11.2 Electrical two-pole characteristic

By definition, every loudspeaker is an electro-acoustic transducer i.e. a two-port device with an electrical and an acoustical port [3]. The electrical port (the two connectors) represents a relatively complicated electrical resistor that may be described by its **impedance** $\underline{Z}$. As a rough approximation, the complex impedance $\underline{Z}$ consists of a series connection of a resistor R (real part) and a coil-impedance pL (imaginary-part), with the inductance L and the complex frequency $p = j\omega$. Both components result from the **voice coil**, a cylindrically wound copper- or aluminum-wire positioned in the air-gap of a strong magnet and taking care of the motive force acting on the membrane. The movement of the membrane has the effect that an (additional) voltage is induced into the voice coil, and for this reason it is necessary to consider, within the framework of a more precise model, the mechanical elements transformed onto the electrical side as well. In fact, membrane-movement and –displacement are factors of mechanical energy that cannot appear out of nowhere but have to have their source on the electrical side of the transducer – which is why these quantities need to factor in the electrical impedance [3].

On the mechanical side, the simplest equivalent circuit diagram (ECD) of the transducer considers a mass (membrane incl. suspension and voice coil), a spring (membrane-suspension), and also a friction resistance modeling the energy losses due to deformation of membrane and suspension. The loading by the radiation impedance may be neglected in the simple model. In **Fig. 11.6**, the frequency responses of the impedance of two typical 12”-speakers (not mounted in any cabinet) are shown.

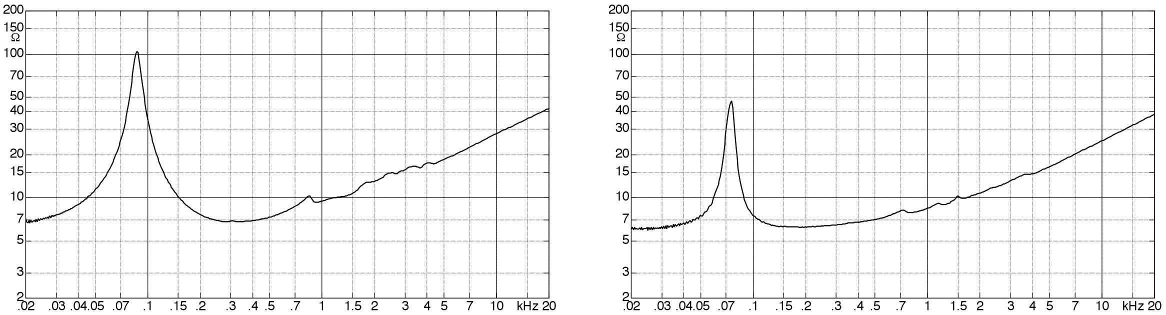

Fig. 11.6: Frequency response (magnitude) of the electr. impedance; left: Celestion Blue, right Eminence L122.

Both frequency responses include a characteristic maximum at low frequencies: together with the spring stiffness s, the mass m forms a velocity-resonance that generates a large counter-active voltage via the transducer-coupling ($U = \alpha \cdot v$, [3]): the current decreases, the loudspeaker is of high impedance at this frequency. For most guitar loudspeakers, this resonance is in the range of about 70 - 100 Hz; for bass speakers it will be somewhat lower. In the impedance-increase at high frequencies, we can recognize the inductive component of the voice coil; however, it is not a simple, frequency-proportional increase but a flatter one. This is due to the fact that it is the magnetic circuit that causes a considerable share of the voice-coil inductance, and in this circuit we find induced eddy-currents that cause a $\sqrt{f}$-characteristic. For this reason it is not possible to model (in a more exact approach) the inductive increase with a single inductance; rather, we require an RL-network. Given less requirements, a single inductance will suffice; this is often set to 1 mH. The small impedance fluctuations around 1 kHz result from partial oscillations of the membrane, i.e. standing waves that preclude the membrane from maintaining its shape. In HiFi-speakers, designers seek to suppress this kind of behavior – conversely, it is not undesired in guitar loudspeakers.

