5.11 Pickup-directionality

Magnetic pickups predominantly detect string vibrations perpendicularly oriented to the surface of the fretboard. The string swings back and forth between areas of higher and areas of lower magnetic field strength causing flux changes in the pickup coil. A motion in parallel to the fretboard makes the sting move merely in areas of approximately equal field strength such that only a small voltage is induced. Other than the polarization of the string vibration it is also the propagation direction of the wave, which we need to consider (in particular for humbuckers).

5.11.1 Polarization-plane of the string

The polar diagram shown in Fig. 5.11.1 tells us about the dependency of the pickup voltage on the angle of the oscillation plane of the vibrating string. To do the measurement, a D'Addario string (PL-026, diameter 0,66 mm) was sinusoidally deflected. The amplitude was 0,4 mm and the distance between string and magnetic pole was 2 mm. The string was centered above the magnetic pole (on the magnetic axis) of a Telecaster bridge pickup.

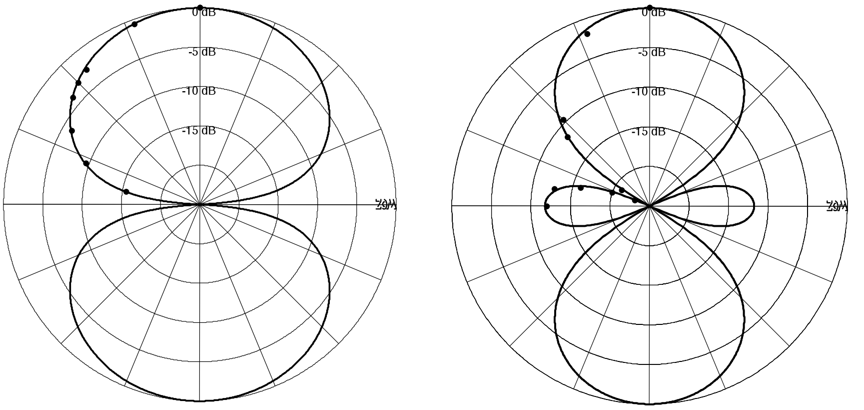

Fig. 5.11.1: Polar diagram of a magnetic pickup (Fender Telecaster, bridge). The line represents the model calculation, the dots show the measured results.
1st harmonic (left),
2nd harmonic (right).

Above the centre of the magnetic pole the **1st harmonic** shows a cosine-shaped dependency with a maximum sensitivity for fretboard-normal oscillation and complete cancellation for fretboard-parallel oscillation. The angle-dependency of the **2nd harmonic** has a zero at 63° and a secondary maximum at 90°. Let us consider for an axially symmetrical magnetic field, a sinusoidal, centered oscillation oriented normally to the axis of symmetry yields. It will yield a field shape which can include – due to the symmetry (even function) – exclusively even powers of the series expansion. In other words it holds exclusively even-numbered harmonics save for a DC component that remains unimportant for the present point of view. However, this changes as soon as the string does not follow a centered path of movement anymore – it may be shifted by string bending or, it may have been positioned eccentrically already during production. Fig. 5.11.2 indicates string positions of an American Standard Stratocaster built in 2002. The distance of the magnetic axis is 10,4 mm uniformly *for all three pickups*. Since the strings are nut running in parallel but diverge from nut to bridge, it is not possible that all 6 strings are centered above the magnets, and therefore the transmission coefficient is not only dependent on the oscillation direction of the string but also on the string position. The latter may be shifted in *two* dimensions.

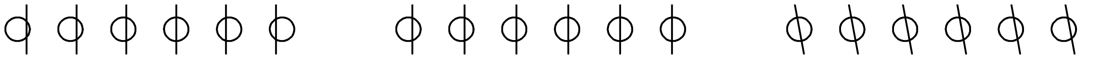

Fig. 5.11.2: String positions over the magnetic poles: neck, middle and bridge pickups (left to right). The strings do not run straight across the bridge pickup but at an angle.

Polar diagrams such as the one given in Fig. 5.11.1 are therefore valid only for their individual case – a generalization is possible to a limited extent only. To detect the dependency of the transmission coefficient on the string position, a number of pickups were measured on the text bench (**Fig. 5.11.3**). The string was subjected to a sinusoidal deflection at a frequency of 85 Hz and shifted while keeping a constant distance over the magnetic poles. Despite the fact that the pickups are of different build (Chapter 5.1 – 5.3), the resulting curves are similar. The pickups differ in their absolute sensitivity (loudness), and moreover the transmission coefficient is dependent on the string position. It is not surprising that the voltage level is largest right on top of the magnetic pole and smallest in between two poles – for a Telecaster the level difference for these two conditions amounts to 5 dB, and it is somewhat smaller for the other pickups. In the figures only one half of the respective pickup is shown since the curves are symmetric relative to the middle of the pickup. The Stratocaster pickup is the one exception since its magnetic poles protrude – in the original condition – differently from the pickup housing (staggered magnets). They were, however, adjusted for equal height during the measurements.

