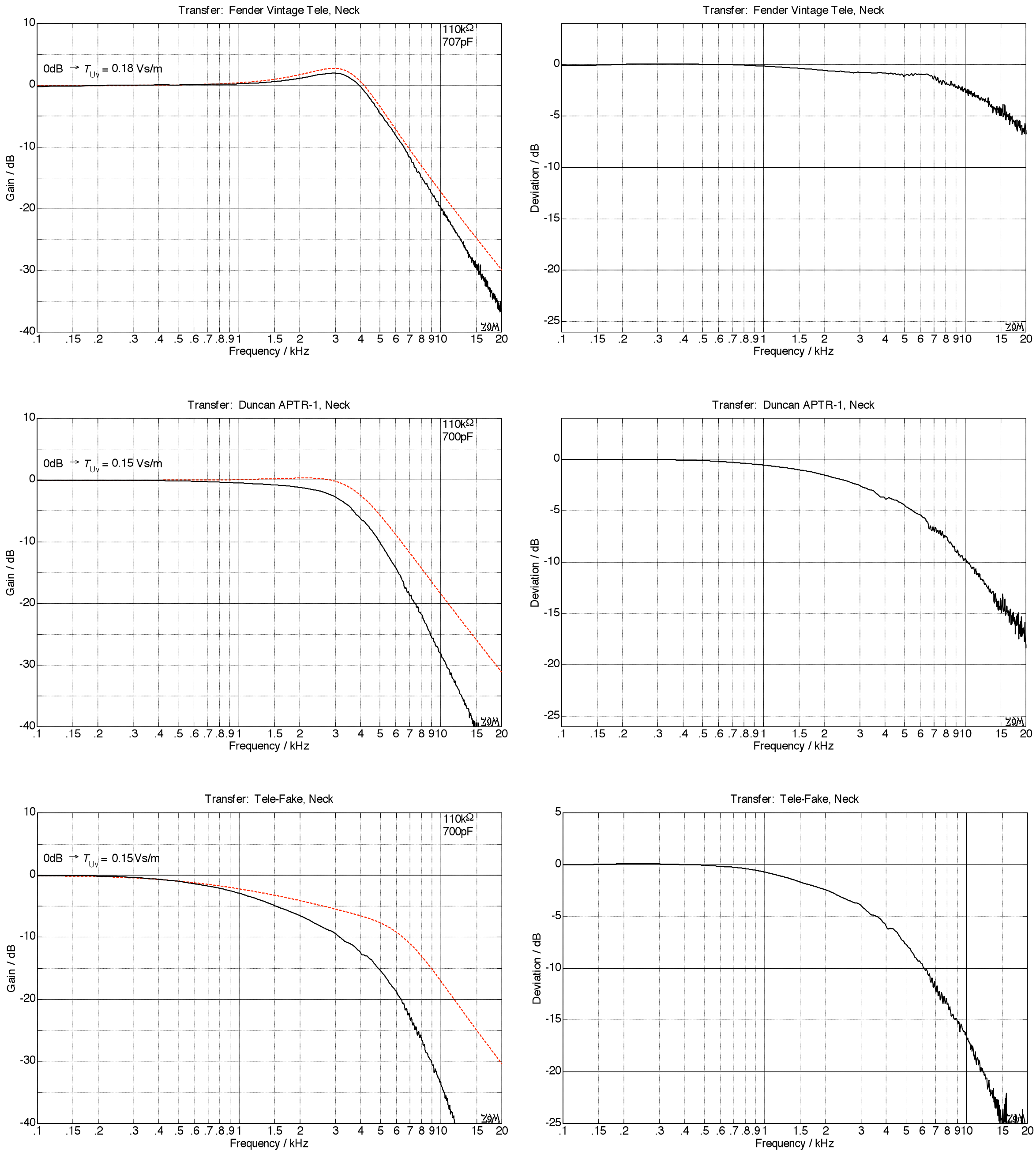


Fig. 5.10.13: Transversal-wave transmission factor: laser-vibrometer (——), ECD-model calculation (----).
Right-hand column: difference between measurement and ECD-model calculation.
1st line: original Fender pickup, Telecaster retrofit set. 2nd line: Duncan APTR-1 ("for Tele®").
3rd line: “cheapo” copy, guitar with Telecaster-like body and similarly looking pickup

Measuring the three Telecaster neck pickups first resulted in three different impedance frequency responses. From these the different transmission frequency responses can be calculated (as shown in Fig. 5.10.13); however, the measurement results diverge significantly. The reason for the discrepancies are **eddy currents** induced by the alternating magnetic field into the metal **cover** (Chapter 5.9.2.2 and 5.9.2.5). While the measurement of the pickup impedance does capture eddy-current dampening, it only succeeds so with regard to the impedance – and not (or only partially) in terms of the effect on the transmission.

