11. Loudspeakers

If you wanna play music, you gotta move some air. For the operation of the acoustic guitar, it is predominantly the vibrating body that generates this air-movement (commonly called sound wave), while in the framework of the electric guitar, that job is done by the loudspeaker. That's the dynamic loudspeaker, specifically, because other transducer types [3] are not called into action as guitar loudspeakers. The diameters of these speakers are specified in inches (1" = 2.54 cm). Most guitar loudspeakers sport 10" or 12", and occasionally also 15"; in small practice amplifiers, 8"-speakers are also common. The guitar loudspeaker is part of the overall instrument – it is supposed to contribute to forming the sound. To put it another way: the guitar speaker should have an atrocious frequency response, and it should distort dreadfully. Okay, maybe not dreadfully – but at least it should distort "adequately". Playing an electric guitar using a HiFi-system will result in a very special sound that is not entirely unusable but not at all reminiscent of Hendrix, Clapton, Beck and Page, either. In the typical sound of an electric guitar that we are accustomed to, not only the guitar player takes part (indeed, that role should never be underestimated), and not only guitar and amplifier contribute – but the loudspeaker, as well. While this book has concentrated so far on guitar and amp, some room shall now be also given to the loudspeaker and its cabinet.

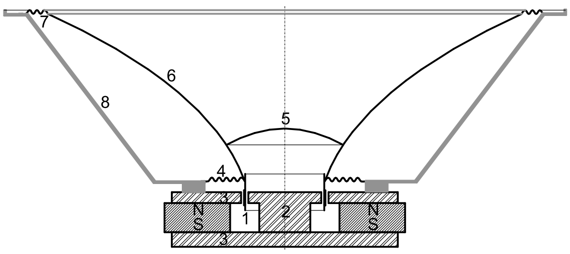
11.1 Build and function

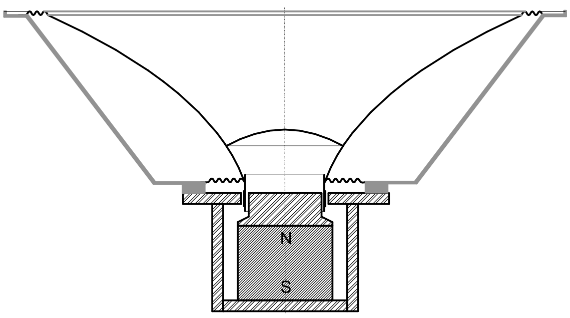
The principle of the dynamic transducer finds its scientific essentials in two simple linear mappings: 1) In a magnetic field, the force acting on a wire conducting a current is $F = B \cdot l \cdot I$, with B = magnetic flux density (induction), I = strength of the current, and l = length of the wire. 2) Moving this wire (in the magnetic field) generates an electric voltage across it: $U = B \cdot l \cdot v$, with v = speed of the movement. The force is termed **Lorentz-force** after the Dutch physicist HENDRIK ANTOON LORENTZ (1853 – 1928), the **induction voltage** usually is linked to the British scientist MICHAEL FARADAY (1791 – 1867). However, not forgotten should be the American physicist JOSEPH HENRY (1797 – 1878) who – independently of Faraday – described the mechanisms of induction, too.

The above-mentioned mapping between electrical quantities (U, I) and mechanical quantities (v, F) is a linear mapping – at least as long as the system parameters B and l remain signal-independent. The latter will of course not be the case anymore for large drive levels. Still, a linear and time-invariant model proves a useful entry point into the description of the transmission behavior of dynamic loudspeakers. That especially for the guitar loudspeaker non-linearity will be essential, that the transmission not only needs to reach a single point in space but an infinite number of these, that in the end time-invariance will not hold – all this foreshadows how complex a model for a speaker can become if we seek to describe "all" characteristics. So let's not go there – the extent of a profound literature search alone would go beyond the scope intended here. The theory presented in the following therefore is limited to the basics, and the examples and measurement protocols given are judiciously selected but not statistically conclusive.

 Translated by Tilmann Zwicker

Fig. 11.1 represents a cross-section through a membrane-loudspeaker. The build variant shown on the right is deployed for Alnico magnets (very high flux density) while the one on the left is conducive when ceramic magnets are used – they require a larger cross-sectional area of flux due to their not-quite-so-high flux density.





1 = air gap w/voice coil and its carrier, 2 = pole core,
3 = pole plate, 4 = centering (spider), 5 = dust cap,
6 = membrane, 7 = suspension, 8 = basket. N/S = magnet.

