6. Piezo pickups

Around 1880, the French physicist Pierre Curie discovered the **piezo-effect**: as crystal sheets of special material are deformed, an electric voltage occurs on their surface. If we mount a small plate of crystal to a guitar top or to a guitar bridge, the vibrations of the guitar lead to deformations of the crystal and therefore to electrical signals. In contrast to the principles of the electro-magnetic transducer, it is not the original string oscillation that is tapped into, but the effect of the latter onto the section of the guitar that can vibrate. This has the advantage that the vibrations of non-magnetic strings can also be captured. However, piezo pickup and magnetic pickup differ not only in the transducer principle but also in their transmission function: the magnetic pickup captures the string velocity (particle velocity v) at one location (single-coil pickup), or at two locations (humbucking pickup) – with position-dependent comb-filter effects (Chapter 2.8). Conversely, the piezo pickup converts the force acting within the bridge (bridge-insert pickup), or it captures the movement of a small area of the guitar top (top-mounted pickup). In the 1960's, top-mounted pickups manufactured by Barcus-Berry started to capture the market as retrofit kits, while in particular the Ovation company fitted their guitars ex-factory with bridge-insert pickups. By now, some solid-body guitars are also feature a piezo pickup as alternative or as supplement to magnetic pickups.

6.1 The piezo-effect

As external forces act on special crystals, an electrical **polarization** results in addition to the deformation – this is due to shifts in the charges located in the material. The descriptive piezo-electric material parameters in fact have a tensor-characteristic, since both the mechanical and the electrical tensions act in three dimensions. For the guitar pickup, however, a simplified description will suffice. A scalar material-characteristic connects both force and electrical voltage, and particle velocity and current with each other in the sense of a two-port (quadripole) electro-mechanical transducer.

Today, most piezo sensors are manufactured from artificially polarized ferro-electric crystal mixtures (**lead zirconium titanate**) that can be optimally matched to the specific applications by suitable doting and composition. **PVDF-foils** (polyvinylidine fluoride) are also deployed. The piezo ceramics are formed from mixed crystals, and need to be polarized after manufacture (sintering, sanding, metalizing) at high temperature by a strong electric DC-field. Over the years, this polarization will decrease again – but only to a relatively insignificant extent so that long-term stability is, as a rule, very good. Thermal or mechanical overload may lead to substantial deterioration of the transmission behavior, but such irreversible changes must not be feared after the sensor has been mounted in place.

The **transducer constant** of a piezo pickup depends on the geometry of the piezo sheet (surface *S*, thickness *h*) and on the material-specific piezo-constant *e*. For an unobstructed thickness-mode transducer, we obtain simple correspondences between the mechanical and electrical quantities that are operating in parallel [3]:

$$\underline{F} = \alpha \cdot \underline{U}; \qquad \underline{I} = \alpha \cdot \underline{v}; \qquad \alpha = e \cdot S / h$$ Transducer equations

The voltage $\underline{U}$ generated at the crystal is proportional to the force $\underline{F}$, the current $\underline{I}$ is proportional to the velocity $\underline{v}$; the transducer constant α is the coefficient of proportionality. In terms of manufacture, the piezo constant *e* can be trimmed over a wide range; typical values are e = 20 ... 50 N/Vm. As a first value for orientation, α is 1 N/V.

Moreover, the piezo crystal does not only convert mechanical quantities into electrical ones but it also includes mechanical and electrical elements. As a simplification, we need to consider the **stiffness** *s* on the mechanical side, and the **capacitance** *C* on the electrical side. It is not surprising that a small sheet of glass-like hardness and a modulus of elasticity of around $5 \cdot 10^{10}$ Pa features a high stiffness. However, a significant share of the stiffness is caused by the electromechanical coupling: we obtain from the capacitance equation $I = C \cdot dU/dt$, via the transducer equations:

$$\alpha \cdot v = C_K \cdot \dot{F} / \alpha \quad \rightarrow \quad \alpha^2 = C_K \cdot \dot{F} / v = C_K \cdot s_C \quad \rightarrow \quad s_C = \alpha^2 / C_K$$

The stiffness s_C (caused electrically and converted to the mechanical side) contributes significantly to the overall stiffness that results from the sum of the *crystal stiffness* s_k and the *capacitance stiffness* s_c: $s = s_K + s_C$. This sum also shows up when considering the **energy scenario**: when compressing a small crystal sheet, potential field-energy is stored (even without the piezo-effect). The piezo-effect causes an electrical voltage – and thus potential electrical energy – to appear across the crystal sheet (a dielectric with high dielectric constant). This potential electrical field-energy is supplied by the mechanical side and generates a load to the mechanical source just like an additional spring.

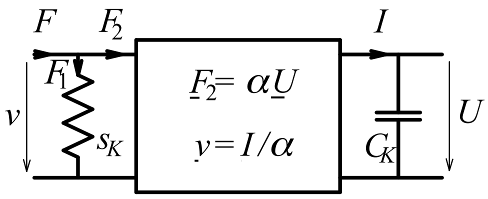

Fig. 6.1: Equivalent circuit of the piezo-transducer. The driving force $\underline{F}$ is divided up into $\underline{F}_1$ and $\underline{F}_2$.

Fig. 6.1 shows the electro-mechanical equivalent circuit diagram. The partial forces $\underline{F}_1$ and $\underline{F}_2$ act in parallel; the representation in the figure (a scalar flow-diagram of the forces) disregards directions in space. As we short the output (U = 0), the input force of the transducer becomes zero, as well, (F_2 = 0), and s_K now is the sole active spring. Literature designates this special load case with a superscript E (clamped field-strength *E*). The **modulus of elasticity** measured under these conditions is symbolically termed with E^{E} (the superscript E is no mathematical exponent here). Given this, we find for s_K:

$$s_K = E^{\mathrm{E}} \cdot S / h$$ Crystal stiffness

Typical values are: $E^{\mathrm{E}} = 5 \cdot 10^{10}$ Pa … $8 \cdot 10^{10}$ Pa (modulus of elasticity without piezo-effect).

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 $\varepsilon_r^S = 1000 \dots 4000$. Given the above, the capacitance of the crystal C_K can be calculated:

$$C_K = \varepsilon_0 \cdot \varepsilon_r^S \cdot S / h; \quad \varepsilon_0 = 8{,}85 \cdot 10^{-12} \text{ As/Vm}$$ 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: $k^2 = W_{mech} / W_\Sigma = C_s / (C_s + C_K) = 0{,}3 \dots \underline{0{,}5}$.

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