5.7 Hum-sensitivity

Magnetic pickups generate an electrical alternating voltage from a magnetic alternating field. This voltage is the wanted signal as long as the alternating field results from the string vibrations. All alternating fields, which are not due to the string vibration, generate, in contrast, undesired **interference**. In the environment of the electric guitar the most common source of interference results from 50-Hz-fields caused by the 230-V-power-network (or 60 Hz at 110 V in the US, or other frequencies and voltages, depending on the country and local power system). A 50-Hz-field coupled into a guitar pickup comes through as a low-frequency interfering tone (49 Hz equals the pitch of G_1) which is called *hum*. Hum interference rarely is of a single frequency – more often it is a complex tone with harmonics at multiples of the fundamental (50, 100, 150, 200 ... Hz – or in non-European power supply systems the harmonics of the local supply frequency). Filtering the fundamental therefore does not help a lot.

The principle of **magnetomotive force** provides us with the basis for the quantitative interference: around a long, straight conductor a magnetic fields with the flux density of $B = \mu_0 I/(2\pi r)$ is created. In this formula, I is the current strength, r is the radial distance, and μ_0 represents the permeability of air $4\pi \cdot 10^{-7}$ Vs/Am. Accordingly, a line carrying 10 A generates a flux density of 1 μT at a distance of 2 m. This seems not to be a lot – however, in a coil of 10 cm^2 with 10000 turns, the resulting flux is 10 μVs, after all, and the corresponding voltage at 50 Hz is 3 mV. For a signal of 100 mV, the signal-to-noise ratio is a mere 30 dB i.e. not a lot. In practice, things are a little different, though – not so much because the magnets on a pickup have a fields-amplifying effect (about +2 dB) but because power current is supplied via two-wire lines. The forward and backward flow generates anti-phasic fields which attenuate each other in their effect. For the situation as given above this results in an improvement of the signal-to-noise ratio by about 50 dB to about 80dB. This would seem adequate – a tape recorder would be very happy with such a dynamic range. Guitar players, however, are no tape recorders (even if they tend to copy and repeat licks ...). They will overdrive their amps, depending on the style of music, by 10 – 30 dB. This again reduces the signal-to-noise ratio in our example to as little as 50 dB, and given e.g. an SPL of the music of 100 dB (VERY moderate Hardrock), a clearly audible hum interference remains. The 50-Hz component is not the actual issue (it may eve be below the hearing threshold, but the almost always present harmonics will be rather disturbing. Also, power transformers, CRT screens, fluorescent lights, switched power supplies or electrical motors can create much stronger interference.

Fig. 5.7.1 shows time function and spectrum of two typical interference signals: the one of a CRT screen causes an impulse-like noise, while the stray field of the mains transformer of a power amplifier generates a distorted sinus wave. The derivative of the sawtooth-shaped ray-deflection in the CRT-screen results in the needle-shaped peaks in the upper signal shown in Fig. 5.7.1; it reaches about 12 mV as a maximum. This interference was recorded with a Stratocaster about half a meter away from the screen, and while this signal does not hold a lot of power, it may already lead to overdriving the amplifier due to its high peak values. The spectrum diminishes only little towards the high frequencies; the guitar amplifier generates a hard, buzzing tone. The stray flux of the power amp transformer includes mainly the 1st, 3rd and 5th harmonics (due to saturation in the core and the hysteresis), and the peak value of the time function is about 0,9 mV. The sound of this interferer is a low hum similar tot he sound of an electrical bass guitar.

