11.4 Directional characteristics

As a loudspeaker radiates sound, it gives rise to a **sound field** around it, i.e. a section in space to which physical quantities can be assigned as a function of location and time. In a sound field, these quantities are the *sound pressure* (p, a scalar), and the *(sound particle-) velocity* (v, a vector). Both quantities are not only dependent on time but also on the location. For frequency responses of loudspeakers, usually the SPL measured "on axis" is given, i.e. the SPL that occurs e.g. 1 m ahead of the membrane. Deviating from this measurement point by a specific angle (e.g. 30°) from the axis, the result is a different frequency response. The reasons for these differences in the frequency responses are differences in travel time (and corresponding interferences) between the sound waves emitted from different sections of the membrane. These are effects summarized with the term **beaming,** or **directionality**.

As a first simplification, the loudspeaker membrane is described as a circular plate (piston diaphragm) vibrating without changing its shape. To explain the directionality, Huygen's principle (well known from optics) is called into action: every differentially small part of the membrane emits a spherical wave, and all these spherical waves superimpose in the free sound field resulting in the radiated sound wave [3]. At a measurement point located axially, all sound waves will have to travel approximately the same distance, and arrive at the same time (with the same phase). However, as we move the measurement point off-axis, the sound paths will differ, and phase shifts – and thus cancellations and beaming – will occur. At low frequencies (= long wave-length), the travel path differences are relatively small and the beaming is less pronounced. However, as the wavelength becomes smaller with rising frequency ($\lambda = c\ /\ f$), already small differences in path-length (e.g. 5 cm) give rise to a noticeable phase-shift (elaborated in [3]). Consequently, the loudspeaker will radiate without beaming (spherically) in the low-frequency range, but as the frequency rises, so will the beaming effect. Usually, the frequency with a wavelength just fitting into the circumference of the loudspeaker is taken as limit from which beaming occurs. For an effective diameter of 27 cm, this results in f_g = 400 Hz. A 12"-speaker therefore features *approximately* (!) two different radiation characteristics: without beaming below 400 Hz, and above 400 Hz a frequency-proportional beaming. So much for the simple piston diaphragm theory, anyway.

Measurements with lasers (Chapter 11.3), however, show that the membrane already "breaks up" (i.e. it fails to keep its shape) upwards of 350 Hz. Therefore the piston-diaphragm theory also breaks: it breaks down, though. To formulate this more obligingly: from 350 Hz, we leave the range of validity of the piston-diaphragm theory. Now, it is simple to shoot down a theory but much harder to present a better theory instead. Of course, there are powerful formula the global significance of which can hardly be shaken, e.g. rot($\boldsymbol{v}$) = 0. Given the (location-dependent) membrane velocity, we may – now already more specifically – formulate the radiated wave as an integral that can be solved at least numerically. In approximation, that is, without saying. However, *one* differential equation won't do the job because the pattern of partial vibrations on the membrane may strongly change already with small frequency variations (e.g. +5 Hz). Also, to put together a directional diagram, the solution is required not only for *one* point in space. Because numerical algorithms for calculating the sound radiation are effortful (and require even more effort in corresponding measurements), the approach using purely metrology can still hold its own next to analytical descriptions. So let's go ahead, and let's measure frequency responses in various directions, put together polar diagrams for various frequencies, and determine frequency dependent directional indices in the AEC or the RC. The following characterizations use the piston diaphragm theory as a basis and compare its teachings with measurement results.

The directional gain Γ of the piston diaphragm is calculated from the Bessel-function J_1:

$$\Gamma(k,\Theta) = 2\cdot J_1[ka\sin(\Theta)]\,/\,ka\sin(\Theta) \qquad \text{Directional gain [3]}$$

Γ is dependent on the wave-number $k = \omega/c$, on the effective membrane radius a, and on the angle Θ defined relative to the loudspeaker axis. The logarithm (with the base 20) of the directional gain is the **directional index** D. For low frequencies, D is approximately zero, as the frequency rises or as the angle Θ increases, D becomes negative. The left-hand section of **Fig. 11.38** shows the directional index, the right-hand section shows the directivity. Directional indices are bi-variant quantities; they depend on frequency and angle. To obtain the directivity, the envelope integral is calculated ("averaged") across all angles – only a frequency-dependency remains. Since the theory of the piston diaphragm is based on an infinite baffle, sound is only radiated into one half-space – and thus d = 3 dB at low frequencies.

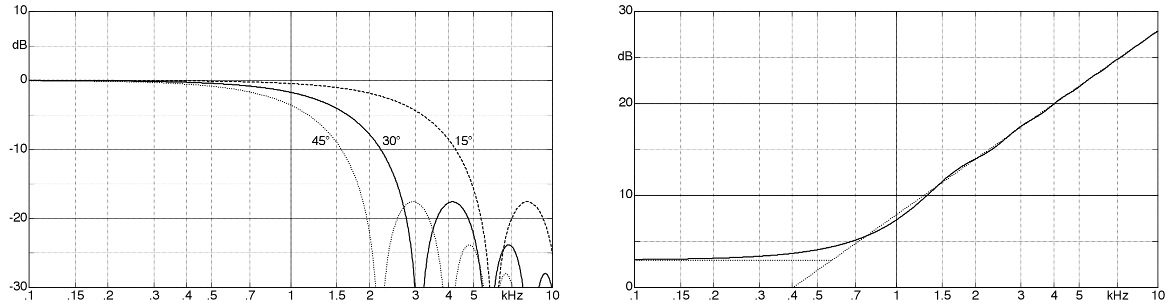

Fig.11.38: Directional index D of the piston diaphragm, a = 13.5 cm, Θ = 15°, 30°, 45°. Right: directivity d.