An experiment exemplifies this: the influence of the cover on the impedance frequency response is shown for a Duncan pickup (APTR-1, "for Tele®"), and we can see effects merely in the range of the resonance. Operating the pickup without cover we can calculate H_{Uv} in the usual way; any differences to the calculation can again be explained by the aperture dampening. **With cover**, two measurement conditions can be distinguished: **normal** (string above the cover) and **upside-down** (pickup turned over). Of course the impedance frequency response will be identical in both cases; the string has no measurable effect. Not so for the transmission frequency response where differences appear. Upside-down, when no cover metal comes between string and coil, we do get an entirely different measurement curve compared to “with cover”, but the differences between calculation and measurement are similar for both cases. In normal configuration (Fig. 5.10.13) the difference between measurement and model calculation amounts to 10 dB already at 10 kHz. Apparently the positioning in space offers another degree of freedom which the model calculation does not cover. An extended model with three coupled, lossy coils would have to be supplemented (the cover acts as a shorting ring), but the usefulness is not in any reasonable relationship to the required effort.

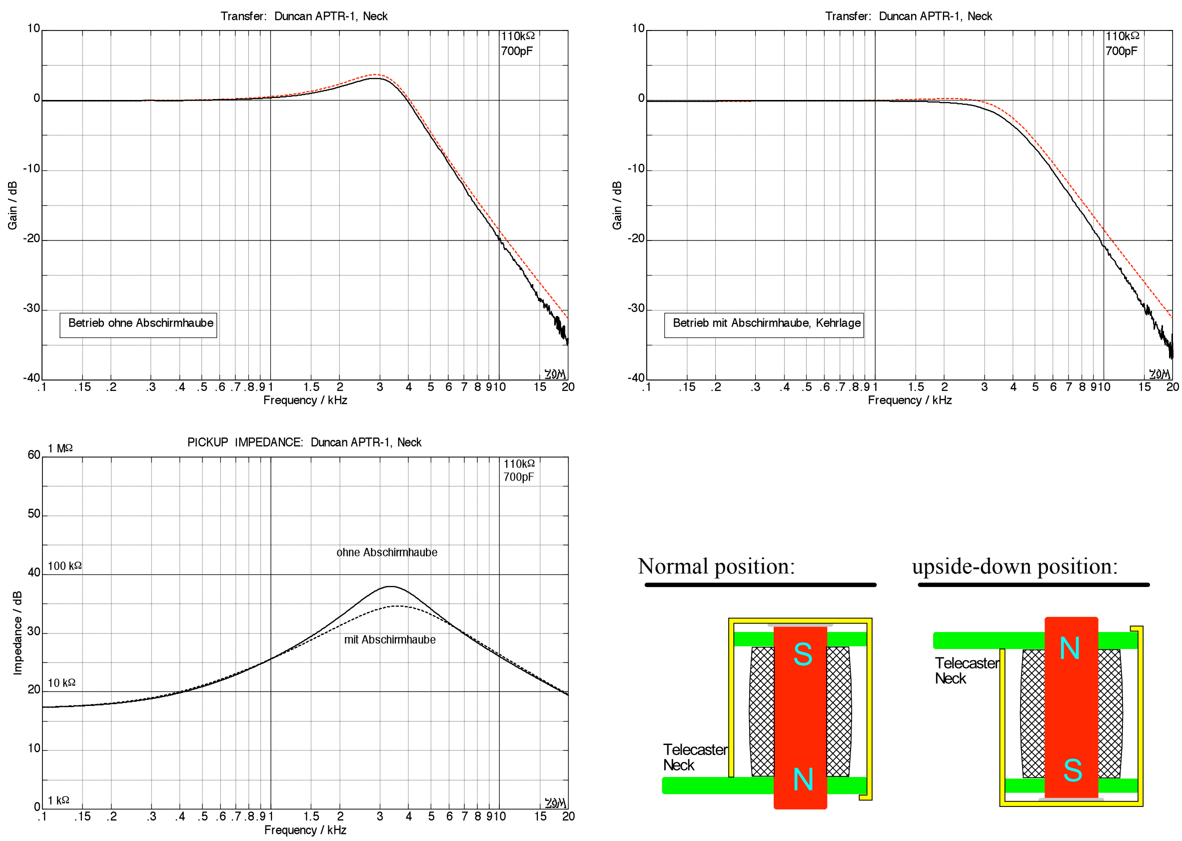


Fig. 5.10.14: Duncan APTR-1, with and without shileding cover (operation of normal position; see Fig. 5.10.13.

All three pickups mentioned in Fig. 5.10.13 find use in similarly looking guitars but their transmission characteristics differ tremendously: the treble reproduction diverges by 12 dB! Where do these differences come from? Without cover, the vintage Tele and the APTR-1 show a similar behavior (Fig. 5.10.15) – as one would expect it due to the similar build. The cheap copy fitted with a bar-magnet does not entirely reach the resonance emphasis presented by the competitors (due to the eddy-currents in the iron slugs), and arrives at a somewhat worse treble reproduction. However, only as the **covers** are mounted, the large differences arrive: the similarity is only in the looks but the electrical characteristics differ significantly. The cover of the Fender pickup is made of 0,5-mm-thick German silver; the other two are made of chrome-plated brass.