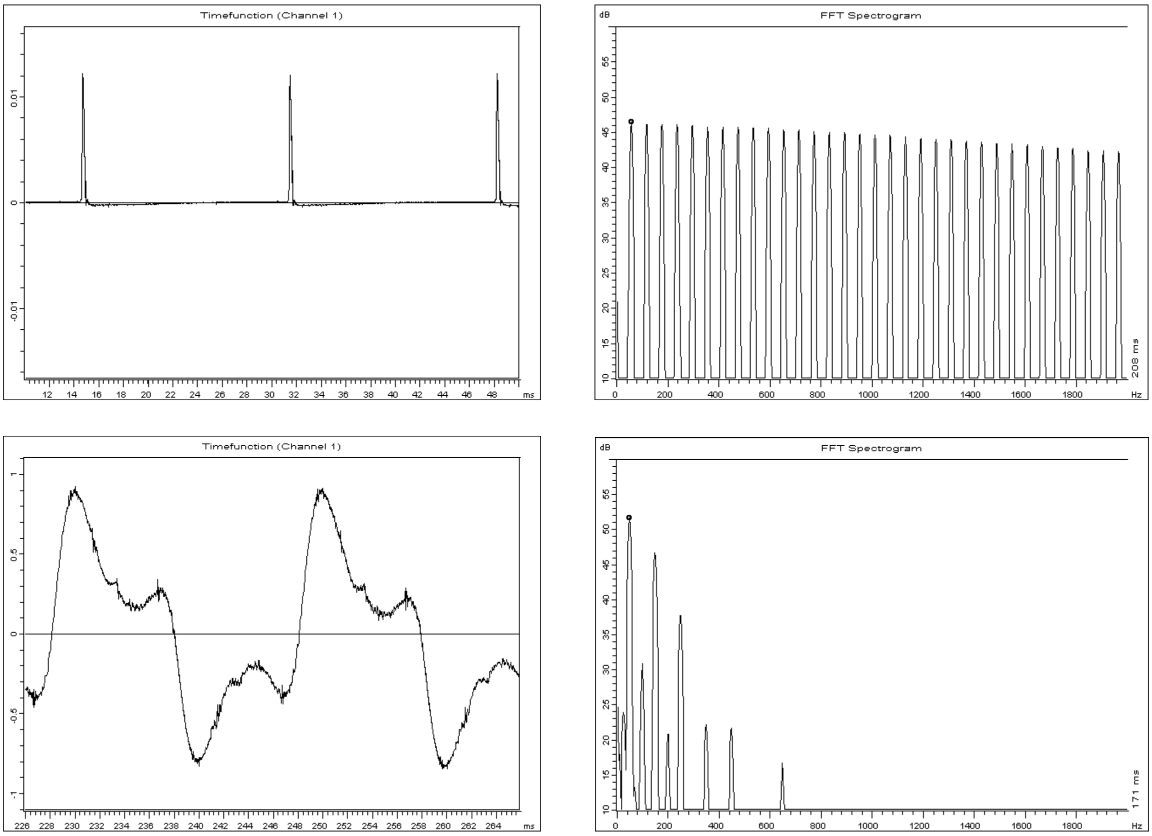
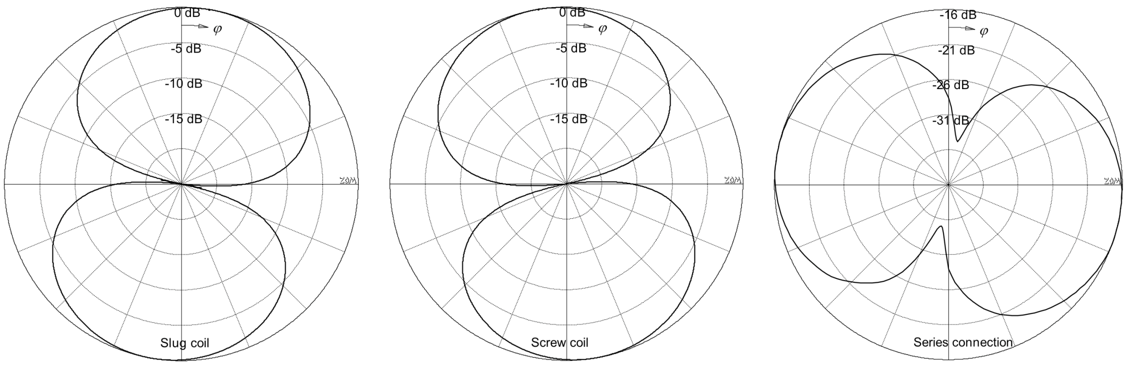


