5.5.5 Polarity

The polarity of the voltage generated by the guitar depends – on top of the string vibration – also on the polarity of the magnet, the direction of the coil winding and the wiring. Old Fender pickups sported a yellow (or white) and a black (or blue) wire; the yellow wire fed the switch while the black went to ground. Very early Fender pickups had the north-pole of the magnets pointing towards the strings but as a rule (from which there are exceptions) the south-pole points "up". Stratocaster pickups are wound clock-wise, Telecaster pickups counter-clock-wise. For the Jazzmaster pickup, the south-poles point "up" for the neck-pickup and "down" of the bridge-pickup. Both are wound in opposite directions so that their signals are added when they are both "on" but the hum-voltages cancel each other out – an advantage which 1970s-Stratocaster pickups also profited from (the middle pickup was reversed in coil winding and magnet orientation). From all this it can either be derived that pickup polarity does not matter much for the sound, or that here lies a secret of the "vintage sound".

For a long time after the publications by G. S. Ohm (1843) and H. v. **Helmholtz** (1863), the hearing system was seen as phase-insensitive: accordingly only the level of the partials define the sound but not their phases. Initially there were contradicting experimental results regarding this assumption until around the middle of the 20th century comprehensive psycho-acoustical experiments could prove without doubt the phase-sensitivity in hearing. However, not all phase changes are audible – which complicates matters. All following considerations refer to **diotic** presentation (i.e. both ears receive the same signal) although, in fact, listening to music involves **dichotic** conditions (i.e. there are different signals at the two ears). However, switching the phase of a pickup results in a diotic signal *change* (i.e. the *differences* at both ears are the same).

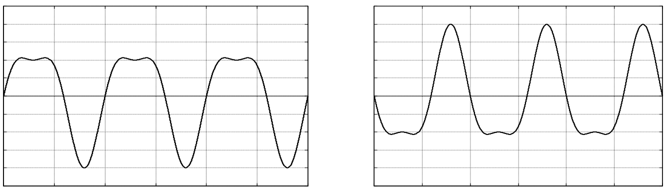

Fig. 5.5.10: time function, compound from 1st and 2nd harmonic; can be projected onto each other via reversing the polarity.

Fig. 5.5.10 depicts two pure ac-time-functions differing only in polarity. With e.g. a fundamental frequency of 200 Hz and a presentation loudness which is not too low, switching between the two signals results in perceiving a small **sound difference**♣. This indicates that the ear can distinguish the absolute phase – in other words, an inward push of the tympanic membrane gives a perception different from the one caused by an outward pull. Physiological experiments measuring the potential in inner-ear-receptors (hair-cells) support this insight: the hair-cells preferably react to an excitation of **one** polarity (bending of the stereocilia in the direction towards the modiolus). This property of the hearing system alone would be reason enough to consider the pickup polarity; still more important, however, is the fact that guitar amplifiers almost always include non-linearities the effect of which is polarity-dependent. Even in the so-called "clean mode" at least the attack of the sound is slightly overdriven, and via "crunch" towards "lead" the **harmonic distortion** increases to an extreme degree – which is not a deficiency but desired tone-shaping. Reversing the input signal would only result in a pure reversal of the output signal in the case that the characteristic curve of the transmission were symmetric re. the origin (odd-numbered distortion products). For even-order distortion, the shape of the signal changes with polarity reversal and so does the level-spectrum of the output (Fig. 5.5.11).

♣ However, at higher frequencies no sound differences can be perceived when switching.

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The left section of **Fig. 5.5.11** shows a non-linear characteristic as it can be found e.g. in a tube pre-amplifier. Using one of the signals from Fig. 5.5.10 as input on the abscissa, the ordinate (output) yields the time functions given in the middle and right-hand sections of Fig. 5.5.11. Even without formal and quantitative description one can directly see the polarity-dependent unbalances resulting from the non-linearity. Depending on the polarity of the input signal two different output signals are created. Only for special half-wave symmetries are the sound differences due to the polarity-reversal limited to the signal attack phase (and therefore remain insignificant); in the general case the phase reversal of a pickup can – depending on the circumstances – lead to audible sound differences.