Fig. 11.7 depicts an equivalent circuit for a loudspeaker-impedance. The resistor designated with R_{Cu} represents the ohmic voice-coil resistance while the LR-array generates the high-frequency increase of the impedance. The parallel-circuit models the three mechanical elements of the membrane. If needed, this circuit may be extended or modified without great effort. At resonance, the impedance of the mechanical membrane-resonator is purely ohmic (W), and it is mapped with $(Bl)^2$ onto the corresponding (ohmic) resistor of the parallel circuit: $R_W = (Bl)^2 / W$. Herein, Bl is the transducer coefficient based on the magnetic flow density B and the length of the voice-coil wire l. Therefore, the resonance-maximum of the loudspeaker impedance is determined mainly be two parameters: the membrane dampening and the transducer coefficient. For this reason, high-value resistances at resonance are often found in speakers with strong magnets.

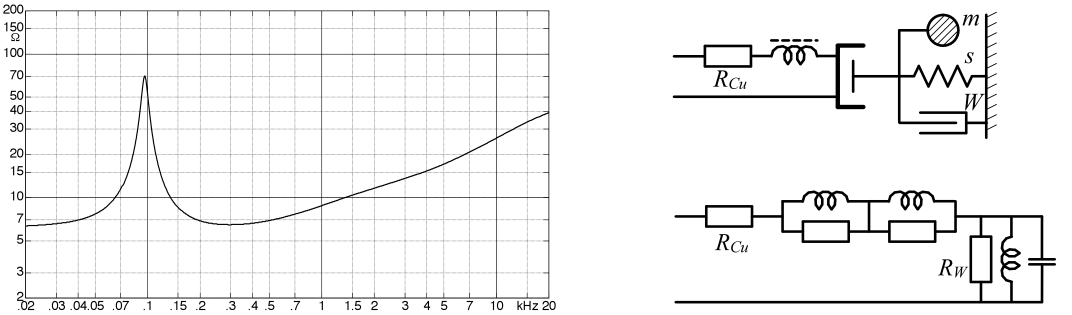

Fig. 11.7: Frequency response of the impedance, and schematic of an equivalent circuit for a loudspeaker [3].

As already mentioned, the membrane movement induces a counteracting voltage, and therefore in a more exact model, special attention needs to be paid to the radiation impedance. At low frequencies, the membrane is predominantly loaded by the **co-vibrating mass of the air** – this will amount to about 7 g for a 12”-speaker (operated without baffle). In absolute terms, that is not much, but it is of considerable magnitude relative to the membrane mass (20 – 50 g). Changing the mounting conditions (baffle, enclosure), this air mass will also vary and detune the resonance (**Fig. 11.8**) Merely adding a baffle will have not much of an effect (the air-mass approx. doubles), but mounting the speaker in an **enclosure** considerably modifies the impedance. Of course, not only the impedance changes – the behavior of the radiation will vary drastically, too. In principle, every change in the electro-acoustical efficiency needs to find its match in the frequency response of the electrical impedance. However, in practice this will, especially in the high-frequency range, not be noticeable because the corresponding changes in the radiation impedance become small compared the mass of the membrane. Moreover, the ohmic resistance of the voice coil will see to it that these small load-variations are practically invisible in the frequency response of the impedance.

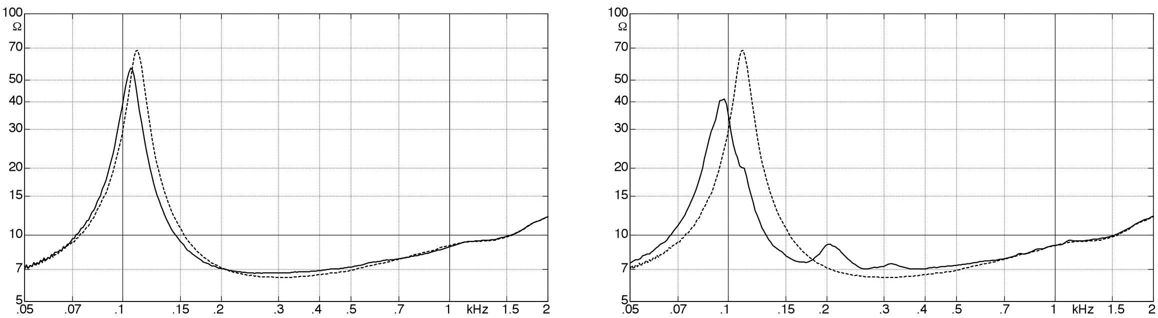

Fig. 11.8: Impedance: loudspeaker without (----) and with baffle (——); right: with and without open housing.