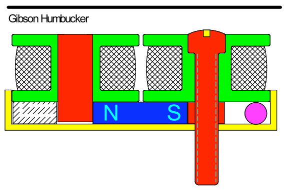
Fig. 5.7.1: Time function (left) and spectrum (right) of interfering signals. The upper two graphs relate to noise due to a CRT screen, the lower graphs show the interference by a transformer. The left graph for the CRT is scaled in Volts; the maximum value is 12 mV. The time function for the transformer is scaled in mV with the maxima being at 0,9 mV. Both level spectra are scaled in dBμ, i.e. relative to 1 μV.

In order to obtain quantitative data on the hum-sensitivity of typical guitar pickups, **measurements** were taken in an artificial interference field created via a pair of **Helmholtz coils** (B_{eff} = 6,5 μT). For singlecoil pickups, the axis of the coil was oriented in parallel to the direction of the field while humbuckers could be rotated. The interfering voltage (measured at 500 Hz) was 0,1 – 0,2 V for singlecoils; for humbuckers the maximum was 30 mV. Taken by themselves, these numbers are not very meaningful – however, in combination with the transfer coefficient of the pickup it is possible to give a **signal-to-noise ratio** (level of the useful signal minus the level of the interference). Of course, a pickup boasting 10000 turns on its coil will reproduce the interfering field more strongly (i.e. louder) compared to a pickup having 5000 turns, but the former will also generate a louder useful signal than the latter. Consequently, the individual relation between voltage of the useful signal and the voltage of the interferer (or the difference between the levels of these signals in dB) is the purposeful measure.

It was striking during most humbucker trials that – in contrast to the euphoric slogans in advertisement – the hum-rejection is rather modest. Seth Lover's statement that *"the 2 coil pickup eliminates the hum"* should not be taken literally. Indeed, the very plausible basic principle of interference compensation using two inverse wound coils requires a design which is symmetric relative to a single central point; this is not there for your typical humbucker. The magnet positioned below the coils bends the magnetic field and downgrades the hum-suppression substantially.

In **Fig. 5.7.2** we see the directional patterns gathered with a Gibson 490R pickup. If only a single coil (without ferromagnetic materials) were rotated in the magnetic field, a cosine-shaped directional pattern would be seen (direction of field, rotation axis and coil axis all being perpendicular to each other). Due to the ferromagnetic being positioned like a "u" the field is bent such that both coils "squint" inwards; the highest sensitivity is found to be off by 9°, directed inward from the coil axis. Interfering fields directed through the pickup in parallel to the axis of the coils can be compensated to good effect. However, if the direction of the field is perpendicular to the coil axis, the compensation effect is only rather moderate.





$$D_1 = \cos(\varphi - 0.16); \qquad D_2 = \cos(\varphi + 0{,}16);$$

$$D = 0{,}935 \cdot \cos(\varphi - 0{,}16) \; - \; \cos(\varphi + 0{,}16)$$

The coil with the slugs is less sensitive by 0,6 dB.

Fig. 5.7.2: Normalized directivities D of the humbucker coils: 1 = coil with slugs, 2 = coil with screws. The pickup (Gibson 490R) subjected to a parallel AC-field of 500 Hz with both coils disconnected and measured separately. The right-hand directional diagram shows the directivity with both coils connected on series. φ = rotational angle of the pickup relative to the magnetic field.

In Fig. 5.7.2 the minimum for the series connection does not occur at φ = 0° (i.e. axial direction of field). This is not due to the magnet but to the differences between the coils which are created on part by differences in the coil winding and in part by differences in the coil core (i.e. the screws and slugs). In practice it is rather irrelevant for which interference direction the pickup is least sensitive since interference can come from any direction. The player's performance will not improve if he/she needs to hold the guitar horizontally to minimize the hum♣. Therefore, it is best to concentrate on **worst-case-**scenarios and consider those interferer directions which create the strongest hum. Magnetic fields with a direction running in parallel to the coil axis are most disturbing for singlecoil pickups. Gibson-type humbuckers are most sensitive to hum-fields running in parallel to the strings (i.e. axis-normal). In coaxial humbuckers (see chapter 5.3) the coil-symmetry is the decisive factor for the direction of strongest interference – normally these pickups hum the most for axis-parallel fields.