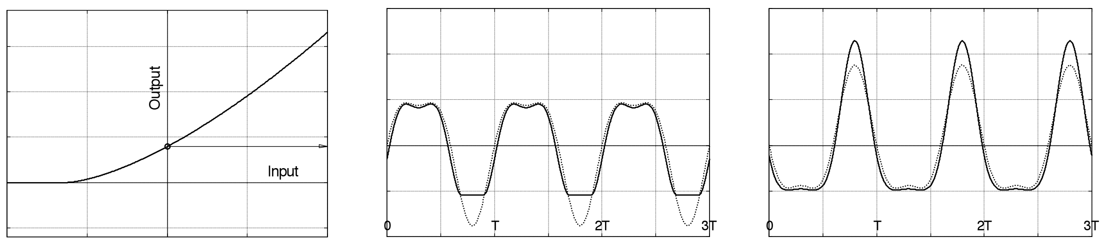


Abb. 5.5.11: nonlinear transmission curve (left), time functions of the signals from Fig. 5.5.10 (-----), after having passed though the nonlinear transmission curve (——). All signals without DC-component.

Next, we will have to look at the question whether – and if so to which degree – the voltage half-waves of magnetic pickups differ. For this, the neck pickup voltage of a Stratocaster (USA) was investigated. Above the magnet pole of the neck pickup, the E_4-string was depressed with a pick and let go abruptly (force step, chapter 1 and 2). The result is a rectangular velocity curve (**Fig. 5.5.12**) to which a triangular displacement corresponds. Due to the non-linear characteristic of the magnet (chapter 5.8), the tip of the flux-density-curve is bent (the tip of the triangle belonging to the linear model is shown as a thin line in Fig. 5.5.12). A differentiation of the flux-density function results in the induced voltage: this is rectangular in the case of a linear magnetic characteristic, and pointed for the non-linear model. The measured voltages show a clear similarity with the slight oscillations being results of the dispersion which is not modeled here (chapter 1.3.2).

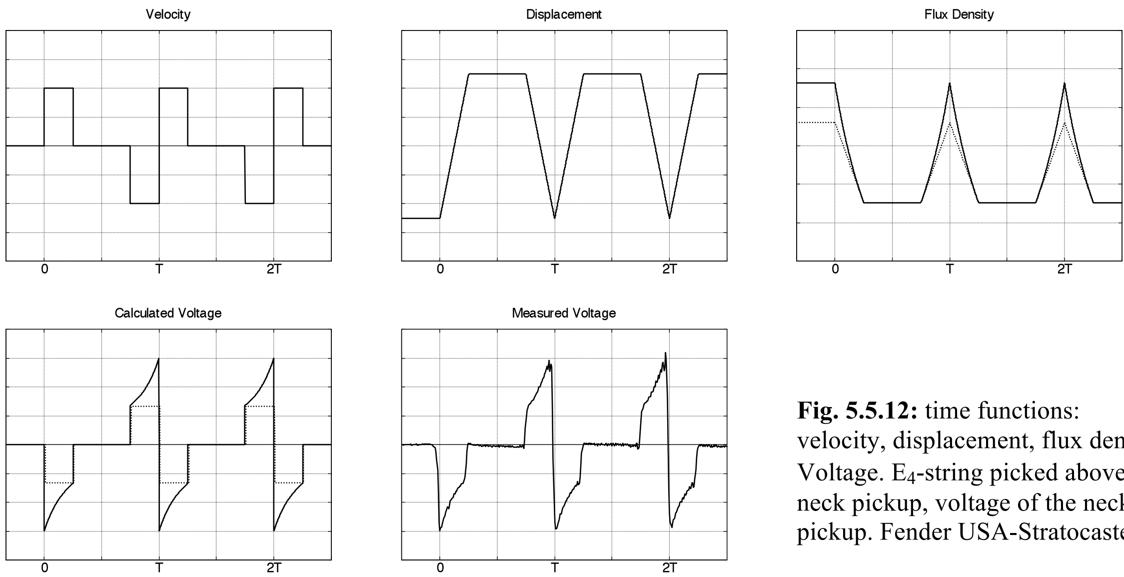


Fig. 5.5.12: time functions: velocity, displacement, flux density, Voltage. E_4-string picked above the neck pickup, voltage of the neck pickup. Fender USA-Stratocaster.

In order to strongly dampen the resonance formed by coil and cable, the Stratocaster pickup was loaded with a 1-kΩ-resistor for these measurements. In the relevant frequency range, coil resistance, coil inductance and the 1-kΩ-resistor act as a first-order low-pass the real pole of which was mathematically compensated by a zero. Additionally, a real pole at f_x = 9000 Hz was included so that the induced voltage was in total filtered by a first-order **low-pass** with a cutoff frequency of 9 kHz.