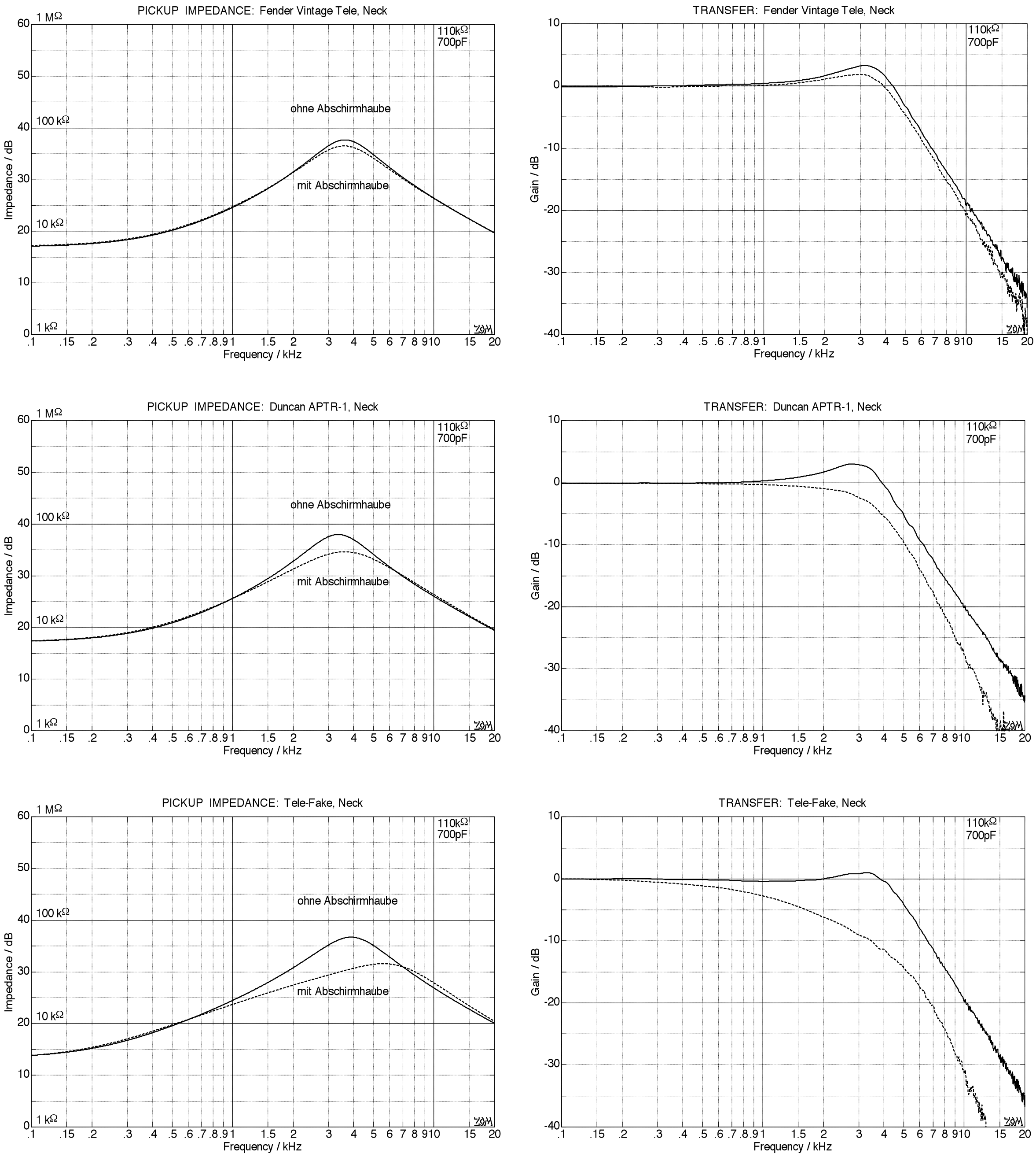


Fig. 5.10.15: Impedance- und transmission-frequenca-responses: pickups with/without cover.

The different conductivity of these metals (Chapter 5.9.2.2) gives varying eddy-current-dampening. The cover of the cheap imitation has a thickness of 0,8 mm and is even more efficient than the one of the APTR-1 (which has 0,5 mm). Of course, it is now a matter of individual evaluation whether one prefers shining treble or boxy mids. However: for the original Fender pickup it was possible to attenuate the treble if so desired. That does not work the other way ‘round. In the Seymour-Duncan brochure the phrase "For tone that sets you apart" is found above the picture of the APTR-1. Apart … to where, now? Be careful what you wish for …. ☺

Humbucker

Humbuckers sample the string vibration at two positions using their two pole pieces per string. Due to the delay between these two points, phase shifts occur and **interference cancellations** happen if the delay matches half a vibration-period. Since the phase-velocity of the propagating transversal wave is different for each string, the humbucker interferences are **string-specific**. Fig. 5.10.16 compares laser measurements and model calculations. The curves shown in the first line of the figure are practically congruent which is impressive proof for the high quality of the model. Three components were considered in the calculation: the aperture filter (**Ap**), the interference filter for a pole distance of 19 mm (**Notch**), and the low pass transmission (**RLC**) derived from the impedance frequency response. Recalculated for a scale of 63 cm, the fundamental frequency amounts to f_G = 130 Hz, the string diameter is 0,7mm.