♣ Come to think of: that may depend on the guitar player, as well, …

Fig. 5.7.3 schematically shows the field distributions for a humbucker. The magnetic flux in both coils is opposed if the direction of the field runs in parallel to the coil axis. This shows that a direction-independent compensation is **in principle not possible**. For the Gibson 490R and axis-normal field direction (i.e. the worst case), the anti-phase connection of the coils reduces the interfering signal merely to one third – referenced to the interfering voltage which would be generated in one coil by the axis-parallel field. Since the coils are connected in series and the useful signals are summed up, we could add another 6 dB and specify the **worst-case hum-suppression to 16 dB**. On the other hand, it should not be forgotten that not all useful signal components are in fact added up: a number of partials of the string vibration are even cancelled out completely due to the sampling of the string at two points.

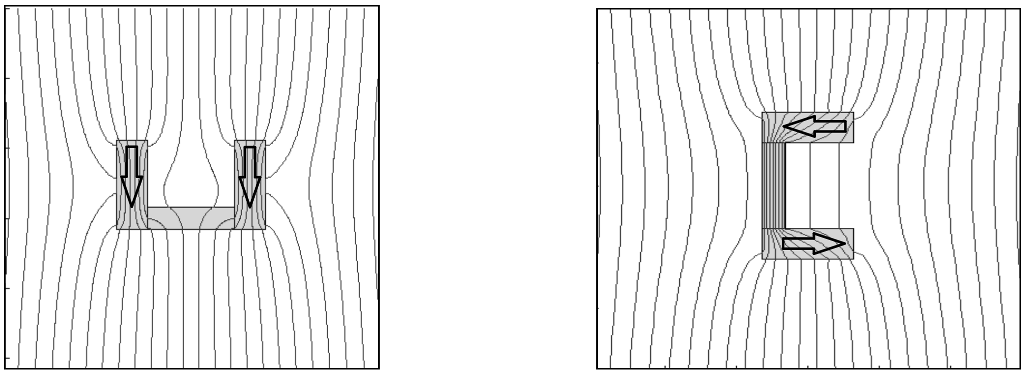


Fig. 5.7.3: Shape of magnetic field running through a Gibson-type humbucker. If the field runs in parallel to the coil axis (left), in-phase voltages are induced. However, for an axis-normal magnetic field (right) anti-phase interference signals are created (just like the signals induced by the strings).

The directionality of the interference suppression could be described in simple formulas in Fig. 5.7.2. For the **frequency dependency** we get more complex relations, however. On the one hand, this is due to the skin-effect but also due to the capacitive coupling between the two coils at higher frequencies. **Fig. 5.7.4** depicts the frequency responses of the transmission with an excitation in the parallel Helmholtz-field. Compared to the single-coil operation the Gibson 490R reduces the interference by merely 10 dB (or 16 dB considering the doubling of the useful signal with both coils in operation). For Fender's coaxial humbucker the gain is **24 dB**, after all.