Fig. 11.1: Cross-section through a membrane-loudspeaker. Left: ceramic magnet; right: Alnico magnet. The shape is largely rotationally symmetric, the ceramic magnet is disc-shaped; the Alnico magnet is cylinder-shaped.

The permanent magnet generates a radial magnetic field in the air gap, and the ring-shaped current-flow in the voice coil has the effect of an axial drive-force on the membrane. The flux density achievable in the air gap is rather high: typically 1 – 1.6 Tesla and occasionally just above that. Both the law of induction and the Lorentz-force require, as a system parameter, the product of flux density B and wire length l; this is the **transducer coefficient** Bl. For an 8-Ω-loudspeaker, Bl often has a value between 10 and 20 N/A indicating that a direct current of I = 3 A is transformed into a force of F = 30 – 60 N. 60 N will hold up a weight corresponding to 6 kg – quite surprising given the fragility of the materials used: the membrane is made of paper, the voice coil of thin copper wire. The geometric data of this **voice coil** are: its diameter *D"* (usually given in inches), its axial length H, its turns number N, its wire length l, and its wire diameter d (often termed conductor diameter). If the insulation is included in the consideration, d increases by about 10%. The electrical coil parameter is the resistance R, at least as long as only low frequencies are discussed. **Fig. 11.2** shows, for a two-layer winding, the dependency of wire diameter d, wire length l, and turns number N on the voice coil diameter *D"* and the voice coil length H – given that the copper resistance remains always at R = 6 Ω. For a 1.5"-coil of 10 mm length, 11 m of wire (∅ = 0.22 mm) are required; with B = 1.5 T, this yields a transducer coefficient of Bl = 16 N/A.

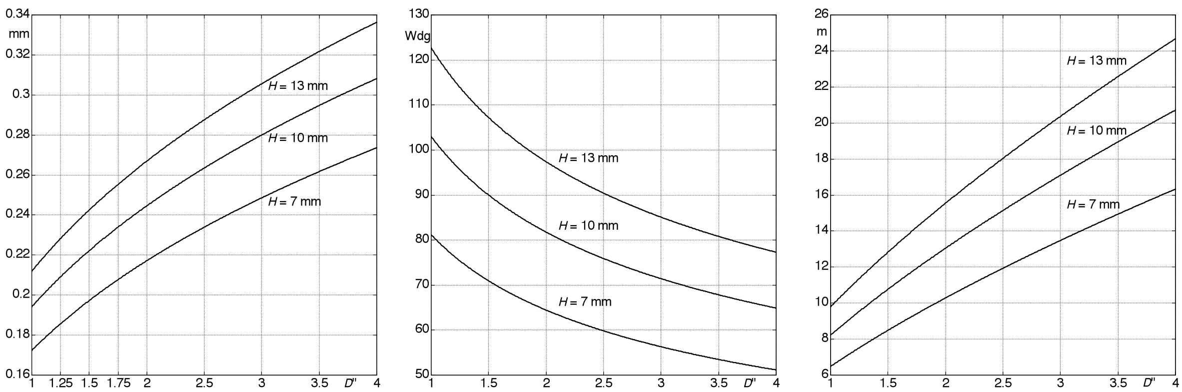


Fig. 11.2: Wire diameter d (left), turns number N (middle), and wire length l (right) depending on voice coil diameter D". DC resistance R = 6 Ω. Parameter in the family of curves: H = axial voice coil length.

The wire-length may easily be calculated from the winding diameter and the number of turns; however, it is the magnetically **effective wire-length** that is of significance to the *Bl*-product, and not the geometric length. **Fig. 11.3** depicts three different cases: coil-length = air-gap-length, as well as a relatively longer and a relatively shorter variant. The magnetic field is focused in the air gap and grows weaker towards the outside. A coil of a length equal to the air gap (formed by the upper pole-plate) will start to leave the (reasonably) homogenous range of the field as soon as the flowing current deflects the coil. This could formally be considered by defining either the flux density or the coil-length as dependent on the displacement. In the second case, the coil is longer than the air gap – here, the length of the air gap would approximately have to serve as the magnetic coil-length. In the third example, the geometric and the magnetic coil-length correspond. For linear operation, the cases b) and c) would have to be chosen because they feature a coil-penetrating flux that remains approximately constant when displacement occurs. With regard to the efficiency, a disadvantage makes itself felt in case b) in that a part of the coil mass needs to be moved that can contribute only little force because it is located in the weak fringe-field. For c), the whole coil is always positioned within the strong field, but additional magnetic energy is required to generate the – little used – fringe-field. Case a) appears to be the efficiency-optimal, as long the non-linear distortion is not under scrutiny. Since minimizing this distortion does not get top billing for guitar loudspeakers, the latter often feature coil-lengths that approximately correspond to the air-gap-length. Conversely, case b) is commonly found in HiFi-speakers.