So much for our (simple) theory – how do measurements in the anechoic chamber compare? For that assessment, a 12"-Celestion-speaker (G12-M) was mounted in a small sealed enclosure (39x39x25 cm^3), and measurements of the SPL were taken at 0° and 35° (**Fig. 11.39**). Easily recognizable is how nicely the curves run in sync up to about 150 Hz – from then on the 35°-curve increasingly deviates from the 0°-curve. However, it is also clearly evident that this deviation corresponds only with a very coarse approximation to the piston-diaphragm theory. In the right-hand section of the figure, the calculated directivity for 35° is included (dashed line) – the curves do take a rather different course. Particularly evident: the figure holds three measurements taken with the enclosure turned by ±90° around the speaker axis (as indicated by the small sketch). We would expect rotationally symmetrical behavior from a single speaker, requiring the membrane to vibrate exclusively in rotationally symmetrical fashion. Which in fact it does – but not exclusively, as shown in Fig. 11.6. In particular in the high-frequency range, a multitude of complex modes occurs that certainly are not all rotationally symmetric. The radiation behavior is correspondingly complex.

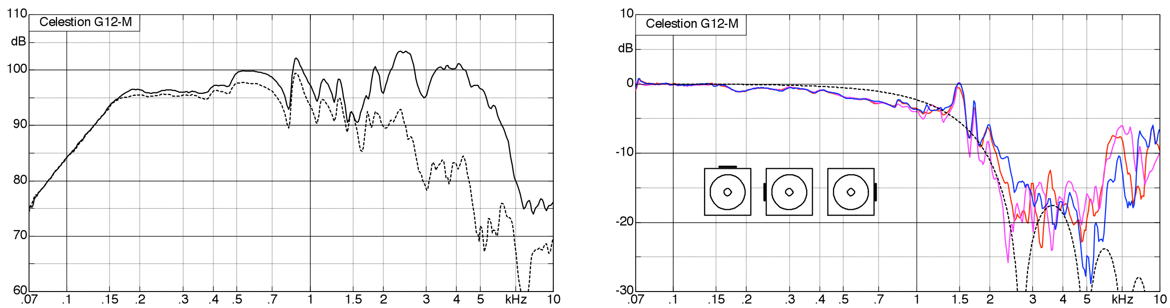

Fig. 11.39: 12"-loudspeker measured in the AEC, with 0° (——) and 35° (---). Right: directivity.

The directional characteristic found in Fig. 11.39 clearly deviates from that of an ideal piston diaphragm. Still, it should not be inferred that only the sound radiated off-axis is going to buck the theory; some effects (e.g. at 1.5 kHz, but also in the high treble range) originate in the axial SPL that for the ideal piston diaphragm should be frequency-independent. Evidently, this is not the case, and for that reason alone the directivity deviates from the nominal curve.

Why in fact is the directional characteristic of the radiation behavior that important? An often-heard comment is that most of the listeners are seated in front of the loudspeaker, and therefore the sound radiated to the side would be insignificant. Well, it is significant, because in the listening room (or hall), the sound radiated off-axis will be reflected by floor, ceiling and walls, and it will reach – as room sound – the ears of the listener with only little delay. It is impossible to exactly describe all individual reflections in a real room because already simple objects (chairs, lamps) feature a highly complex reflection behavior. That's why we make do with the directivity. It is quite useful as an approximation: a high directivity means much direct sound and little room sound. Sure: that room … its special absorber-distribution ... the position of the listener … and much more. Still, we need to simplify in order to push forward to the essentials. When operating two loudspeakers with significantly different directivity, the above statement holds as a simplification: more beaming = less room sound.

Like the directional index, the directivity d is calculated using the first-order Bessel-function (J_1). Approximately, d rises at a rate of 20dB/dec above the cutoff frequency, with the latter being defined by its wavelength $\lambda \triangleq$ effective membrane-circumference (12" → 400Hz).

$$d = 10 \cdot \lg \frac{(ka)^2}{1 - J_1(2ka)/ka} \mathrm{dB}$$

Directivity [3]

The larger the membrane is, the lower the frequency where the beaming starts: a 15"-speaker has stronger beaming than a 10"-spekaer, but four 10"-speakers have a more pronounced beaming than a 15"-speaker because the effective membrane area of the former quartet is larger than the membrane area of the latter. **Fig. 11.40** juxtaposes theory and measurement results. As already mentioned, measuring the directivity is difficult because the "artifacts" encountered in reverberation chamber and anechoic chamber can add up. However, if we do not regard the directivity as a system-immanent quantity (which in fact it is not, anyway) but as relating to the environment, then the measurements become sufficiently reliable, and even a negative directivity appears purposeful: at low frequencies, the loudspeaker positioned in the reverberation chamber has a higher efficiency compared to the positioning in the anechoic full-space (Chapter 11.5). If we do not attribute any significance to differences as small as up to 1 dB, the basic curve can be interpreted nicely, especially when comparing several loudspeakers measured in the same room.