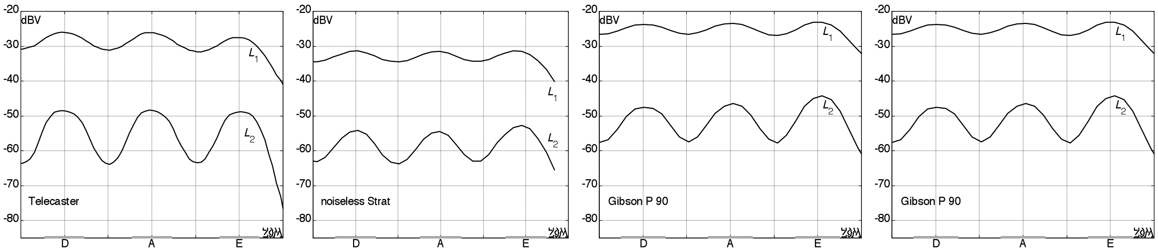

Fig. 5.11.3: Location dependency of the level of the 1st and 2nd harmonic; string motion normal to the fretboard plane. Amplitude 0,4 mm, string-to-magnet distance 2 mm, intrinsic distortion of the shaker compensated for.

Fig. 5.11.4 depicts corresponding results for string vibration polarized in parallel to the fretboard plane. There are general similarities but also significant differences to the fretboard-normal motion. However, we must not be tempted to explain inter-individual sound differences from these diagrams. In **listening experiments** we found neither a sideways shift in the string position (keeping the string-to-magnet distance constant) nor a change in the string vibration polarization to have any *significant* effects. That does not exclude certain smaller effects becoming apparent in the sound for individual cases but it does qualify the significance (or rather insignificance) of such effects. For example, the sound changes much more, as the string is plucked at a different position of with a different pick. A big difference is heard between picking a string in a fretboard-parallel motion and "plucking" it perpendicularly such that it hits the fretboard; this difference, however, stems from the strings hitting the frets i.e. from the mechanical vibration (and not the directionality of the pickup).

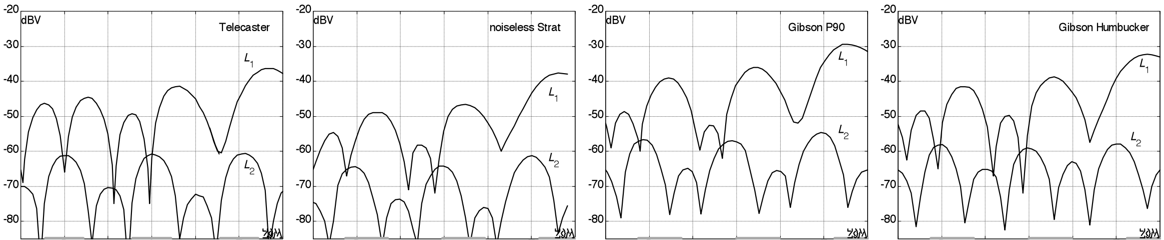

Fig. 5.11.4: Location dependency of the level of the 1st and 2nd harmonic; string motion parallel to the fretboard plane. Amplitude 0,4 mm, string-to-magnet distance 2 mm, intrinsic distortion of the shaker compensated for.

Fig. 5.11.5 shows the results for the measurements of all 4 pickups on top of each other. The curves were vertically shifted such that the divergences are minimal. For fretboard-normal oscillation there are only minute differences for the 1st harmonic; larger differences exist for the minima of the 2nd harmonic but this is insignificant due to the much lower level compared to the 1st harmonic. Fretboard-parallel string vibration causes more pronounced differences since zeros in the transfer function (i.e. cancellations) are passed through and thus small imbalances in the magnetic field can have effects on the voltage level. The difference in the height of the maxima in the right-hand figure is due to the finite number of magnets, which causes a magnetic field diverging toward the outer range. If a large number of magnets were lined up we would see maxima of equal height (save for the outer magnets).