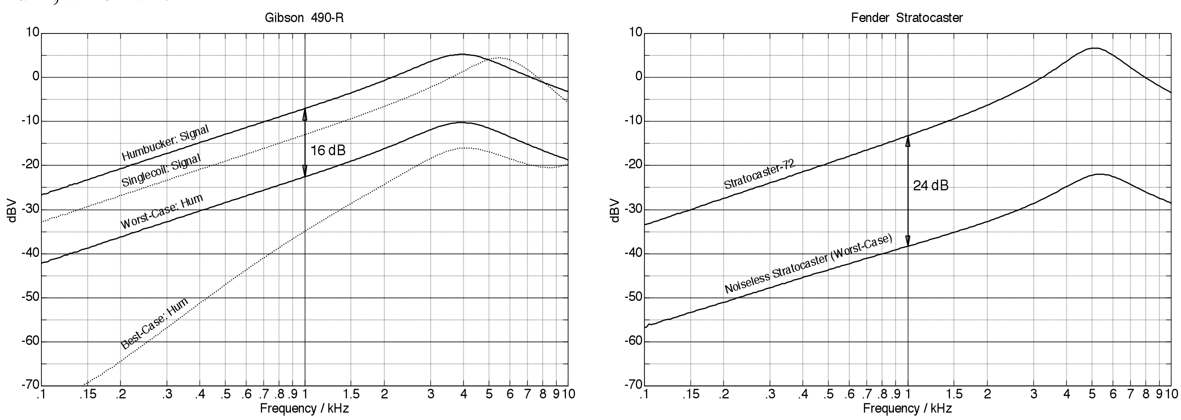


Fig. 5.7.4: Frequency dependency in the parallel Helmholtz field (6,5 μT_{eff}). The pickups were loaded each with 200kΩ // 330pF. For comparison, the right-hand section shows Stratocaster pickups with comparable sensitivity.

The transmission factors shown in Fig. 5.7.4 are not quite applicable to the real-world operation: for the interference generation, the Helmholtz coils are a good standard; however, this does not hold for the generation of the useful signal, because the air-gap changes caused by the string vibration have a locally very limited effect. To achieve a comparable assessment, the following **measurement method** was used. For each pickup, the interference voltage level was measured at 520 Hz and an effective flux density of 6,5 μT (worst case). To determine the sensitivity to the useful signal, a 0,66-mm-string was moved in front of the magnet poles in axial direction at 84 Hz and an amplitude of 0,4 mm. The S/N-ratio (level of the useful signal minus level of the interfering signal) derived from these readings was arbitrarily increased by 11,5 dB such that for the Stratocaster pickup – which was used as reference – a **standardized hum rejection of 0 dB** resulted. Using this definition, pickups with positive hum rejection are less interference-prone that the reference pickup. The best results were achieved by the Joe-Barden Strat pickup and the Gretsch FilterTron – due to their symmetric construction.

The following **table** lists the data taken during the measurements done according to the above approach. The double-digit representation for the hum-rejection of the singlecoils does not imply that indeed an accuracy of 0,2 dB was achieved. Such a high accuracy is actually not required, anyway, since differences of e.g. 1 dB are normally not detectable. However, the low hum-sensitivity of the Gretsch **HiLo-Tron** is noticed. This pickup shows that one level alone does not have much informative value: the hum level of the SDS1 is actually 2 dB higher – the SDS1 delivers a much higher useful signal level. On the other hand, the DP172 is even less sensitive that the HiLo-Tron – its hum-level is however lower by almost 8 dB. We must moreover also not forget that factors other than these pickup-parameters do play a role: the HiLo-Tron is known for its brilliant (i.e. bright) sound and will presumably be used by most guitar players for a more "clean" sound using little distortion in the amplifier. This is rather different for the SDS1: with its high output and mid-range emphasis, it is predestined for "crunch" i.e. a distorted reproduction. Distortion, however, implies high gain, and thus relatively loud hum.

Tonabnehmer §)	Hum-level /dBV	Signal-level / dBV	S/N-ratio / dB
"Telecaster"-Fake (Neck)			
Fender Jazzmaster-62 (Bridge)			
Fender Jazzmaster-62 (Neck)			
Duncan APTR-1 (Telecaster-Type, Neck)			
Fender Telecaster-52 (Neck)			
Duncan SSL-1 (Strat-Type)			
Schaller			
Fender Stratocaster (bar magnet)			
Fender Stratocaster-72 (G-Magnet)			
DiMarzio DP172 (Telecaster-Type Neck)			
Fender Telecaster-73 (Bridge, D-Magnet)			
Rockinger P-90			
Fender Telecaster-70 (Bridge), w/out plate			
Rockinger Strat-Type (bar-magnet)			
Rickenbacker (Toaster-Pickup)			
DiMarzio SDS-1			
Fender Texas-Tele (Bridge, D-Magnet)			
Fender Telecaster-70 (Bridge)			
Fender Stratocaster (USA Standard)			
Ibanez Blazer			
Gibson P-90			
"Telecaster"-Fake (Bridge)			
Fender Telecaster-52 (Bridge)			
Duncan APTL-1 (Telecaster-Type, Bridge)			
Gretsch HiLoTron			
Fender Jaguar (Neck)			
Lace-Sensor gold			
Squier Humbucker			
Gibson 490R			
Gibson Burstbucker #2			
Gibson ES 335 (Neck, 1968)			
Gibson 57 classic			
Fender Noiseless Stratocaster (Neck)			
DiMarzio DP184			
Gibson Tony Iommi			
Gretsch FilterTron			
Joe Barden (Strat-Type, Bridge)			