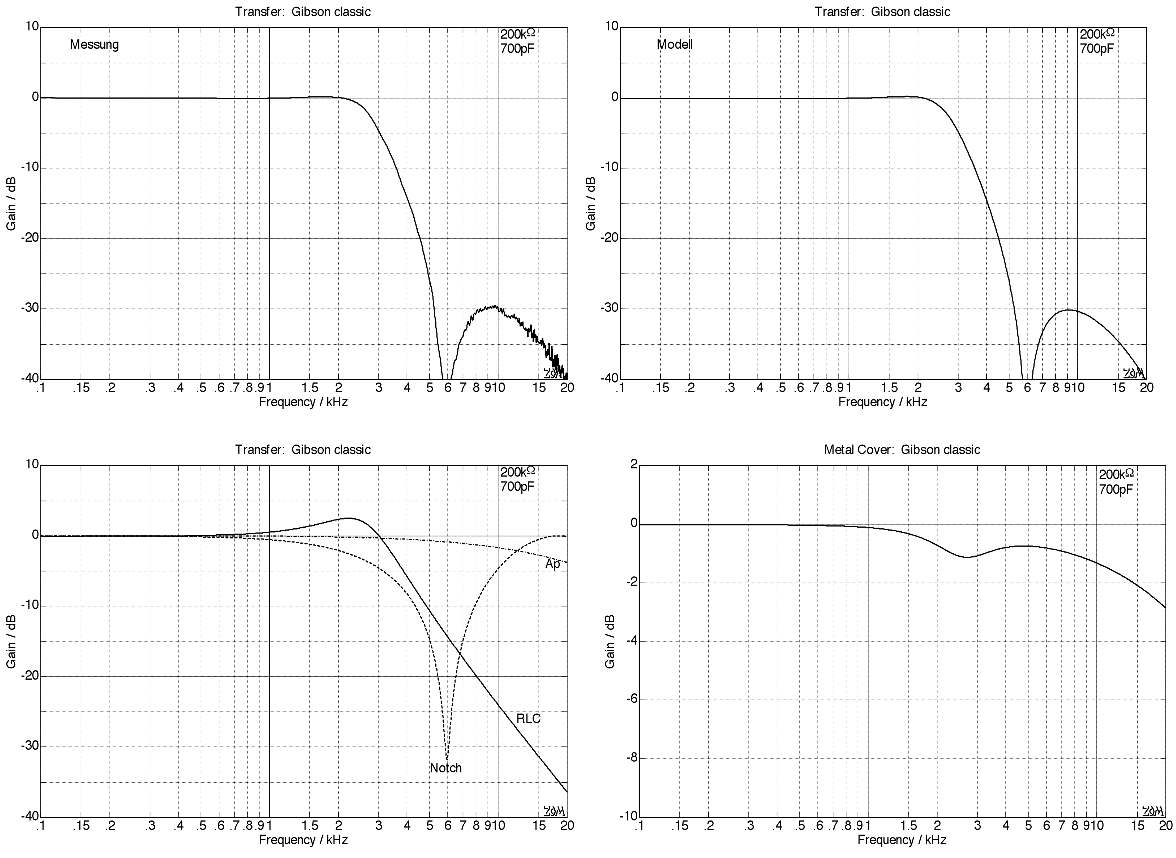


Fig. 5.10.16: Gibson-Humbucker ('57 classic). Laser-measurement (upper left), model-calc. (upper right.). Components of the model-calculation (lower left). The treble attenuation of the metal cover is shown lower right.

The measurements and calculations depicted in Fig. 5.10.16 were done for the string used on the test-bench; **Fig. 5.10.17** gives the transmission frequency responses for real guitar-conditions. The left-hand part of the figure relates to a long-ish guitar cable (700 pF), the right hand part holds for a load capacity of 330 pF (Chapter 9.4 and 9.6). The interference gap for the low E-string (E2) is located at 3 kHz i.e. just at the range which would be particularly emphasized by a Fender singlecoil. In conjunction with the treble attenuation caused by the LC-low pass, a transmission frequency response results for the Gibson Humbucker (and its innumerable copies) which evokes a Tschebyscheff-low-pass: that's how treble is efficiently cut. Another 5 dB are lost in the treble range if (as it was the case for many Gibson guitars in the 70's and 80's) potentiometers of 100 kΩ ("Tone") and 300 kΩ ("Volume") are utilized rather than 500-kΩ-versions. Tone is in the eye of the beholder ….