Both calculation and measurement show that with a dispersion-free model of the string pickup voltage is created which remains symmetric to the time-axis – even if a non-linear characteristic of the magnet is used as the basis. Dispersion-effects play no role for the thin guitar strings, and consequently calculation and measurement are in good agreement. However, on the E_2-string the frequency-dependence of the wave-propagation velocity (**dispersion**) leads to deformations of the time function already after one single period (**Fig. 5.5.13**); the half-cycles loose their symmetry and thus the possibility arises that the sound changes when the polarity of a pickup is reversed. Still, changes in the time-function do not always lead to audible sound changes. The hearing system in not an oscilloscope; rather, the sound-signal is split up into frequency bands (**critical bands**), and only the output of these analyzing band-filters are subject to the time-dependency analysis. Phase shifts occurring between signals falling into different critical bands may not cause any changes in he perceived sound. Phase shifts within a critical band may on the pother hand very well lead to audible roughness- and/or pitch-changes [Fleischer 1978].

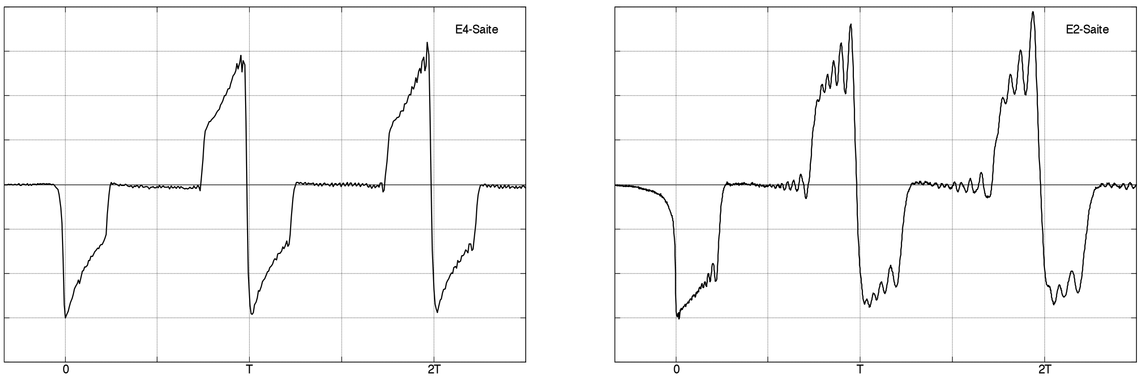
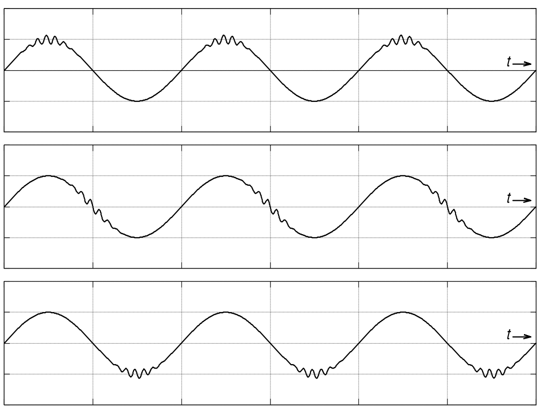


Fig. 5.5.13: measured pickup voltage (Stratocaster), normalized. For the E_2-string the dispersion-caused oscillations are particularly striking (compare to chapter 1.4). The E_4-string is, however, not entirely dispersion-free, either: after about 7 periods clear dispersion-caused unbalances are visible (not shown in the figure),



The superposition of a low- and a high-frequency oscillation shown in Fig. 5.5.13 is reminiscent of the measurements regarding masked-period-patterns carried out by Zwicker [12]. Whether the tone-burst is audible depends on its position within the phase of the lower-frequency tone. (**Abb. 5.5.14**). Despite equal magnitude spectra, the three signals shown in this figure sound differently – the masking effect of the lower-frequency component is phase-dependent.

Fig. 5.5.14: test signal for masking-period-pattern experiments [12].

