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.

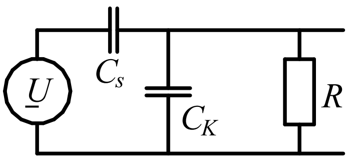


Fig. 6.2: Equivalent circuit of the transducer

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.

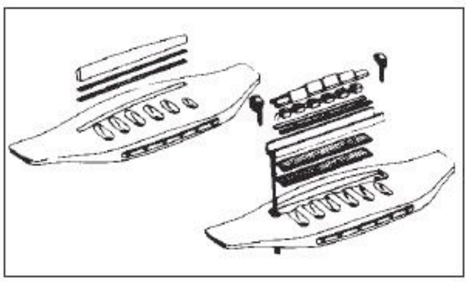


Fig. 6.3: Two different piezo pickups (Ovation).

For the **measurements**, the guitar was laid – within its opened case – on a stone table (with a weight of 250 kg). An electromechanical shaker (B&K 4810) generated translational vibrations; force and acceleration could be measured with an impedance-measurement head (B&K 8001). A small chisel blade was screwed into the impedance head and set onto the saddle-piece of the bridge, and the load for the pickup during the measurements was 2 MΩ. **Fig. 6.4** shows the measured frequency-dependence of the transmission factor, with the corresponding ideal curve of a 2nd-order low-pass indicated as a dashed line. The resonance frequency is located at about 3,9 kHz, the Q-factor is about 18.

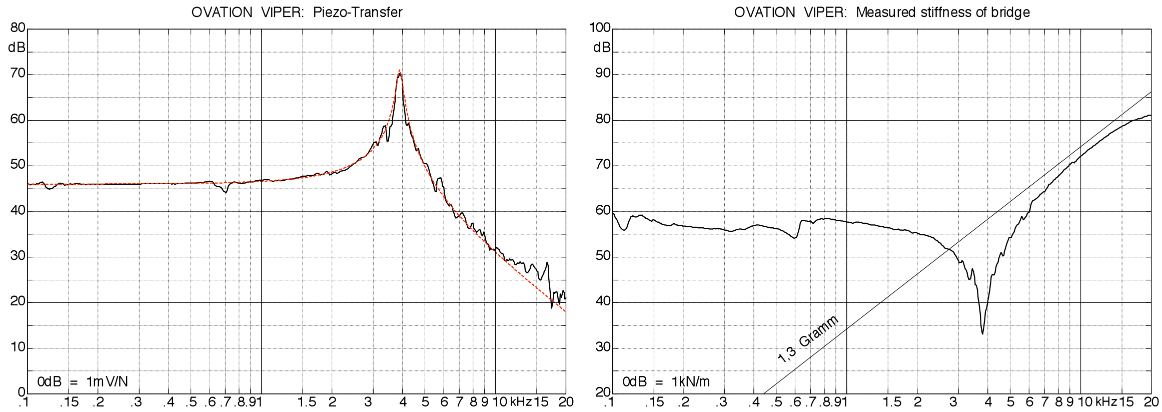
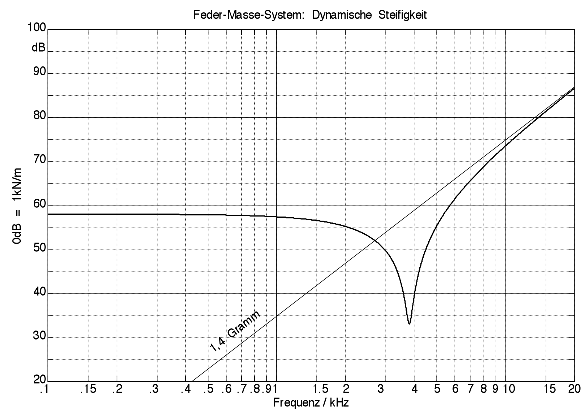
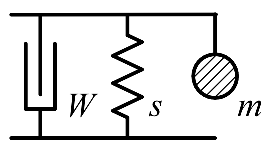


Fig. 6.4: Transmission (left) and dynamic stiffness (right) of the piezo pickup (Ovation).