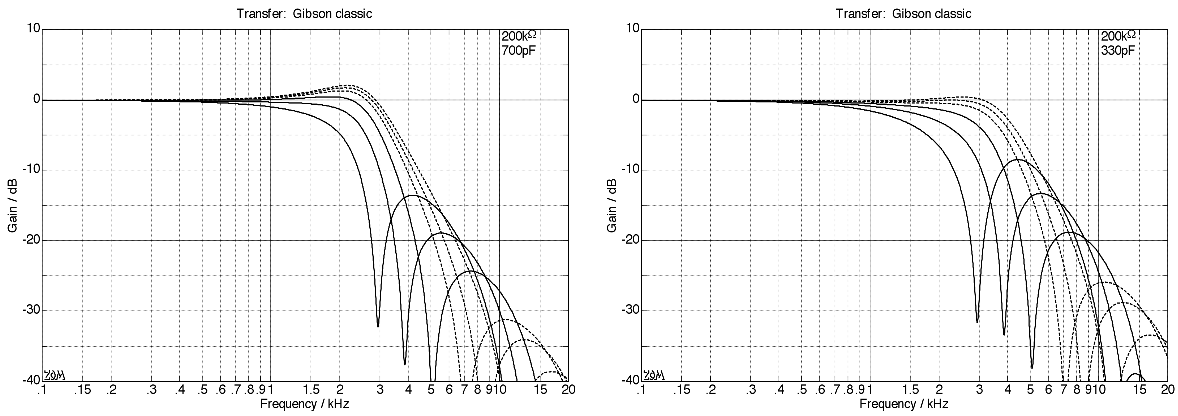


Fig. 5.10.17: Gibson-Humbucker ('57 classic). Stringspecific transmission function, with varying *C*. Due to the dispersive wave propagation the second interference gap is not at trice the frequency but considerably higher: high-frequency components run disproportionally faster (Chapter. 1.3.1).

Not all humbuckers feature the pole-distance of 19 mm as given by the Seth-Lover-developed Gibson Humbucker. For the Fender Humbucker (incidentally also developed by Seth Lover) we find 20 mm and for the Gibson Mini-Humbucker 13 mm, while for humbuckers in a single-coil format the distance is as small as 6 – 9 mm. In the same way that the pole-distance decreases, the notch-frequency increases. If the magnet poles are reduced to narrow blades with a separation of the (middle of the) blades of 7,5 mm – as it is the case e.g. for the **Joe-Barden-**pickup or the **DiMarzio** DP-184 – the notch frequency is pushed to higher ranges.

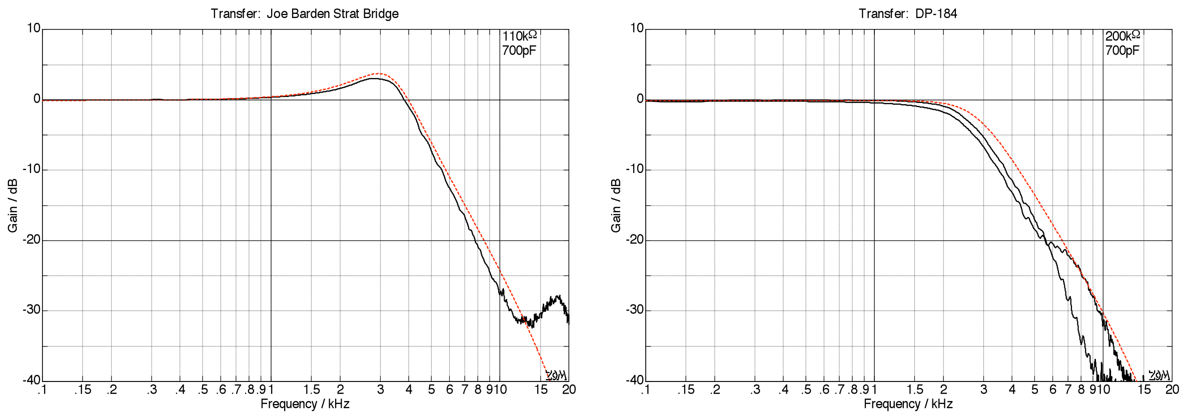


Fig. 5.10.18: Transmission frequency repsonse: humbucker of 7,5 mm blade-distance (Joe Barden, DiMarzio). Laser-measurement (——), model-calculation (RLC, notch, aperturefilter ----). String diameter 0,7 mm, f_G = 130 Hz.

Without dispersion a 0,4-fold pole-distance-decrease would increase the notch-frequency by a factor of 2,5, in reality, however, it increases (string-specifically) by a factor of 4 to 5. The corresponding theory (dispersive wave propagation, Chapter 1.3.1) is a good match to the measurement results. In addition there are effects that are more difficult to model such as non-negligible inductive and capacitive coupling between the two coils – in particular relevant for humbuckers with small pole- or blade-distance. Under some conditions the transmission characteristic can be dependent on the propagation direction of the transversal wave (Chapter 5.11). Simple transfer-models give the resulting complicated frequency responses merely with modest accuracy (**Fig. 5.10.18**). The maximum showing in the 18-kHz-range for the Joe-Barden-pickup (which could be interpreted as a dipole-resonance) is indeed due to the coupling-resonance of the two coils. For the sound this side-maximum is insignificant.

