5.12 Pickup noise

Every pickup generates undesired noise. The magnetic pickup converts magnetic interference fields into noise voltages (Chapter 5.7), but it also creates already without the presence of any magnetic field a broadband noise. As the term “broadband” indicates, the spectrum of this noise is distributed continuously from very low to very high frequencies. The reasons are conducting electrons in the copper wire which can move freely and perform stochastic movements. The superposition of all these charge-movements leads to a noise voltage having a normal (= Gaussian) distribution and being measured as an RMS-value $\widetilde{U}$. For a given absolute temperature T, a measurement bandwidth B, and with Boltzmann’s constant k, the resistance R yields:

$$\widetilde{U} = \sqrt{4kTBR} = 0{,}127\mu\mathrm{V} \cdot \sqrt{B/\mathrm{kHz} \cdot R/\mathrm{k\Omega}} \qquad \text{Thermal noise voltage}$$

For example, a 10-kΩ-resistor would generate a noise voltage of 1,27 µV for a measurement bandwidth of 10 kHz. However, this calculation is only valid for real (i.e. purely ohmic) resistors without any loading. As a first consideration it will suffice to model the magnetic pickup via its coil resistance R, its inductance L, the load capacity C (predominantly contributed by the cable, and the cross-resistance R_q (**Fig. 5.12.1**). R_q is made of three parallel resistors: the amplifier input resistance (typically about 1 MΩ), the volume potentiometer of the guitar, and the tone potentiometer connected via a “tone”-capacitor. With respect to noise voltages, this “tone”-capacitor may be seen as a short so that all three resistances are connected in parallel. For a typical Stratocaster pickup we find, for example: R = 6000 Ω, L = 2,2 H, C = 0,7 nF, R_q = 111 kΩ. Merely the ohmic resistances in the circuit generate thermal noise; it is modeled for R via the series-connected noise voltage source U, and for R_q via the parallel-connected noise current source I. Both noise processes run independently of each other so that their effects can be superimposed after separate calculation. We do need to consider that the two RMS-voltages have to be added according to the **Pythagorean** law – as it is required for interacting incoherent signals. For the calculation we first omit the current source and obtain the terminal voltage generated by U; subsequently a short replaces the voltage source and the terminal voltage generated by I is calculated. The two terminal voltages are each squared and then added; the square root of the result is the actual noise voltage.

The spectral distribution of the noise is shown in the **noise spectrum** with the frequency running along the abscissa. Along the ordinate we find the noise power spectral density (W/Hz), or the normalized square-root of it – the so-called **noise voltage density**

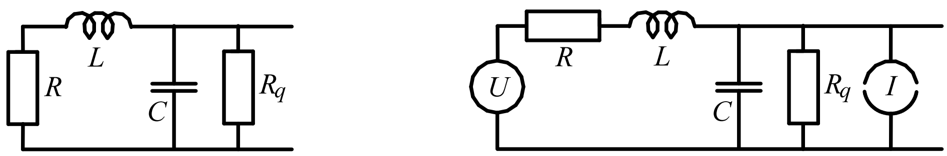
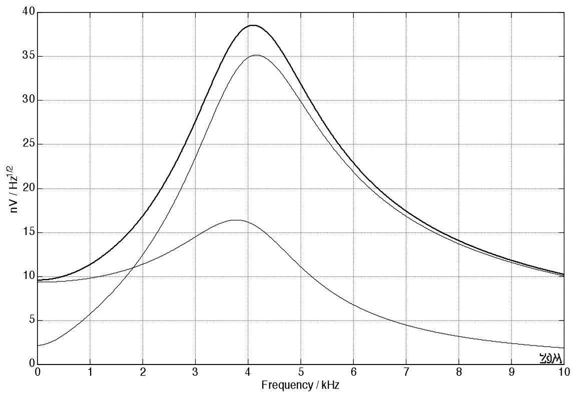


Fig. 5.12.1: Equivalent circuit diagram of pickup; left without, right including noise sources. The ECD is the basis for the noise spectra shown in Fig. 5.12.2.