The shown transmission behavior must not be interpreted as the "frequency response" of the guitar. In the left graph of Fig. 6.4, we see the frequency dependence of the 20-fold logarithm of the quotient U/F; with U = voltage at the piezo and F = measured force. However, the force measured in the impedance head does not correspond exactly to the force at the bridge; rather, a small additional mass is also measured – this mass is due to the mounting plate of the impedance head towards the load. In other words: during the measurement, there is a small **additional mass** of 1,4 gram located on the bridge, and the effect of this mass is also measured. Together with the stiffness of the bridge, the additional mass generates a resonance at 3,9 kHz. To confirm this hypothesis, the **right-hand graph** of Fig. 6.4 shows the quotient of the measured force F and the measured deflection x (again in the usual dB-scaling i.e. the 20-fold logarithm). For f > 100 Hz, we can nicely recognize the behavior of a mass-spring system, with its idealization shown in **Fig. 6.5**. As a simplification, the guitar bridge acts as a stiffness (about 800 kN/m), and together with the additional mass contributed by the impedance head, it forms a resonance at 3.9 kHz.





W=1,9Ns/m; s=800kN/m; m=1,4g.

Fig. 6.5: Dynamic stiffness F/x of an ideal spring-mass system.

 Translated by Tilmann Zwicker

The resonance at 3.9 kHz results from the cooperation of the stiffness s_R of the bridge pieces and the additional mass m_0 generated by the end plate of the impedance head and the chisel blade. The exact value of m_0 can easily be measured applying a no-load condition of the impedance head: **Fig. 6.6** correspondingly shows the magnitude of the complex quotient $\underline{F}/\underline{a}$. For an ideal mass, a frequency-independent graph would have to result; any deviations are effects of structural resonances (impedance head and cable).

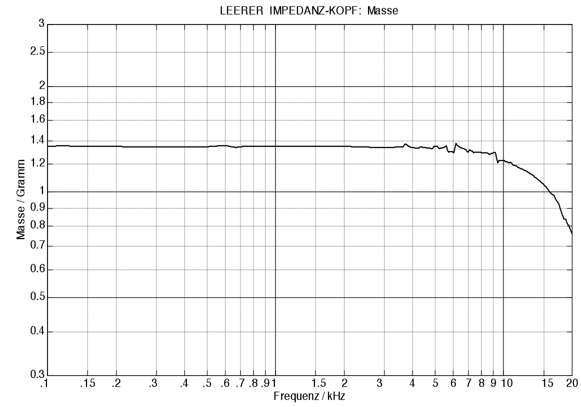


Abb. 6.6: Magnitude of the co-vibrating complex mass $\underline{F}/\underline{a}$ of the impedance head (incl. chisel). “LEERER IMPEDANZ-KOPF: Masse” = empty impedance head: mass; “Frequenz” = frequency

Assuming time-invariance (not reachable to a full 100%), any artifacts of the measurement head may largely be **compensated**: first, the force- and acceleration-signals are digitally recorded with highest possible quality for the empty measurement head. In a second step, the corresponding analytical signals $\underline{F}$ and $\underline{a}$ are generated using a Hilbert transform. The quotient of $\underline{F}$ and $\underline{a}$, suitable averaged, yields the complex mass $\underline{m}_0 = \underline{F}/\underline{a}$. In order to achieve the compensation when the head is under load, $\underline{m}_0$ is simply subtracted from the measured $\underline{F}/\underline{a}$-quotient. **Fig. 6.7** depicts the results achieved with this compensation. As transmission factor, we get a value of 0,2 V/N (frequency-independent, as a 1st-order approximation), for the bridge-stiffness, about 800 kN/m result.

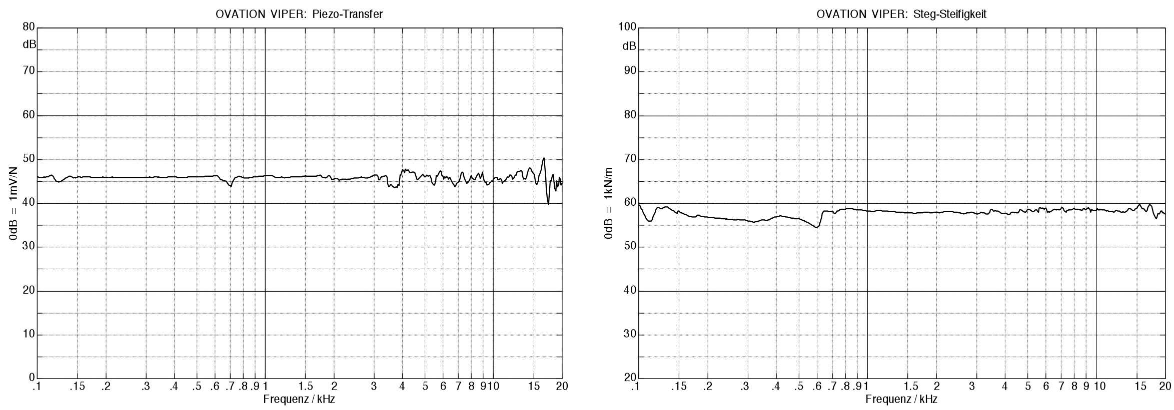


Fig. 6.7: Measurements with compensation of the measurement-head artifacts. Transmission factor (left), bridge stiffness (“Steg-Steifigkeit”, right). “Frequenz” = frequency.