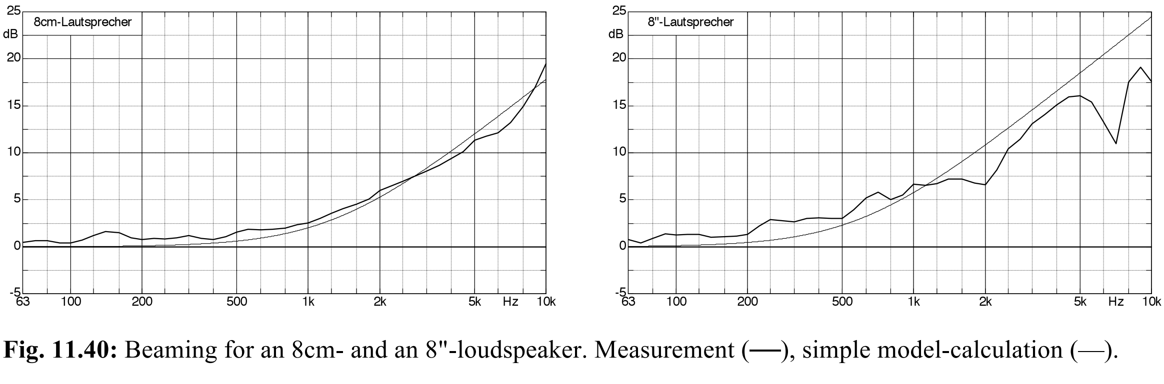

Fig. 11.40: Beaming for an 8cm- and an 8"-loudspeaker. Measurement (—), simple model-calculation (—).

The rather bad match between measurement and theory seen in Fig. 11.40 for the 8”-speaker is not likely to be a result of unsuitable instrumentation: the theory simply does not fit the speaker – in the higher frequency range, the membrane is not vibrating anymore without a change in shape. The beaming-minimum at 7 kHz has its basis in a destructive interference that leads to a minimum in the *axial* radiation. Half the wavelength amounts to a mere 2.5 cm at this frequency, and cancellations are easily conceivable. The off-axis radiation is not subject to this interference, and that leads to the effect of a minimum in the directivity. The latter does depend on two quantities: on the direct sound, and on the diffuse (room) sound. Consequently, a minimum in the directivity may be obtained via two ways: by efficient radiation of diffuse sound, or by inefficient radiation of the direct sound.

With **Fig. 11.41**, we return to the 12”-speaker that was already used for most of the previously presented measurements: the Celestion G12-M. The left-hand picture shows measurements with a small sealed enclosure. Up to 1 kHz, the beaming is somewhat stronger than calculated using the simple theory – that may be due to the enclosure: at 39cm x 39cm, the front panel is not actually infinite but already larger than the effective membrane diameter (27 cm). The curve above 1 kHz cannot be clearly attributed anymore to anomalies of *a single* sound field: both direct- and diffuse-sound deviate significantly from the simple piston diaphragm theory.

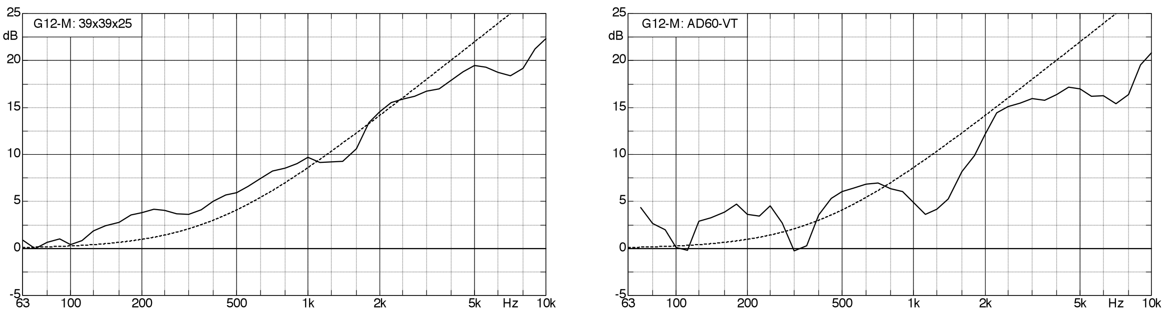

Fig. 11.41: Frequency response of the directivity: G12-M, mounted in two different enclosures.