Table: hum-rejection. Interfering field: parallel single-frequency magnetic field, f = 520 Hz, B_{eff} = 6,5 μT. String vibration: f = 84 Hz, amplitude 0,4 mm, distance of string to magnet = 2mm, D'Addario PL-026. The pickup was loaded with 50 kΩ fro this measurement.

§) The actual values are reserved for the printed version of the book

The levels of hum in the **Jazzmaster**- and the Stratocaster-pickups differ by 7 and 8 dB, respectively. This difference matches the ratio of the surfaces (2:1) and the assumed number of turns (ca. 1:0,9). The stronger hum-sensitivity of the Jazzmaster-pickup would be compensated if the useful signal level would also be stronger by 7 – 8 dB. However, the gain relative to the Stratocaster pickup is only about 5 dB i.e. the Jazzmaster-pickup "hums more". The difference of barely 3 dB is however not dramatic, plus the spectrum of the interference plays a role, as well. Connected to the typical circuitry, the Jazzmaster pickup has a stronger resonance peak than the Stratocaster pickup: in case of a broadband interference (e.g. fluorescent lights, or phase angle control) the Jazzmaster carries both the useful signal and the interference equally. However, if the interference has its emphasis at low frequencies (incandescent light, or power transformers), the Jazzmaster wins out because the useful signal is emphasized. As long as the differences in the signal-to-noise ratios (measured at 84 Hz / 520 Hz) are merely a few dB there will be no big effect noticeable in practice.

Humbuckers do play in another league: relative to a singlecoil they show a significant S/N-gain of 19 to more than 40 dB as long as they are subject to interferers generating parallel magnetic field lines (as generated by distant hum sources or by Helmholtz coils). A power transformer operating close to a humbucker will generate a strong field with bent field lines and may cause strong disturbance despite the hum-rejection effect. Moreover, the two coils of a humbucker may not have the same sensitivity: if the number of turns or the core materials are different, the compensation effect may be incomplete.

Many singlecoil-guitars fitted with more than one pickup feature a **hum compensation** via different direction (cw or ccw) of the winding and opposed magnet polarity of the pickups. As two pickups are selected in combination, a humbucking-effect happens. Occasionally a **compensation coil** is built into the guitar – it includes no magnet and reacts only to the interference. Connected in series with the pickups coil, and given correct dimensioning, it reduces the interference. Since the useful signal has to travel through an enlarged inductance, the resonance frequency decreases, as well. Changes in sound are possible. Connecting the compensation coil in parallel (as it was tried with moderate success e.g. in the P100) increases the resonance frequency.

In closing it should be mentioned that **magnetic shielding** is possible but is inefficient and impractical. Fully encapsulating the pickup would be pointless since it could not sense the string vibration anymore. Shielding covers around both the pickup *and* the string do exists, but the musicians see them as obstacle (or best as transport safety) and remove them (sometimes to use them as ashtrays ....) . However, shielding against **electrical fields** which are capacitively coupled to the pickups from voltage-carrying lines, is possible and purposeful. Shielding foils and conductive paint serve well for this. Still, it should be considered that the magnetic fields will induce an **eddy current** into any conductive surface which may dampen the pickup resonance. For this reason, high quality shielding covers are made from nickel silver (German silver) and possibly in addition can include slots (see chapter 5.9).