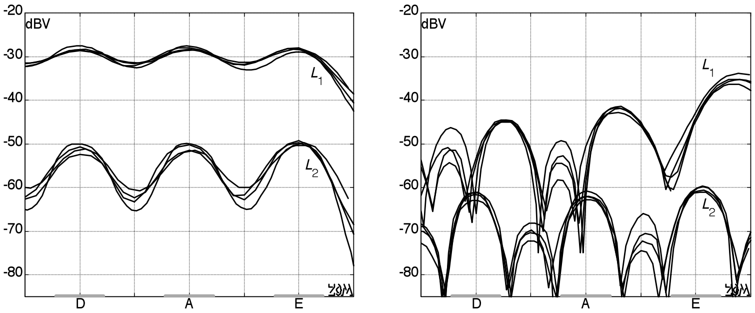

Fig. 5.11.5: Location dependency of the level of the 1st and 2nd harmonic; string motion normal to the fretboard plane (left), parallel to the fretboard plane (right).

In the range of the E-string all curves have a similar shape, despite the fact that:

- the Telecaster magnet is cylindrical with a plane face,
- the Stratocaster magnet is beveled with a wraparound,
- roundhead screws focus the field of a bar magnet for the P90,
- for each string a slug and a screw focus the field for the humbucker.

Towards the middle of the pickup we do see (for the string vibration in parallel to the fretboard plane) difference of in excess of 10 dB but their relevance immediately needs to be put in question again: 1) the real string does not vibrate exclusively in the fretboard-parallel plane; 2) if indeed this difference were of any significance, the A- and the D-string would sound differently than the E-string which could not be confirmed at all in listening tests. In fact, all three strings generated e.g. for the Stratocaster the expected sound without any string-specific special feature (of course, the pitches did differ).

5.11.2 Direction of the wave-propagation

As discussed in the previous chapter, magnetic pickups have directionality with regard to the orientation of the string-oscillation. However, under certain conditions the transmission characteristic of the pickup also depends on the propagation direction of the wave travelling along the string. This effect does not manifest itself in axially symmetrical pickups, but as soon as the design is asymmetrical, the wave running in one direction can generate a different induction voltage compared to the wave running in the other direction.

Fig. 5.11.6 explains the context with a simplified block-diagram. A string is sampled at two locations. A transversal wave propagates along the string; its direction is defined as "forward" with the index V (from the German "vorwärts") and "reverse" with the index R. Between the two sampling points we find a **phase-delay** τ that may show any kind of dependency on frequency (dispersion). A humbucker readily serves as practical example – with it the distance between the sampling points typically amounts to 19 mm.

Fig. 5.11.6: Block-diagram for a string oscillation sampled at two locations.

The two sampling signals (induction voltages) each run through a filter, the transfer-function of which is defined by $\underline{H}_1$ and $\underline{H}_2$, respectively; subsequently the two signals are added. In a first step the overall transfer function can be set to:

$$\underline{H}_V = \underline{H}_1 + e^{-j\omega\tau} \cdot \underline{H}_2; \qquad \underline{H}_R = \underline{H}_2 + e^{-j\omega\tau} \cdot \underline{H}_1$$

however this would lead to different points of reference: for the forward traveling wave this would be the input of $\underline{H}_1$ and for the reverse wave it would be $\underline{H}_2$. It is conducive to chose the **pickup mid-point** as reference for the time, and thus to reformulate the transfer functions accordingly:

$$\underline{H}_V = e^{+j\omega\tau/2} \cdot \underline{H}_1 + e^{-j\omega\tau/2} \cdot \underline{H}_2; \qquad \underline{H}_R = e^{-j\omega\tau/2} \cdot \underline{H}_1 + e^{+j\omega\tau/2} \cdot \underline{H}_2 .$$

For the filters (pickup RLC low pass) several special cases need to be distinguished: $\underline{H}_2 = \underline{H}_1$, $\underline{H}_2 = k \cdot \underline{H}_1$, and $\underline{H}_2 \neq \underline{H}_1$. The case of identical filtering ($\underline{H}_2 = \underline{H}_1 = \underline{H}$) correspond to axially symmetrical structure, and the two transfer functions are **identical**: $\underline{H}_V = \underline{H}_R$. The Gretsch humbucker "Filter-Tron" is an example for a real case of this kind:

$$\underline{H}_V = e^{+j\omega\tau/2} \cdot \underline{H}_1 + e^{-j\omega\tau/2} \cdot \underline{H}_2 = 2\cos(\omega\tau/2) \cdot \underline{H} = \underline{H}_R; \qquad \underline{H}_1 = \underline{H}_2 = \underline{H}$$

The second special case comes with the two transfer functions differing by a *real* factor k: $\underline{H}_2 = k \cdot \underline{H}_1$. The two expression in brackets are the conjugate complex of each other, and the two transfer functions are **equal in their magnitude**; $|\underline{H}_V| = |\underline{H}_R|$. The phase functions differ, however, which needs to be considered when superimposing waves:

$$\underline{H}_V = \underline{H}_1 \cdot \left(e^{+j\omega\tau/2} + k \cdot e^{-j\omega\tau/2}\right); \qquad \underline{H}_R = \underline{H}_1 \cdot \left(e^{-j\omega\tau/2} + k \cdot e^{+j\omega\tau/2}\right); \qquad \underline{H}_2 = k \cdot \underline{H}_1$$