For the right-hand graph in Fig. 11.41, the G12-M was mounted in the open-back VOX-cabinet already used in Chapter 11.3. This cabinet shows everything <u>but</u> a dipole-characteristic! As main effect, we recognize two beaming-minima (350 Hz, 1.2 kHz) on the one hand, and on the other hand a global widening of the treble-reproduction (reduction of beaming). Given the high-frequency beaming of the loudspeaker, it will not make a difference for the on-axis AEC-measurement whether the rear panel is open or closed. For measurements in the RC, however, a difference will show because the same amount of power is radiated from the rear of the speaker (in idealized thinking: level of diffuse sound +3dB). At low and middle frequencies the superposition of the sound waves radiated from the front and from the rear leads to comb-filter-like ripples in the directivity. Again, it is predominantly the sound radiated to the front that forces the shape of the frequency response in the beaming: the minima at 350 Hz and 1.2 kHz are found with axial AEC-measurements, as well – as e.g. Fig. 11.24 shows for all measured Celestion-speakers

Shape and type of the cabinet contribute significantly to the loudspeaker-sound. That also holds for HiFi speaker arrangements, but here the direct SPL should be as much as possible frequency-independent, and the directivity should rise evenly across the frequency such that in the end the speaker will sound good (i.e. neutrally) despite the enclosure-specifics. Conversely, for the guitar speaker the cabinet provides a distinct filter; its directionality cannot be changed electronically.

How dominant the influence of the cabinet is in comparison to variations of the loudspeaker may be seen from **Fig. 11.42** – it includes the directivities of several Celestion speakers all mounted in the VOX AD60-VT-cabinet. At first glance all the curves are of very similar shape – at second glance one speaker is strikingly different at 8 kHz: it is the Celestion "Blue". After what has been stated above regarding that speaker, at last we have an objectifiable rationale in favor of this speaker … possibly a late satisfaction for all those still paying off the debts caused by that speaker. Of course, we shall not even start questioning how significant the frequency range in question actually is (☺ Abb. 11.25).

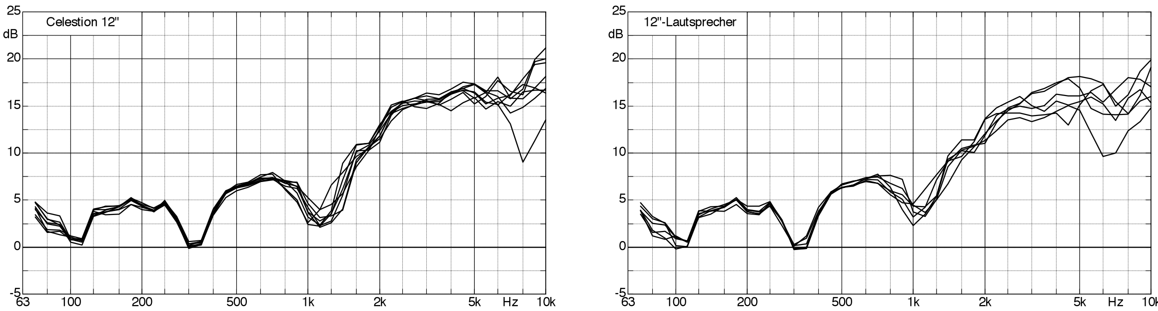

Fig. 11.42: Frequency responses of the directivity for various 12"-loudspeakers: Celestion, Jensen, Eminence.

In the right-hand section of the figure we find a few loudspeakers with a more strongly differing directivity: Jensen and Eminence. The general reason is quickly identified: their membranes show more diversity than those of the Celestion speakers: size of dust cap, corrugations, depth of membrane, diameter of the voice coil. Still, the main effect is caused by the enclosure; the opening in the rear takes care of characteristic beaming-minima. A directivity of 0 dB is often interpreted as **spherical radiation** although this is not always applicable. The degree of beaming (or beaming factor) relates the intensity radiated in the axial direction to the averaged intensity radiated in all directions [3]. If – due to an interference-cancellation (pole) – no sound is radiated axially, the beaming-factor is zero and the directivity is $-\infty$. If axially only little sound is radiated but in all other directions beaming occurs, d = 0 dB may result – despite the fact that there is no spherical characteristic.

Directional diagrams give clues regarding the direction-dependency of sound radiation. In corresponding measurement setups, the object to be measured rotates by 360° on a revolving table, and the SPL is registered dependent on the rotation angle. The resulting diagram is usually laid out using polar coordinates. **Fig.11.43** exemplifies 3 directional diagrams measured with the AD60-VT. None of the diagrams shows the dipole-typical radiation pattern – this is due to the cabinet acting as a phase-shifting filter for the wave emitted to the rear.