We can easily derive the most important membrane parameters from the *electrical* frequency response of the impedance – this is without any mechanical measurements. With s and m, the resonator has two degrees of freedom but only a single known quantity: f_{Res}. However, detuning of the resonance by applying a small additional mass to the membrane yields two further known quantities and only one additional unknown variable. The system therefore has a solution [3]. In practice, difficulties may be encountered, though: for example if – due to a large dust-cap – a relatively big mass-ring needs to be laid onto the membrane. In this case, it may be that the membrane-stiffness between voice coil and additional mass already has disturbing effect such that the frequency response of the impedance does not merely show a detuned maximum but two maxima. This scenario requires an extension of the equivalent circuit diagram. It may also help to work with two additional masses. The typical **membrane mass** of a 12”-speaker will be in the order of 20 – 50 g, typical **stiffness** will be about 5 - 10 kN/m (without the stiffness of the air inside an enclosure) – in singular cases a bit more.

To determine the **transducer coefficient** (*Bl*), measuring a transmission-quantity is necessary. The membrane-acceleration $\ddot{x} = g$ can be ascertained relatively easily: if $\ddot{x}$ is only even slightly above the earth’s gravitational pull, small particles (e.g. sand) set on top of the membrane will start to dance. Typical transducer coefficients are found to be in the range of $Bl = 10 - 20$ N/A.

As the figures presented so far show, the DC-resistance of an 8-Ω.speaker is not actually 8 Ω but less: about 6 – 7 Ω may be seen as customary. This is at room temperature! In operation, **the voice coil heats up** to above 200°C under certain conditions, and the resistance rises correspondingly by up to 80% (for example from 6.5 Ω to 12 Ω). If the speaker is operated from a stiff voltage source, the power taken in by the loudspeaker decreases be a third, as does the radiated sound[♣]! Likewise, with a tube amplifier having no negative feedback (that in principle is similar to a current source) the received power will drop, as well, if the amplifier is pushed to the drive limit. This volume-drop caused by the heating-up of high-power loudspeakers is system-immanent – undesirable but unavoidable. For ceramic magnets, a further effect may manifest itself: their flux density may noticeable drop off with rising temperature. Alnico magnets show this behavior only at temperatures that considerably higher than the operating range of guitar loudspeakers; the flux density of these magnets is practically independent of temperature.

It is understood that an amplifier needs to feature stable operation (i.e. no RF-oscillations) not just with an ohmic nominal resistance but with a complex speaker load, as well. Therefore, measurements with a real loudspeaker loading need to be taken in fact not just because otherwise any instability would not be noticed, but because only that way the typical output signals occur. Irrespective of whether we have operation with a stiff voltage source or a stiff current source, the electrical impedance of a loudspeaker is crucial for its transmission behavior. The power fed from an amplifier is dependent on the actual loudspeaker impedance, and the nominal value (e.g. 8 Ω) only offers an orientation value. Combined with tube amplifiers with their transformer coupling at the output, we get a particularly complicated system with non-linear source- and load-impedances. Swapping the loudspeaker may cause considerable changes in the transmission behavior especially around 100 Hz – these changes are caused already at the interface output-transformer/loudspeaker. Further contributions are made by the radiation characteristics of the individual loudspeaker.

[♣] The exact value will depend on the internal impedance of the power supply.