5.10.6 Measuring accuracy (or rather measurement inaccuracy)

Test-stand-measurements support objective measurement data but they are carried out in an un-typical situation (“in vitro”). There are differences to the behavior of the actually played guitar (“in vivo”), and in addition we need to consider that all measurements contain errors. Having doubts about the value of measurement results is therefore permitted. On the other hand, subjective evaluations (e.g. given while playing a guitar) need to be questioned, as well: they may have been expressed by a hard-of-hearing guitarist, or by somebody playing under-the-influence, or may have been written up by a guitar-tester in dire need of money. Even a combination of all three conditions is conceivable. An evaluation may also simply have been given in a special (possibly non-reproducible) mood; thus it expresses a subjective opinion of little relevance to the public. Chapter 8 addresses the world of psychoacoustics while the following paragraphs deal with the measurement errors occurring with bench-tests.

1) Most of the pickups investigated show a rather poor production quality: each single magnet generates a different flux density, the air-gaps are different, the mounting plate is distorted, or the magnets are lopsided. Even simple distance measurements become problematic – plus regular measuring tools made of steel cannot be used due to the magnetic attraction forces. For dynamic measurements non-ferrous metals need to be excluded as well, since eddy-currents generated within them lead to undesirable dampening. On the other hand, using a test bench put together exclusively from regular plastic easily leads to measurement tolerances of 0,1 mm – for critical distance measurements this may often be already too much. Even much more difficult are diameter measurements of strings: to determine the cross-sectional area of a 10-mil-string with an accuracy of 1%, we need to measure the diameter with an accuracy of 1,3 μm. Normal micrometer screws reach 10 μm tolerance which leads already to an error of 8% for the area.

2) For electrical measurements, the situation is somewhat more positive: voltage- and current-values can be taken with an error of about 1%; in individual cases even more precisely. Measuring magnetic quantities brings again a decrease in accuracy: errors of 5% are probably the typical range.

3) An even greater problem resides with the **string-magnetization**: magnetic pickups work only with ferromagnetic strings, and their operating point moves along a hysteresis loop. The transmission factor of a pickup can change by as much as 3 dB (!) if the string is brought close to the pickup magnet and then moved away again to its rest position … plus there are many paths within the three-dimensional space to get to a specific location! An example shall exemplify the associated difficulties (**Fig. 5.10.19**): in the left-hand section of the figure the

pickup (a Gibson Humbucker) is moved along the strings across the cranks of the rotating string (motor-test-bench). The paths "to and from" yield two different curves (—— d = 2 mm, ------ d = 4 mm). The right-hand section shows the voltage-level curve as a function of the distance d; the crank was rotated across the slug-coil of the humbucker (left maximum in the left section). It required many complementing measurements to arrive at meaningful and practically relevant measurement curves – and to arrive at the "subjectively correct objectivity".

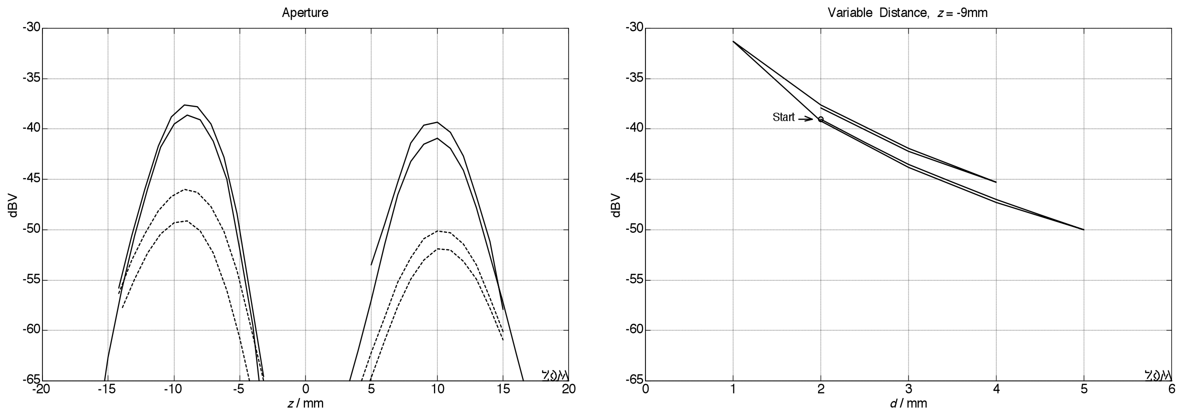


Fig. 5.10.19: Dependency of the voltage level on the pickup shift along the string (left) and on the string-to-magnetic-pole distance (right). Motor-testbench (Chapter 5.4.4).