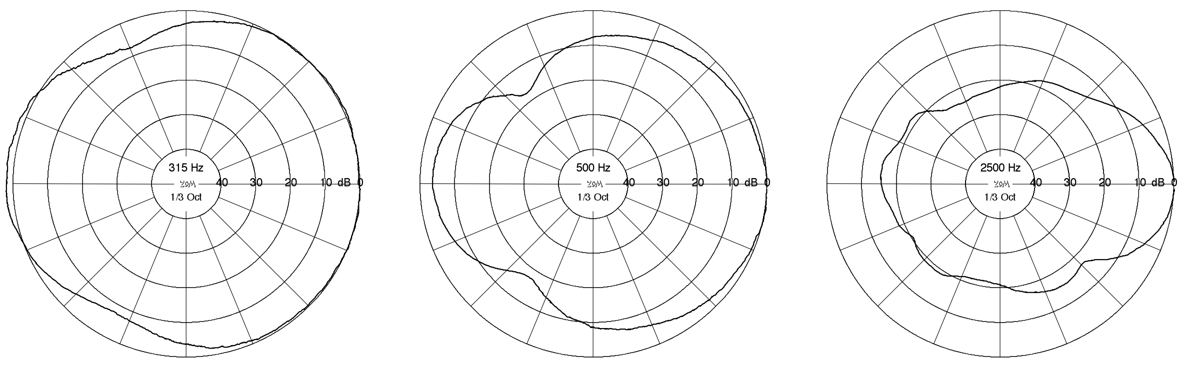

Fig. 11.43: Horizontal directional diagrams measured with third-octave-noise. Loudspeaker in AD60-VT-cabinet.

Directional diagrams have descriptive qualities but can only exemplify one single plane – as such they have limitations. For a circular membrane, often a rotation-symmetric radiation is implied, coupled to the hope that a single measurement (per frequency!) will be sufficient. Often, this is a reasonable approach, but just to be safe we should take additional measurements. **Fig. 11.44** shows horizontal directional diagrams – in contrast to Fig. 11.43, a sinusoidal test-signal was used, though. At 400 Hz a perfect symmetry exists, while at higher frequencies, any asymmetric shape may occur due to membrane resonances. Since these shapes are highly dependent on frequency, the information contained in directional diagrams needs to be drastically reduced in order to remain clear. Therefore, noise (of octave- or 1/3rd-octave bandwidth) is often employed as test signal – this has the effect of an averaging across the corresponding frequency interval. Using that approach, the small variations contained in directional diagrams are not an expression of high directional selectivity but the result of stochastic processes. Given an optimized averaging time-constant, misinterpretations are not to be expected – if necessary, fluctuations can be reduced via averaging over several turns of the rotational table.

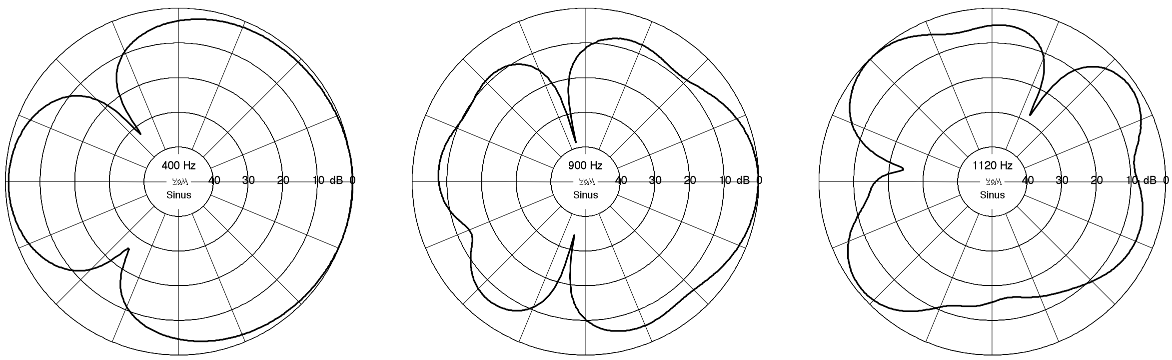

Fig. 11.44: Horizontal directional diagrams, measured with a sinusoidal signal. 12"-speaker, AD60-VT-cabinet.

Installed in a sealed cabinet, a loudspeaker will operate as a spherical source; with a rear opening in the cabinet, a dipole will result. However, the stiffness of the air contained in the cabinet forms, in conjunction with the inert (mass-dominated) radiation impedance of the opening, an acoustic filter creating phase-shifts, and therefore the directional diagrams have the shape of a (logarithmized!) eight only at very low frequencies. Already at 200 Hz, this dipole-behavior is all but gone, and the horizontal directional diagram approaches a circular shape. In **Fig. 11.45** we find a comparison between the original VOX and a variant where the rear was closed off with a board. The latter does not provide a complete seal, however: the slits foreseen to provide ventilation for the amplifier section let sound pass through. Horizontal directional diagrams for the AD60-VT cabinet with open and closed rear wall are juxtaposed in **Fig. 11.46** (measured in the AEC using 1/3rd-octave noise).