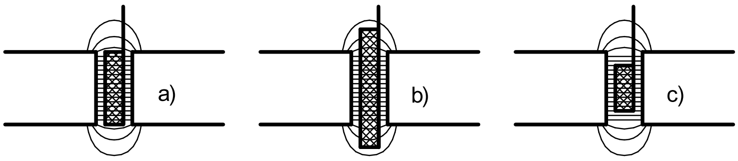


Fig. 11.3: Different voice-coils in the air gap.

In order to obtain a large transducer coefficient *Bl*, flux density and wire-length need to be large. However, because the flux-guiding pole pieces will saturate, it is not possible to indefinitely increase the flux density. A simple solution appears to present itself for the wire-length: large diameter of the voice-coil and/or large (effective) voice-coil-length seems attractive. However, both these approaches cause an increase in the vibrating mass, and thus a decrease in efficiency. On the other hand, a large transducer coefficient will increase the motive force and therefore also the efficiency. The latter is important, but not the one single criterion: power capacity and high-frequency behavior need to be up the desired overall performance. The manufacturers have found their own ways to develop marketable speakers. There is the British philosophy that guitar loudspeakers should have a membrane diameter of 12” and maximum voice-coil diameter of 2”. And then there is the approach found on the other side of the Atlantic that demands (among other things) that nobody – and especially not the Brits – will tell an American how to do things. And so – with a sneer of superiority – 12”-speakers with 4”-voice-coils are produced. Nowadays, there is some restraint to dump Brit-ware into the Boston harbor, but the stuff still somehow feels trashy. Or so advertising tells us. Still, despite the 600-W-behemoths with the loud-n-proud 4”-voice-coil fabricated (or at least designed) under the Stars & Stripes, Yanks (and Rebels – and those from the West-Coast, as well) – as far as they play guitar – scour the Internet for that legendary blue British Celestion that will take no more than a measly 15 W. Well, eight of those standing united in a Marshall stack will easily deal with 120 W, after all. Also, if the real original blue ones are not available anymore: allegedly, Celestion has unearthed the olde machinery and produces *original-replicas* on it. In A.D. 2000, those replicants were offered at the steal of 584 Euro. Per unit, that is. 8 x 584 = 4672 Euro … you should be able to beat that down to 4500. Then, only be careful that your roadie – after a particularly smoky night – does not solder a mains-cable to the newly-acquired treasure …

12"-loudspeakers are manufactured with very different voice coils: customary are diameters between 1” and 4”, with a resulting moving mass of 25 to 75 g. Indeed, a larger voice coils is naturally heavier – but it allows for a larger transducer coefficient, as well, and it can dissipate more heat. In the low-frequency domain, these are already the essential parameters, while in the higher frequency range, the voice coil will influence the partial oscillations of the membrane (Chladni♣).

The involved quantities will be exemplified in the following: a 12”-speaker is operated at 200 Hz – this is above the resonance frequency and therefore we have mass-control, and it is below the cutoff-frequency of the radiation – thus there is mass-loading [3]. Simplifying the loudspeaker impedance to 8 Ω, a current of 0.35 A is required for an operation at 1 W. With a transducer coefficient of Bl = 14 N/A we get a motive force of 5 N. This force generates, in conjunction with the moving mass (e.g. 28 g), a membrane acceleration of a = 177 m/s^2 – mind you, that’s no less than the 18-fold gravitational pull of the earth! In fact, this is not unusual for a loudspeaker; at full power, these values will be much higher. From the acceleration we calculate (via integration) the membrane velocity (0.14 m/s), and another integration yields the displacement: 0.11 mm. Since we have been using RMS-values so far, the displacement needs to be multiplied by 1.4 to obtain the maximum displacement of 0.16 mm. Increasing the current 10-fold (to 3.5 A), the power rises from 1 W to 100 W, and the displacement grows to 1.6 mm (given linearity). Now, before we classify the displacement as an unproblematic quantity, let’s quickly recall that the displacement has a low-pass characteristic (with the speaker driven from a stiff current source): reducing the frequency will increase the displacement. With the power of two, that is! At 100 Hz we already have 6.3 mm, and at 20 Hz that would make … 16 cm. No, not really, because here the resonance enters the game: if the loudspeaker would have its main resonance at 100 Hz, it would operate stiffness-controlled below that frequency, with proportionality between force and spring stiffness. But back to 200 Hz: with the membrane velocity as calculated above, we can call in the effective membrane area (530 cm^2) and the real part of the radiation impedance, and compute the effective power radiated onto a half-space: P_{ak} = 48 mW. Distributing this acoustic power over a hemisphere of a radius of 1 m, a sound intensity of 7.8 mW/m^2 results, which yields a **sound pressure level** of L = 99 dB. This value applies to a non-beaming radiation into a half-space.