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Before we apply the masked-period-patters to guitar signals, we need to rather consider that the time functions shown in Fig. 5.5.12 and 5.13 are derivatives of the string velocity; i.e. the signal will never reach the tympanic membrane in this shape. First, already the pickup resonance effects changes on the signal, then guitar amplifier and loudspeaker add their own considerable part, plus last the sound wave has to travel through the listening room until it finally reaches the ear of the listener or the player. In **Fig. 5.5.15** the pickup voltages as they show up for a Stratocaster loaded with 513pF // 1MΩ. Along the time axis non-symmetries can appear which appear significant o the eye – however the eye does not judge the sound. In fact, the hearing system struggles despite the obvious non-symmetries to recognize any sound differences. Even more explicitly this is shown by **Fig. 5.5.16**: both these impulses sound the same!

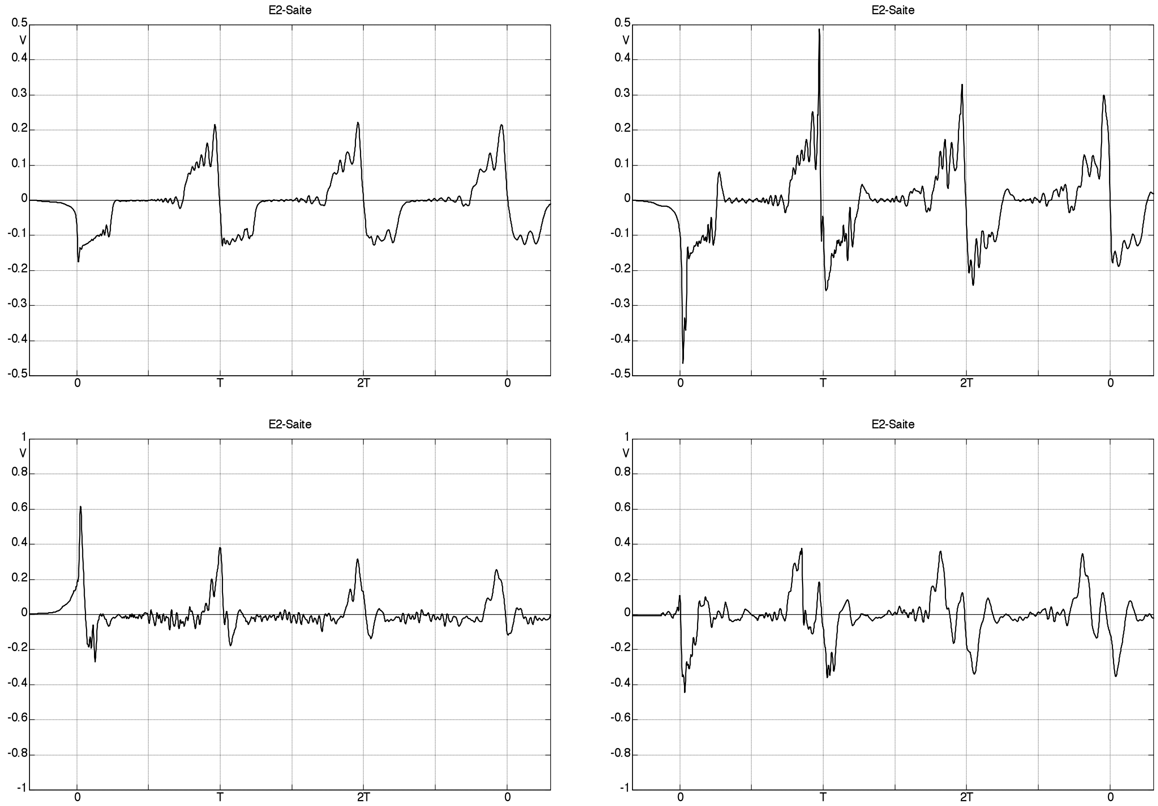

Abb. 5.5.15: pickup voltages, USA-Stratocaster, neck pickup. E_2-string pressed down above the neck pickup with a pick and then released (top left and right); virtuoso-like" picked (bottom left and right). Left and right show two different attempts.

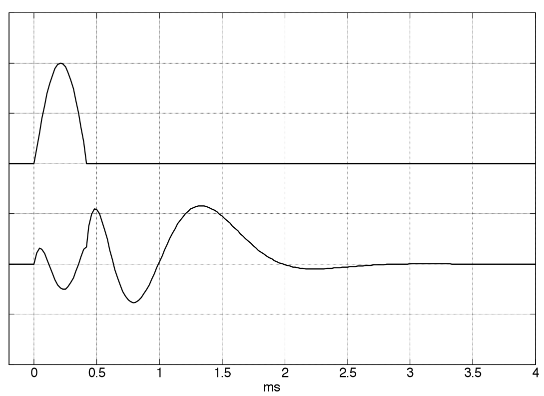

Fig. 5.5.16: two impulses which can be projected upon each other via all-pass filtering. Since the group-delay distortions remain below the threshold of 2 ms (as it is relevant to the ear), this filtering is not audible.