In summary: as expected, the investigated piezo-pickup (Ovation EA-68) operates as a force→voltage-converter with a transmission coefficient of 0,2 V/N. The guitar bridge acts as stiffness of about 800 kN/m. For the simple model, these values are frequency-independent; the 3,9-kHz-resonance is and artifact caused by the drive. A closer check reveals small structural resonances not reflected via the simple model.

Fig. 6.8 condenses the results obtained so far into an equivalent circuit diagram. On the electrical side of the two-port network of the transducer, we see the capacitance of the crystal, while the mechanical side holds the stiffness of the crystal s_K and the stiffness of the bridge pieces s_R. The bridge piece is a plastic piece shaped like a pitched roof; it sits on top of the crystal and represents the connection to the string. The stiffness of the bridge piece is smaller than that of the crystal by about three orders of magnitude. Due to this relationship, changes in the electrical load (e.g. shorts) cannot be measured at the mechanical pickup-input (at F) – these changes do cause a difference in the input impedance of the transducer (at F_2), but they are completely insignificant relative to s_R: when connecting two spring in series, the softer one dominates. For the same reason, changes in the mechanical loading (e.g. the mass of the shaker to be connected at the far right in Fig. 6.8) cannot be measured on the electrical side: the very stiff spring s_K dominates since in a parallel arrangement of two springs, the softer spring has little impact on the overall stiffness.

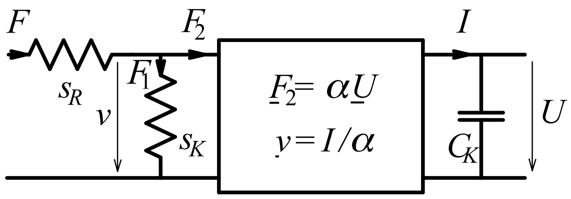


Abb. 6.8: Equivalent circuit diagram of the piezo pickup (Ovation EA-68).

However, with the measured transmission coefficient $T_{UF} = U/F = 0{,}2$ V/N, and with the pickup capacitance $C = 1{,}45$ nF, we have merely two conditions for the three variables s_K, α, and C_K at our disposal; only s_R is fully defined by the resonance at 3,9 kHz and the mass of the measuring head. Sind there is no supplementary condition available without invasive (and therefore undesirable) action, the ratio $C_s/C_K = s_C/s_K$ was **arbitrarily** taken to be 50%. Given this, we can nevertheless define input and output impedance, as well as the transfer function within the framework of the limits of the model – uncertainty remains only when calculating back to the material parameters. Such an uncertainty, however, exists anyway, since the distributions in space of the mechanical tensions in the piezo and in the bridge pieces is unknown.

The following calculations are based on the assumption that there is no single crystal strip across the whole bridge, but that there is a small, square crystal plate beneath each string, connected with its neighbor by two contact wires. As a mechanical excitation of one bridge piece occurs, only *one single* crystal plate will generate an electrical signal, and the other five crystal plates have the effect of an electric load. For such a string-specific crystal plate, the calculation yields:

$$\alpha = 0{,}28 \text{ N/V}, \quad C_K = 161 \text{ pF}, \quad s_K = 9{,}7 \cdot 10^8 \text{ N/m}, \quad s_R = 7{,}6 \cdot 10^5 \text{ N/m}.$$

Using these data, the model proposed in Fig. 6.8 can explain the following measured quantities: the electrical impedance (as a pure capacitance), the mechanical impedance (as a pure spring), the impedance-behavior shown in Fig. 6.5 as a mass is set onto the piezo), and the frequency-independent transmission behavior. The resonance peaks seen in Fig. 6.7 are not modeled. We will see how resilient this model is as the direction of the signal flow is reversed, i.e. as the sensor is turned into an actor when we apply an electrical voltage. For this case, the above model (using the same parameters) needs to be able to explain the measurement results (Chapter 6.5).