Fig. 11.2 has already shown that, for a given DC-resistance (e.g. 6 Ω), the wire-length, the wire-diameter and the turns-number may not be chosen independently from each other. One of the parameters is the length of the voice coil, another is the number of layers. Fig. 11.2 was calculated for a **two-layer winding**, but a four-layer winding would be possible, as well, resulting in an increase of the wire-length and –diameter. The transducer coefficient, and correspondingly the efficiency, would profit from the greater length. At the same time, however, the mass that needs to be moved would increase, and a wider air-gap would be required to contain the double-thickness winding. Increasing the width of the air-gab reduces the magnetic flux density i.e. the transducer coefficient. To compensate for the B-decrease, the magnet – the most expensive component of the loudspeaker – would have to be made larger. For the power capacity, the relations are not entirely trivial, either. The power fed to the voice coil needs to be dissipated for the most part via convection (= heat transfer) through the coil surface. However, a four-layer winding has almost the same surface as a same-length two-layer winding –the corresponding gain would be insubstantial. Every manufacturer needs to find their own strategy of optimization; there are two- and four-layer coils on the market, and even coils with rectangular wire, all in order to push for that last further bit of efficiency.

♣ Ernst Chladni (1756 – 1827), pioneer in experimental acoustics.

In fact, it is quite astonishing that a wire area of 25 cm^2 can withstand 200 W, and that 5 A can flow through a thin enameled copper wire without melting it. The current capacity of corresponding wires in a transformer amounts to 3 - 5 A/mm^2 – in a loudspeaker, this value is easily exceeded by a factor of ten. It is the **current density** that usually is seen as the load-limit: current per cross-sectional surface – apparently, there is a line that should not be crossed. If too many Amperes flow through one square-centimeter, the wire goes kaput? No, that's not the case. Across the wire-resistance, the current causes a voltage drop that, when multiplied by the current, represents the absorbed power. 2.83 V · 0.35 A = 1 W, for example (without any phase shift between U und I). Instead of the unit Watt, we may also use the unit kilo-calory as customary in thermodynamics: 1 W = 0.86 kcal/h. If an electrical resistor is fed with 1 W for an hour, this corresponds to an energy supply of 0,86 kcal. This energy cannot disappear; part of it is transferred to other objects, and part of it leads to a temperature-increase in the resistor. To enable the resistor to dissipate any caloric energy, its temperature *needs* to be increased. From the temperature difference relative to the surrounding air, the caloric energy dissipated via **convection** is calculated, and from the temperature difference relative to surrounding objects the energy transferred via **radiation** can be determined. The former is more important than the latter. A resistor (or in the present case: an enameled copper wire) that cannot dissipate heat well enough will heat up strongly, and it is here where the danger lies: if it gets too hot, it will go kaput, after all. First, the insulating lacquer and the glue will burn, and at too high a temperature the copper will even melt (melting point is 1083 °C). Therefore, it is not the cross-sectional area of the wire that is of importance but rather the surface of the heated object (together with further parameters). The value of the current density thus is not an adequate parameter to estimate the power capacity. Copper traces in printed circuit boards bear testimony to this, too: here, 200 A/mm^2 are not a rarity.

The voice coil needs to pass the energy fed to it predominantly as heat; indeed the share converted into oscillation energy (and sound) may almost be disregarded in comparison. The flowing current heats up the voice coil which heats up the surrounding air; the latter in turn needs to pass its caloric energy as well as at all possible to the field-focusing pole-plates. For that reason, too (i.e. not only in order to achieve a high flux density), a narrow air gap is advantageous. If the voice coil is longer than the air gap, the protruding part is in particular danger to overheat, because the distance to the cooling-providing pole plates is larger. An added extension (necessarily made of non-magnetic material, e.g. aluminum) serves well in this case (**Fig. 11.4**). This extender has no bearing on the static magnetic field but it does on the heat transfer. The dynamic magnetic field will be affected – however, this may indeed be desirable: the eddy current induced in the extender pushes the AC-field out of the magnetic circuit (low-pass), and decreases the non-linearity caused by the field's modulation. Whether a **pole piece vent** is helpful can only be determined in the individual case: given an airtight dust-cap (calotte), a pump results that pumps cooling air into the air gap. However, the effect of a non-linear spring is created also. The vent decreases the non-linearity, and the cooling effect, as well [Klippel W., JAES Vol 52, 2004].