The thermal noise power of an ohmic resistor R amounts to $4kTB$ and is independent of the resistor value. The noise power referenced to the bandwidth B is called the power spectral density **PSD** = $4kT = 1{,}62 \cdot 10^{-20}$ W/Hz, with 293K (room temperature) used for T. Since the power spectral density has the same value for each frequency region (i.e. it is independent of f), this noise is termed **white noise**; as is the case for white light, "all frequencies are contributing". In circuit technology, the noise voltage density e_n is normally used instead of the PSD; it is obtained by dividing the noise voltage $\tilde{U}$ by the square root of the bandwidth: $e_n = \sqrt{4kTR}$. A 6-kΩ-resistor generates white noise with a noise voltage density of $9{,}85\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$. In Fig. 5.12.1, this value characterizes the noise voltage source designated U. However, the noise arriving at the terminal is not a white noise anymore but it is low-pass filtered by L and C. The left-hand section of **Fig. 5.12.2** shows, in the lowest curve, the frequency dependency of the noise voltage density generated by R and found at the output terminals. The resonance emphasis caused by the low pass is clearly recognizable at 3,8 kHz.

The second noise source is the cross resistance R_q. Its noise is expediently modeled via a parallel-connected noise current source, the spectral noise current density i_n of which is e_n / R_q. 111 kΩ yields $382\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$. To calculate the terminal voltage generated by this resistance, i_n needs to be multiplied with the absolute value of the circuit impedance; this result is given in the left part of **Fig. 5.12.2** by the middle curve. Below 1,8 kHz, the noise contributions of the coils resistance R dominate, and above this frequency the noise contributions of the potentiometer/amplifier-resistances R_q. The latter in fact deliver the overall largest share of the noise. For the figure, a constant percentage bandwidth of **1/12th of an octave** was chosen. The relative 1/12th-octave-bandwidth is 5,8% corresponding to 5,8 Hz absolute bandwidth at 100 Hz, and to 58 Hz at 1 kHz. A noise voltage density of $9{,}85\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ generates – for a bandwidth of 5,8 Hz – a noise voltage of 23,7 nV (corresponding to a voltage level of –152,5 dBV). In the right-hand section of Fig. 5.12.2, the white-noise-levels of amplifying devices (tube, FET, operational amplifier) for $5{,}5\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (ECC83, LT1113), and $18\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (TL071), respectively, are shown as dotted lines. The TL071 downgrades the pickup noise below 2 kHz while the ECC83 and LT1113 add almost no noise at all. For **FET-operational amplifiers** and **tubes**, the effects of noise currents ($10\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$) can be ignored. Using a bipolar-transistor op-amp such as a NE5532 having about ca. $500\,\mathrm{fA}/\sqrt{\mathrm{Hz}}$ would, however, not be purposeful, despite the good e_n-value.



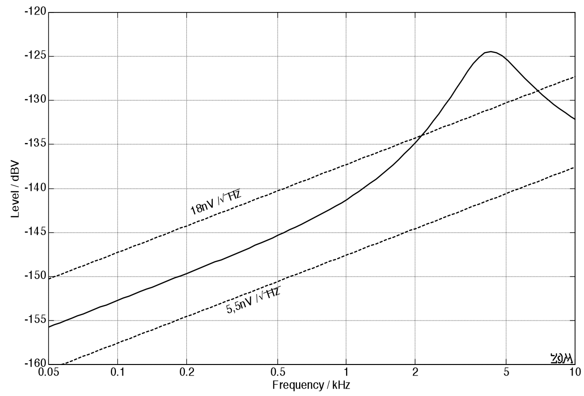


Fig. 5.12.2: Noise voltage denstity of a pickup (left), 1/12th-octave-level (right). Calculation done for the ECD of Fig. 5.12.1 with R = 6kΩ, L = 2,2H, C = 700pF, R_p = 111kΩ. => $U_{overall}$ = 2,2 µV.