The modulus of elasticity E^E describes the mechanical elasticity of the piezo-material for full decoupling, as it is achievable for any value of α if the electrodes on the piezo sheet are shorted. For electrical measurements, on the other hand, the decoupling occurs for every value of α if any movement is prevented. As a thought experiment: for $v = 0$, the secondary current of the transducer is zero, and therefore only the capacitance of the crystal C_K remains. In literature, this special case is designated with a superscript S (clamped mechanical relative deformation *S*). Typical values for the relative dielectric constant are $\varepsilon_r^S = 1000 \ldots 4000$. Given the above, the capacitance of the crystal C_K can be calculated:

$$C_K = \varepsilon_0 \cdot \varepsilon_r^S \cdot S / h; \qquad \varepsilon_0 = 8{,}85 \cdot 10^{-12} \text{ As/Vm}$$ Crystal-capacitance

For regular (unclamped) operation, we measure – on the electrical side – two capacitances connected in parallel: the *crystal-capacitance* C_K, and the *spring capacitance* C_s caused by the mechanical side:

$$C_s = \alpha^2 / s_K$$ Spring-capacitance

In summary: For electrical no-load, i.e. the open-circuit situation with only C_K having an effect on the electrical side, we measure two stiffnesses on the mechanical side: $s = s_K + s_C$. For mechanical no-load with only s_K having an effect on the mechanical side, we measure two capacitances on the electrical side: $C = C_K + C_s$. The reactive load that is transformed by the transducer to the respective other side is: $C_s / C_K = s_C / s_K \approx 50...100\%$. Given high-grade electro-mechanical or mechano-electrical linkage♣, we may assume $C_s \approx C_K$; depending on the piezo material, lower values are possible, as well.

6.2 Electrical loading

An open-circuit connection at the transducer represents an **idealization** that does not really exist in this form. For a piezo-electric guitar pickup, the electrical side is loaded via the cable (acting as a capacitance) and the input impedance of the amplifier, while on the mechanical side, the bridge and the strings need to be considered. Let us assume as a first approach an imprinted force $\underline{F}$ to be the mechanical source. In order to calculate the output voltage, the simplest approach is to transform both this force and the crystal stiffness onto the electrical side [3]:

$$\underline{U} = \underline{F} / \alpha \qquad C_s = \alpha^2 / s_K$$ Transformed quantities

This transformation yields a purely electrical network that may be investigated using the known approaches for network analysis. Of particular importance is the effect of the electrical load impedance on the **transmission function** $\underline{H}$. The input impedance of a guitar amplifier typically amounts to 1 MΩ; relative to this, a line input can be of much lower impedance (e.g. 50 kΩ). The capacitive internal impedance of the pickup forms – on cooperation with the input impedance of the amplifier – a first-order high-pass (**Fig. 6.2**).

♣ Linkage-factor: $k^2 = W_{mech} / W_\Sigma = C_s / (C_s + C_K) = 0{,}3 \ldots \underline{0{,}5}$.

 Translated by Tilmann Zwicker

Seen from the side of the load resistance, the two capacitances are connected in parallel, and they therefore are added up to calculate the cutoff-frequency of the high-pass (3-dB-frequency): $C = C_K + C_s$.

$$f_g = \frac{1}{2\pi R(C_K + C_s)} = \frac{1}{2\pi RC}$$

Cutoff-frequency of the high-pass

With C = 1,5 nF and R = 1 MΩ, we obtain f_g = 106 Hz, which is a value matching the frequency range of the guitar. For R = 50 kΩ (line input), the cutoff frequency would rise to 2,1 kHz, corresponding to a complete loss of the lows. Even less suitable would be a microphone input: its input impedance usually amounts to only about 2 kΩ.

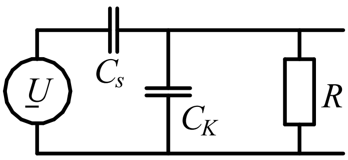

Fig. 6.2: Equivalent circuit of the transducer

For an **active** piezo pickup, the input impedance of the guitar amplifier is immaterial – a battery-operated preamplifier with low output impedance is integrated into the guitar, and makes for a problem-free connection to line inputs. A **passive** piezo system, however, does not include a preamplifier, and the pickup-signal needs to be fed to the guitar amplifier using a shielded cable. High-quality cables represent merely a capacitive load (Chapter 9.4), and therefore increase C_K. On the one hand, this has the effect of a broadband signal attenuation (capacitive divider), on the other hand it decreases the cutoff frequency of the high-pass. The ubiquitous assumption that a **long cable** would attenuate in particular the treble range does not hold for the piezo pickup – the internal impedance of the latter does not have a resistive character but a capacitive one.

6.3 The piezo-transducer as a sensor

In its operation as a sensor, the guitar pickup converts mechanical input signals (string vibrations) into electrical output signals. This represents the normal case; an operation as actor – which is also possible – is of interest only in the context of metrology (Chapter 6.5). According to the idealization used so far, the piezo transducer works as force-to-voltage converter. It captures in particular the AC-component of the bearing force the strings cause, and generates a correspondingly proportional voltage. The bearing force does not act directly onto the piezo crystal, though – a **pickup housing**, with its masses and springs, represents a mechanical filter. The effects of this filter will be investigated from a metrology-point-of-view in the following, using an Ovation pickup (Fig. 6.3) as example.

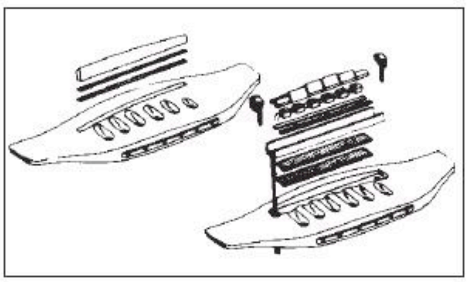

Fig. 6.3: Two different piezo pickups (Ovation).