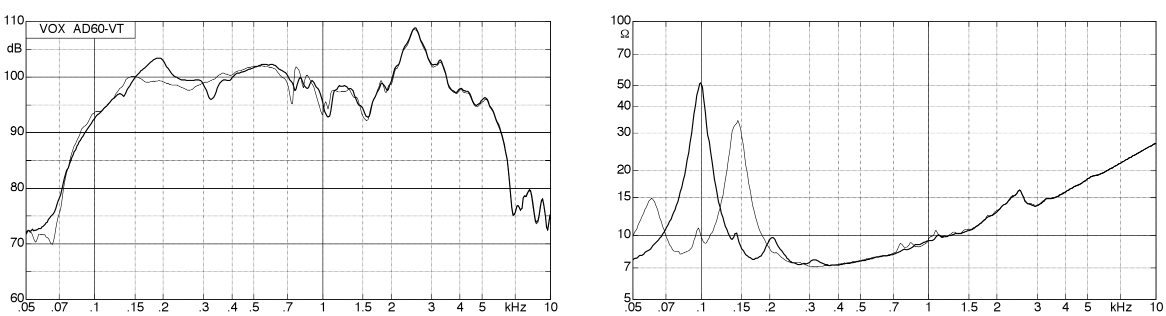

Fig. 11.45: VOX AD60-VT: rear wall closed with board (──) vs. original condition (──).

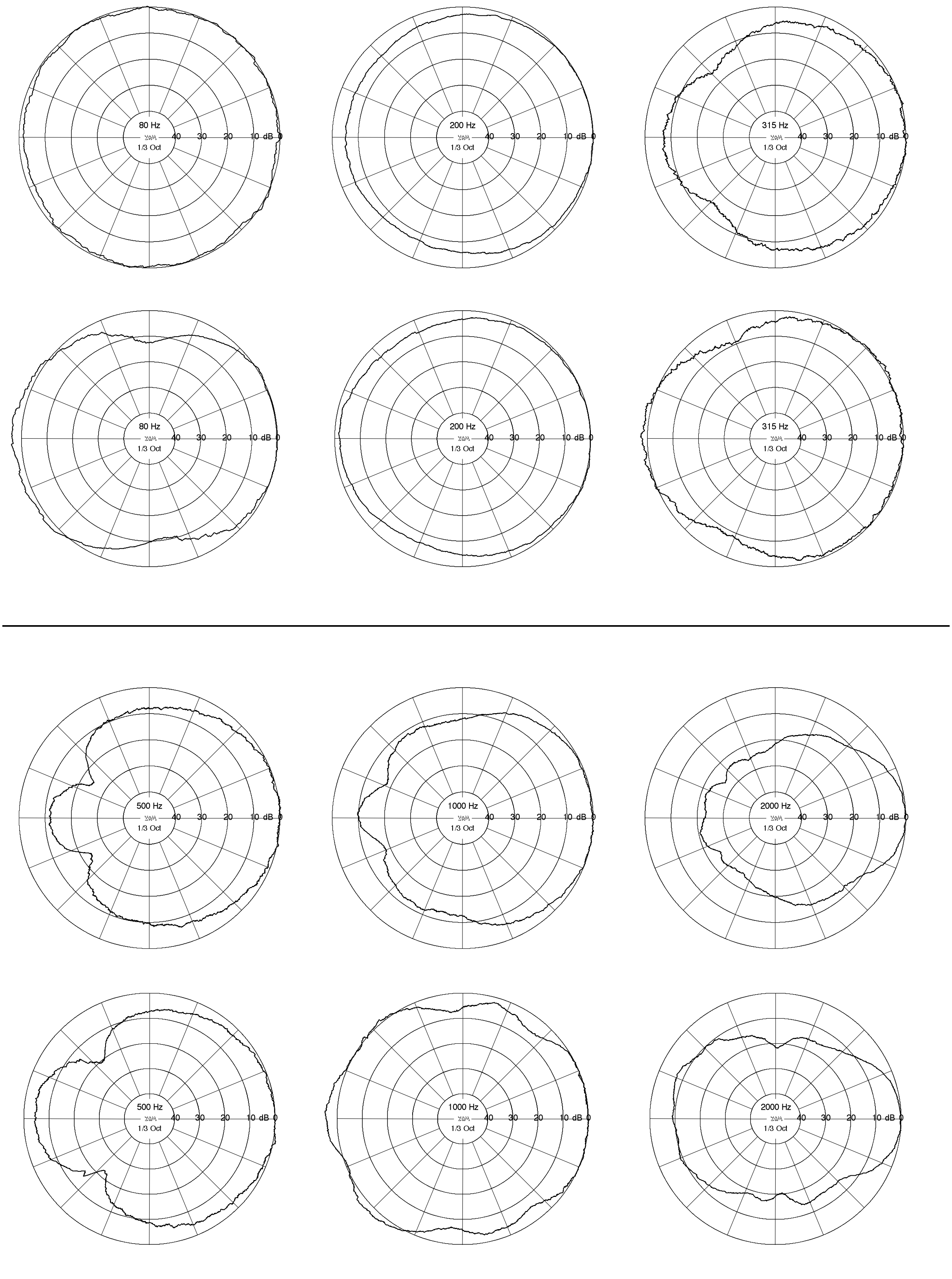

Fig. 11.46: Horizontal directional diagrams with sealed (1st and 3rd line) and open rear wall of the AF60-VT. The dipole-characteristic begins to become visible at 80 Hz, while at 200 Hz barely any differences are visible. In same ranges, more sound is radiated to the rear than to the front (e.g. at 315 Hz); this is caused by an impedance-transformation (an effect of the cabinet cavity).