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As shown in Fig. 5.5.11, the nonlinearities occurring in amplifiers cause a polarity-dependent limiting of the guitar signal, but the main differences most often happen with the short impulse peaks – the limiting of which changes little in the overall sound. The signal is subject to significant alterations only as it is radiated off the loudspeaker: in **Fig. 5.5.17** the voltages generated by two **microphones positioned within a listening room** with a distance of 50 cm. Despite major divergences in the time function, these differences are perceived merely as a general change in the treble content without any special significance.

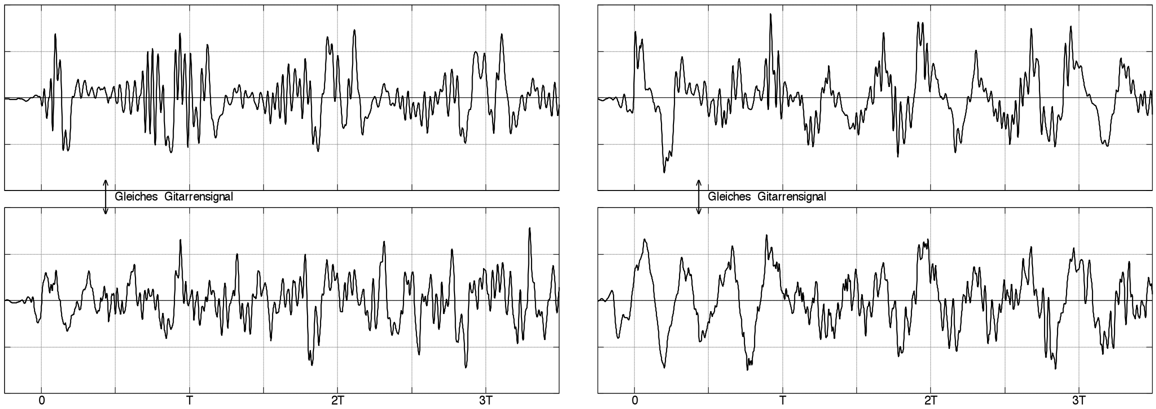

Fig. 5.5.17: microphone voltages at 0,5m in front of the amplifier (top) and inclined at 1 m in front of the amplifier. Fender-Stratocaster, Fender-Deluxe-Amp. Two different attempts shown left and right, respectively.

We note as **intermediate result**: reversing the polarity of a pickup leads to clearly *visible* differences in the voltage-time function. Our hearing, however, does not observe these differences at all, or just marginally. In no way are differences due to polarity-reversal obtainable in the sense of *clearly better* or *clearly worse*. Consequently, no recommendation is possible regarding which polarity would be preferable. Still, two special operating states merit additional consideration: the combination of several pickups and the feedback via the air.

As the guitar is played loudly using amplifier and loudspeaker, an air-wave emitted by the loudspeaker strikes the guitar body and excites vibrations in it and also in the strings. These vibrations are fed back to the amplifier and thus we obtain a **feedback circuit**. With a sufficiently high gain within the feedback circuit the guitar starts to play "by itself" [literature: control engineering]. The pitch of this self-oscillation depends on a number of factors including the polarity of the closed-loop-gain: reversing the pickup polarity leads to a change in the sound. However, the same happens as one changes the position of the guitar by e.g. 10 cm (i.e. the phase in the feedback loop changes); as such the pickup polarity is irrelevant even when considering feedback.

The fact that the sound changes drastically as the polarity of one pickup in a **combination** of pickups is reversed requires not a lot of explanation. More interesting is the question whether there are audible differences if both direction of the turns in a coil <u>and</u> the polarity of the magnet are reversed (e.g. for the middle pickup of a Stratocaster) to achieve hum-suppression in the combination of pickups (RW/RP middle pickup). Indeed, we could expect an effect if the two pickups were magnetically coupled to a significant extent. Measurements, however, show merely a 0,6%-coupling-factor which is much too little to give audible effects. The measured level differences are, with 0,05 dB, far below threshold. Incidentally, for the forces of magnetic attraction the rule applies that they are <u>not</u> polarity dependent!

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