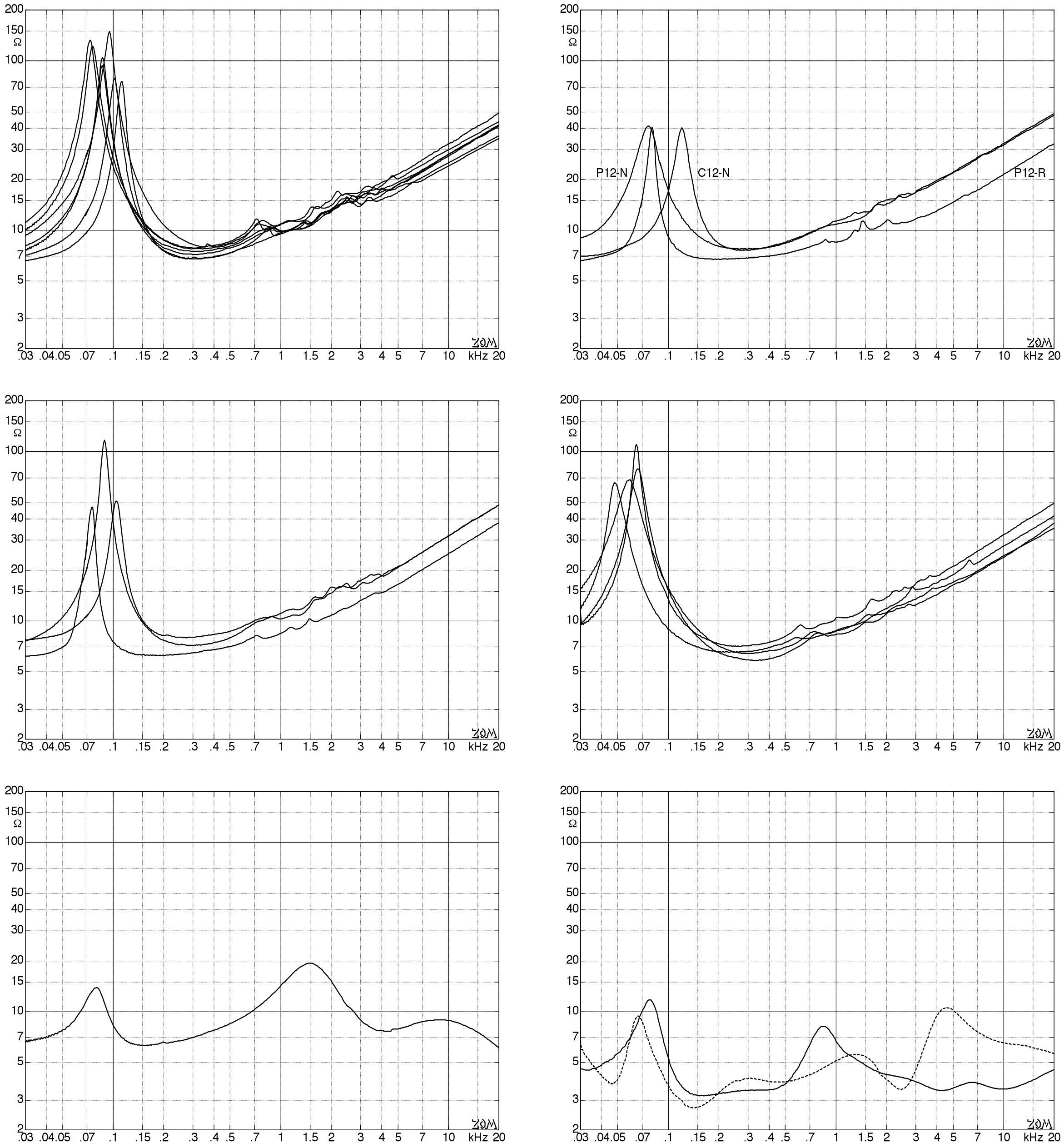

Fig. 11.9: Frequency response of the impedance of 8-Ω-speakers. Upper left: Celestion, upper right: Jensen. Center left: Eminence, center right: 12"-loudspeakers with resonance frequencies below 70 Hz. Lower left: 2-way-speaker (Canton, 8 Ω), lower right: 3-way speakers (Canton, 4Ω).

In **Fig. 11.9** the frequency responses of the impedances of a number of 12”-speakers are shown. All measurements were taken in the anechoic chamber and with un-mounted speakers (i.e. without enclosure). The curves are in principle similar but differences show up in the details. The lower two diagrams show a comparison to HiFi-speakers. All impedance curves were taken with low voltage i.e. in the linear range. Chapter 11.6 will discuss that the voltage/current correspondence may be non-linear, as well.