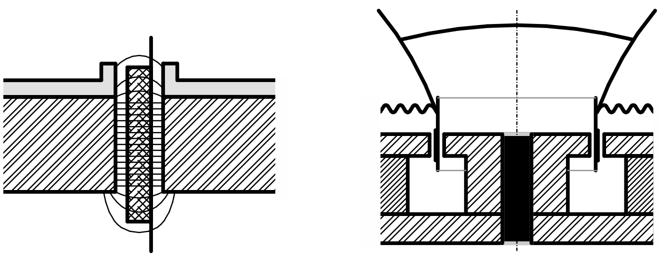


Fig. 11.4: Pole plate with non-magnetic cooling extension (left), pole-core with vent for ventilation (right).

In operation, the voice coil gets very hot, but its material (usually copper, sometimes aluminum) can deal with this issue quite well. Not so insulating material, glue and bobbin. Early on in the era of loudspeakers, the voice-coil carrier was made of paper: thin and lightweight – but not very temperature-resistant, with about 100 – 120°C being the limit for continuous operation. Accordingly, the first 12”-speakers were specified at a power capacity of merely 15W. As new plastics were developed, materials with higher resilience appeared, for example **Nomex** (meta-aramid) consisting of polyamide fibers and enduring up to 220°C. **Kapton** can withstand even higher temperatures: the manufacturer (DuPont) specifies 230°C, but loudspeaker manufacturers readily rely on the short-term specification of up to 400°C. If that is still not good enough: bobbins made from aluminum would take even higher temperature loads. They did not catch on for guitar loudspeakers, however.

Kapton has proven itself as standard material in more recent loudspeakers, but Nomex and even paper are still deployed, as well. The main reason is the sound. Manufacturers such as Eminence attest the paper-bobbin a slightly warmer sound while Kapton allegedly produces a somewhat more brilliant sound. Nomex supposedly gives an intermediate result. In any case, these would not be big differences – shape and build of the membrane have a much more considerable effect here. Eminence offers a 12”-speaker (L-122) optionally with paper- or Kapton-bobbin, with – of course – different power capacity: 20 W and 35 W, respectively, which is a common value for 1”-voice-coils. At the same time, Eminence also offers five further 12”- guitar speakers, among them a 100-W-speaker with a 2”-voice-coil on a Kapton bobbin. Options include “British” membranes, on paper- or Kapton-bobbins.

Temperature-resilience and efficiency are without doubt important features of a loudspeaker, but the main criterion is the sound. Even if the voice-coil may have a small share in this, the membrane (also termed diaphragm) is what takes care of the sound radiation, and it is the component most crucial to the sound. Following simple piston-membrane theory, we have frequency-independent power radiation between the resonance- and the cutoff-frequencies (e.g. between 90 and 600 Hz). Above this, the radiated power drops off with $1/f^2$. At low frequencies, the speaker radiates the sound power into a half-room; from about 600 Hz, beaming sets in, and the power decreasing with $1/f^2$ is increasingly focused onto a smaller section of the room. This piston-membrane theory holds, however, only for a rigidly oscillating membrane not changing its shape at all. At middle and high frequencies, the real membrane vibrates not rigidly but it “breaks up”, i.e. it vibrates in **eigenmodes** (standing waves, partial oscillations). This “life of its own” of the membrane (not initially covered by the simple theory) is undesirable for HiFi-speakers but positively welcome in guitar loudspeakers: it does enrich the guitar sound with invigorating high-frequency interferences. As already noted: color-free, neutral reproduction is not the objective in a guitar loudspeaker. And so the loudspeaker designer batters up the membrane with many a corrugation – such that it may generate as many partial oscillations as possible up to about 5 kHz. In **Fig. 11.5**, one of these circumferential corrugations is shown. Loudspeakers made by Celestion (a brand often used in guitar amplifiers) in most cases include 8 corrugations; in speakers by Jensen (another highly popular brand) we find up to 12 corrugations. More details regarding membrane oscillations are to follow in Chapter 11.3.

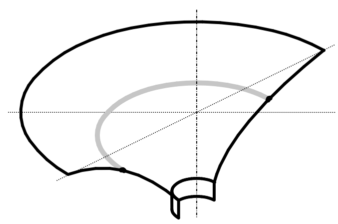


Fig. 11.5: Membrane with corrugation