Fig. 11.47 shows how strongly the cabinet influences the sound-beaming. All measurements were done using the same cabinet with or without a rear panel (i.e. closed resp. open). For both variants, the 10"-speaker features less beaming in the high-frequency range – however, the cabinet-specific differences far outweigh the loudspeaker/diameter-specific differences. The directivity is negative at 315 Hz – this again is due to the direct sound radiated to the front and showing an interference minimum (rear-ward diffraction wave) at that frequency.

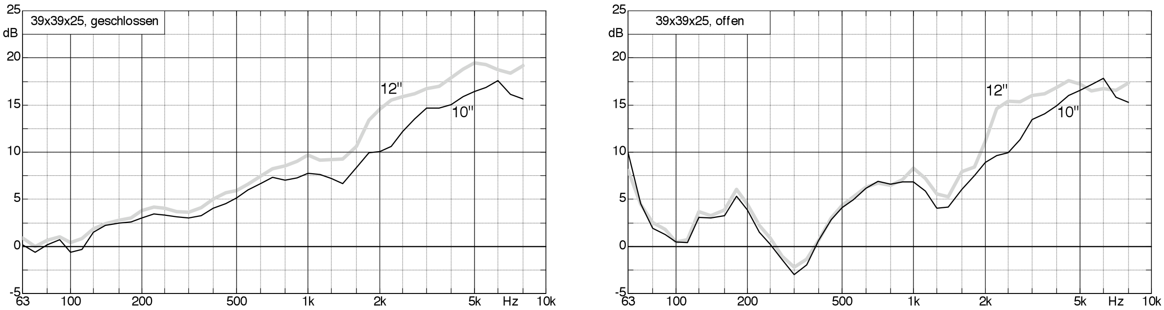

Fig. 11.47: Comparison of the directivity of the closed and the open cabinet; G12-M vs. P10-R.

If two or more loudspeakers are mounted in a cabinet, the beaming increases because the membrane area grows. Corresponding measurements that support this general statement are shown in **Fig. 11.48**. Differences are visible in the details, though: first, the enclosure shapes are different, and second, the sound power radiated to the rear is loudspeaker-specific. Finally, **Fig. 11.49** presents the directivity of loudspeaker cabinets that are designed to reproduce the whole frequency range relevant for music transmission (so-called "full-range" speakers). Their directivity should increase as evenly as possible – this is achieved quite well in the Quinto.

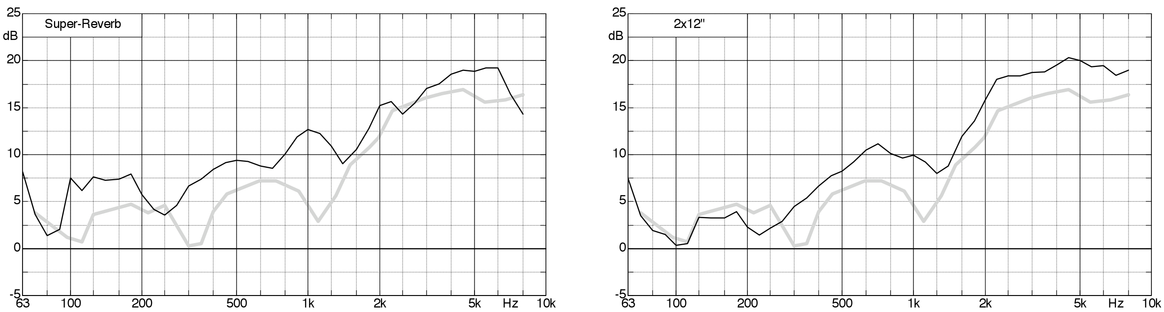

Fig. 11.48: Left: Fender Super-Reverb, 4x10", Jensen P10-R; right: typical 2x12"-Box, Celestion G12-M. Grey curve = VOX AD60-VT (1x12") for comparison. The directivity is given as a function of frequency.

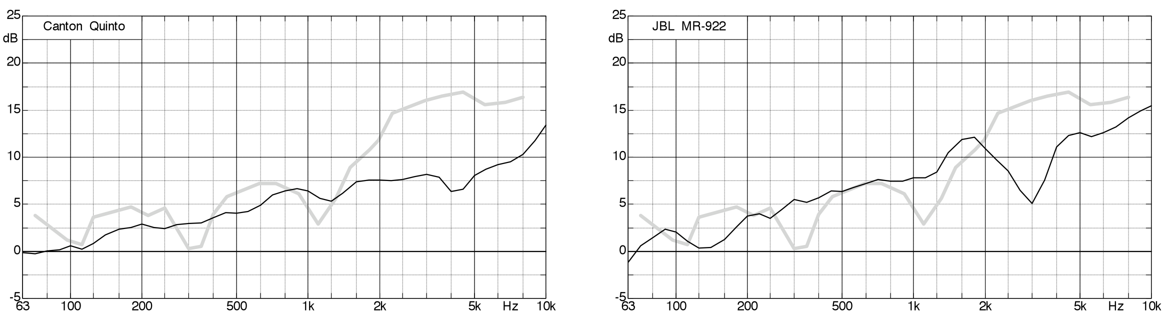

Fig. 11.49: Directivity of a HiFi-Box (left) and a small full-range-box for stage use (right).
Grey curve = VOX AD60-VT (1x12") for comparison. The directivity is given as a function of frequency.