4) In order to see whether the data collected from an individual pickup are indeed **representative** for this type in general, it would in fact be necessary to pick a sample including more than just one single element. However, the price per unit of € 186 (in 2003) is prohibitive for such an approach, and – as "extrapolation" – the speculation remains that all pickups of this type received the same more or less crooked and messy assembly. (Here, the business administrator nods, and with a stern expression points to the fact that a single alnico magnet is already as expensive as 40 cents: "one needs to make a little profit, after all".)

5) We may be critical regarding the motor-test-bench, and note that
- the string-crank we used does not represent an infinitesimal short impulse, that
- a rotational movement is happening, and that
- transformation in the frequency domain requires a linear system.

Moreover, the string does not maintain its cylindrical shape at the crank but gets minimally bent (steel wire cannot be cranked in another way). For 1 mm crank amplitude and a desired measuring dynamic of 40 dB, the required production tolerance is as small as10 µm. …. Or maybe 60 dB were desired – in that case you need to bump it all up to 1 µm tolerance. … Oh, right: and please do install the whole shebang on plastic bearings free of friction and mechanical play …..

6) The **shaker-test-bench**, as well, includes typical artifacts: the string does not vibrate in one plane but along a slightly elliptical path; the magnetic drive of the shaker generates a magnetic crosstalk; measurements are limited to the low-frequency range due to self-resonances; the drive is non-linear and time-variant due to it heating up. Plus much more.

7) The **laser-vibrometer** operates with sufficient accuracy if mounted on a heavy stone-table (this was the case for our experiments). In order to keep the noise low, a suitable narrow-band-filtering is required, as discussed e.g. in chapter 6.

8) In order to be able to exactly specify the effective coil surface, a wire as thin as possible should be used for all **measurement coils**. However, the thinner the wire, the greater the risk of damage (as a compromise, 60 – 80 μm magnet wire could be used).

9) Measurements which include forming the integral of the measurement signal (e.g. to derive the velocity from the acceleration) are falsified by **amplifier offsets**. Even for low-offset op-amps sometimes just moving the air above the housing of the op-amp is sufficient to produce measurable drift-effects. With a corresponding effort, this problem proves to be just about manageable.

In the end, we obtain some relief from comparing the individual measurement results: it ain't all that inaccurate. As long as one does not approach the problems with excessive expectations, and as long as one avoids real blunders (which do wait to happen, though), the test–bench–measurements yield reliable results. The comparison of measuring results taken over many years corroborates the (subjective) assumption that the typical accuracy of a test-bench is comparable to that of a precision-SPL-meter, and amounts to about 1 dB.

5.10.7 FEM-calculations

Besides unwavering faith ("ONLY pre CBS"), listening experiments ("vintage vs. new") and measurement ("3D-laser") – and maybe sheer ignorance – the only other way to describe the function of a pickup "exactly" seems to be mathematical/physical finitization. The magnetic field is cut into hundreds of thousands of fragments (the finite elements) for which a computer calculates (for hours) the exact field-distribution. The more expensive the software and the larger the number of elements, the better this works. And so the ambitious hobby-scientist enthusiastically posts his colorful fluxograms on the Internet – to deliver the definitive proof why the Strat pickup sounds differently than the XY-90. Please heed two words of wisdom from a professional scientist who threw in the towel after half a year: forget it.

It isn't that these finite models are generally bad – the problems lie in the data entered by the user. But first things first. Field calculations are simple if direct current flows through a straight wire of infinite length. That ain't the case for a gittar pickup? Okay then. Let's open the toolbox for permanent magnets and click on "cylindrical magnet". Go to "Mesher", on to "Solver", do a color plot …. and off into the bin it goes. Any questions? Sure – lots!

The field of *one* **cylindrical magnet** is a relatively simple one because it features rotational symmetry. One might be able to ignore that a pickup includes 6 of them (let's "approximate"), and as well that there is a string; oh … 6 strings, even. Didn't someone say checking out a string-less guitar: "*for a beginner that will suffice.*" But seriously, the magnetic field without string is of course only of any use as a starting point. Statements regarding the transmission behavior work only with inclusion of the string. That, however, makes the rotational symmetry go out the window; the calculation effort rises dramatically. We could see that as a challenge: those with lots of experience with the cross-linking should be able to master the geometry, set the boundary elements correctly (a job not at all trivial), and have the field calculated with string. Now, this field needs to travel through air, with the relative permeability $\mu_r = 1$. And through a steel string with a high permeability (due of the ferromagnetism). And through a permanent magnet with a rather small μ_r. Limiting the effort, a search leads $\mu_r = 4$ for alnico and to $\mu_r = 40$ for steel. Again: off into the bin it all goes.