The third case can be described by a complex factor ($\underline{H}_2 = \underline{k}\cdot\underline{H}_1$) and includes different overall transfer functions for each of two waves travelling in two directions. This scenario is the one of all humbuckers with **different coils**, and for humbuckers in singlecoil-mode for which the coupling of the magnetic field is non-negligible.

$$\underline{H}_V = \underline{H}_1 \cdot \left(e^{+j\omega\tau/2} + \underline{k}\cdot e^{-j\omega\tau/2}\right); \qquad \underline{H}_R = \underline{H}_1 \cdot \left(e^{-j\omega\tau/2} + \underline{k}\cdot e^{+j\omega\tau/2}\right); \qquad \underline{H}_2 = \underline{k}\cdot\underline{H}_1$$

Fig. 5.11.7 shows an example for strong differences between the two filter functions: a DiMarzio **DP-184** was operated in “split mode", i.e. only one of its coils was connected while the other was left open (electrical idle). We may not conclude from this type of operation that the coil in idle does not contribute: due to the unavoidable winding capacitances (in this case around 500 pF), currents are also flowing in the disconnected coils – they generate a magnetic field which has effects on the other (connected) coil. The split-mode distinguishes itself from true single-coil operation in particular in the range around the resonance frequency. While the connected coil represents a low-pass system (e.g. $\underline{H}_1$), the idle coil works as a band-pass ($\underline{H}_2$), and consequently $\underline{H}_1$ and $\underline{H}_2$ differ significantly, with a resulting strong dependency on direction.

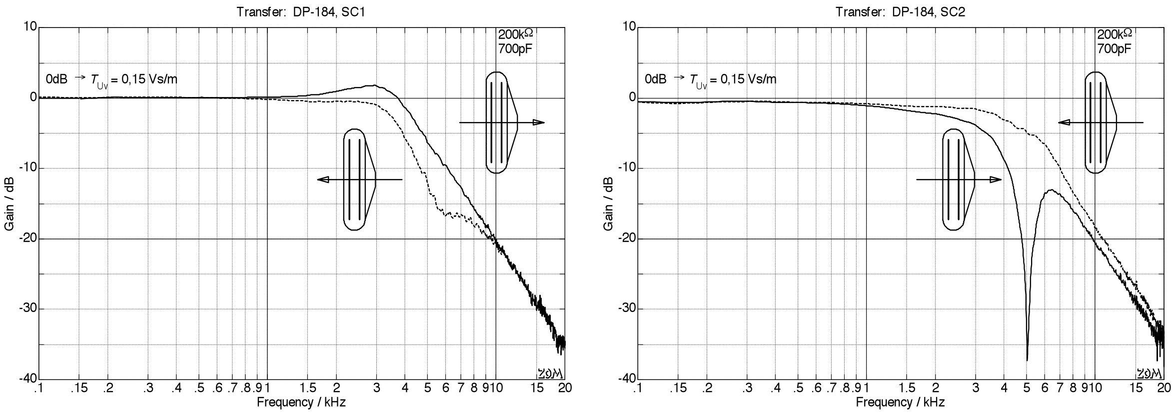

Fig. 5.11.7: Transmission measurement (laser-vibrometer): DiMarzio DP-184 in singlecoil-mode.

We observe directionality, as well, when connecting the two coils in series (**Fig. 5.11.8**), although the differences are smaller than those experienced with single-coil operation. Based on the measurement results, we may assume that both coils have the same number of windings, but obviously the wire diameter is different leading to different DC-resistances (3757 vs. 5100 Ω) and different winding- and coupling-capacitances.

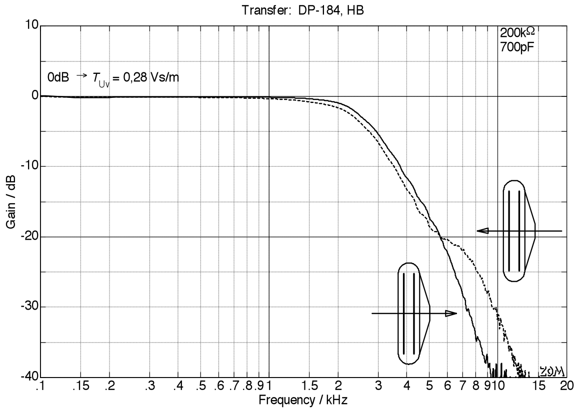

Fig. 5.11.8: : Transmission measurement (laser-vibrometer): DiMarzio DP-184 in humbucking-mode