The area-rich **15”-loudspeakers** should actually show particularly strong beaming effects – but measurements support this hypothesis only in part (**Fig. 11.50**). For both the Fane and the Powercell, the directivity decreases again in the highest frequency range. Possibly, this is connected to the large dust-caps of these speakers: both sport air-tight dust-caps acting as high-frequency emitters with a diameter of naturally not 38 cm but merely 10 cm. However, no further measurements regarding this hypothesis were conducted.

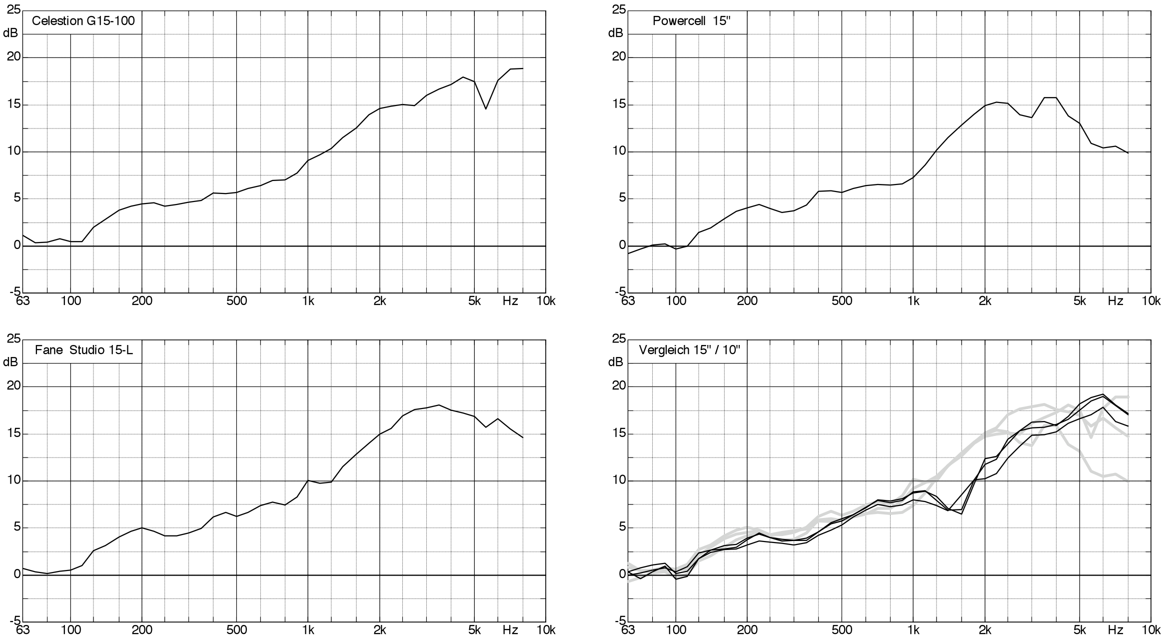

Fig. 11.50: Directivity of 15"-loudspeakers. Lower right: comparison 15” vs. 10” speaker.

The last section in Fig. 11.50 depicts a comparison between 15”- and **10”-loudspeakers**. Below 1 kHz, differences are rather limited; only above this limit, things become more specific. According to the simple piston-diaphragm theory, we should see a difference of 3.5 dB. Prerequisite would, however, be an infinite baffle – but the measured loudspeakers were installed in airtight boxes of different sizes (10" ⇒ 39x39x25 cm^3, 15" ⇒ 40x74x36 cm^3).

As a last point, a special characteristic of 2x12”-combos shall be considered: almost always, the loudspeakers in the corresponding cabinets are mounted *horizontally next to each other,* conversely to the speakers in public address systems where the speaker chassis are mounted *vertically above each other*. The vertically aligned column has the advantage that the vertical beaming is increased (less sound to floor and ceiling), while horizontally a wide-angle radiation is retained. That the 2x12”-combo is realized exactly the other way ‘round may be the result of a desired visual look and feel, but also a necessity required by the amplifier-chassis: you need quite a bit of space to line up 11 knobs (like in the Twin-Reverb). Fender’s first foray into tall cabinets and two rows of control knobs (1967, in the first Solid-State amplifier series) pretty much was a disaster (possibly not merely due to the geometric configuration…): comments included the terms “ugly refrigerators” or “TV-trays”. With regard to beaming and sound dispersion, the tall, slender design would certainly have had advantages. (Translator’s note: maybe the more vertically oriented sound dispersion is something favoured by the musician standing in front of the amp? Especially when using the “tilt-back” legs customary in these amps, the vertical spreading out of the sound makes it less crucial at what distance the guitarist stands relative to the amp, and how tall he/she is. Also, more sound is aimed at the guitarist when playing – too? – loud …)