Your regular FEM software will model ferromagnetic materials with a *BH*-characteristic. One *BH*-characteristic, that is. That's because that way you don't have to distinguish which branch of the hysteresis-curve holds the operating point. So, the simulation gives us an approximate impression of the field shape – but what about being accurate? Will the big effort bring ultimate perfection? Well, both the string and the magnet are magnetically hard, and therefore the two hysteresis-branches differ considerably: off then to get more computer power (if one gets that kind of support to begin with ….) and to calculating the two branches. Two? I.e. merely the boundary curves which in fact each hold an infinite number of *BH*-pairings? Now the "Solver" can't manage it anymore, the iteration fails to converge, the software capitulates. Ah – but the newest release takes care of this issue as well! Super! So now we have two different non-linear performance maps of the materials, and can only hope that magnet and string abide by these. Does the newest release include a button for **anisotropy**, i.e. the fact that the magnetic characteristics of metals are dependent on direction? In the simple model, isotropy is used as a basis, but the string was *drawn* during the manufacturing process and therefore subjected to significant mechanical stress in one direction – so at least we should check whether it really acts isotropically. Alnico-V-magnets are certainly anisotropic, ceramic magnets often as well. Plus, unfortunately only a small part of the magnetic flux flows through the cylinder in the axial direction while a significant part penetrates the cylinder mantle at an angle. In conclusion: no final perfection, and in spite of mathematical overkill we merely have a rough approximation.

As the proud owners of colorful fluxograms with increasingly fine resolution and barely visible finitization we now believe we have the license for carrying out the final step: the **dynamic analysis**. Now the sting is to vibrate i.e. it changes its distance to the magnet. We suggest our desire to the FEM-software in the form of discretization: instead of one string/magnet distance we do an overnight calculation-run for 10 of them (not more, let's start small and not exaggerate). This yields 10 different magnetic fluxes, and as difference between them we obtain the quantity on which the induced voltage depends: the change of the magnetic flux over time.

The highly optimistic assumption at the basis of this result is that material data we use are close to reality – although rarely anybody will have tensorial data of anisotropic ferromagnetics at their disposal. Let us imply that we would indeed have access to such numbers – how do we continue? Eddy currents form in the magnet, and they displace the magnetic field which we have just calculated with much effort! So: either we limit ourselves to 82,4 Hz (that's at least something, isn't it?), or we justify even (much!) more calculation effort and do a truly dynamic run. But then we realize at some point that the difference of two approximately correct numbers will have a mightily big error margin. So again and finally: off it all goes into the bin.

For all those still not convinced (because 5 months of work have been already invested, and because the nice software support people were so kind to eradicate all programming errors): as the magnetic field changes (which it does due to the vibration of the string), the *BH*-point does not run along the hysteresis-family of curves. The gradient of the hysteresis curve is the **differential permeability** but what we need is the **reversible permeability** which is smaller that the differential one (Chapter 4.10.3). In the end we have therefore now a hodge-podge collection of approximated dependencies the difference of which is not the mathematical "ultima ratio" but still remains a coarse estimate. Not bad if you have nothing else to do … but don't show it, will you?!

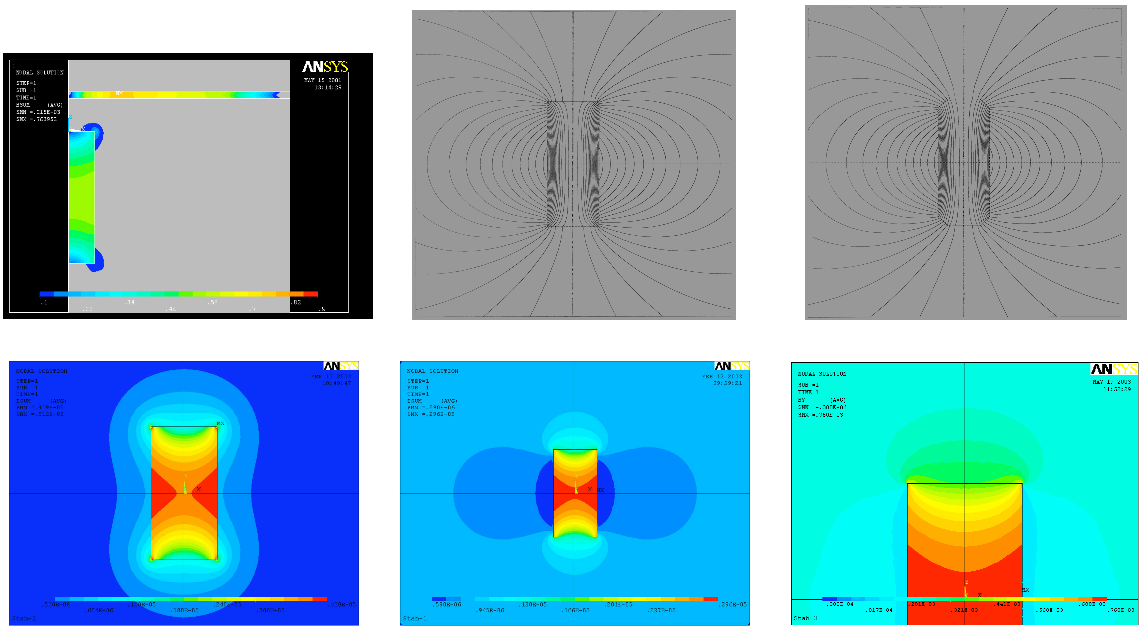


Fig. 5.10.20: FEM-graphs