Manipulating Directivity

Content

Introduction

There are different ways to manipulate the dispersion behavior of a loudspeaker. In the following the possibilities of creating a narrow directivity and their properties are discussed.

The dispersion is visualized using BEM simulations (ABEC and AxiDriver). This has the advantage that ideal conditions can be created that preclude a mutual overlapping of the physical modes of action.

The isobaric plots are normalized to 0° in order to show only the radiation behavior. It is therefore assumed that a loudspeaker is always linearly equalized and angled directly at the listener.

Diaphragm

Size

The diaphragm diameter is responsible for a steadily increasing directivity, which starts at about half the wavelength corresponding to the diameter in the dimension under consideration. This means that in the case of rectangular diaphragms, the horizontal and vertical dispersion can be considered separately (e.g., in the case of ribbons). The larger the diaphragm diameter, the earlier the narrowing begins.

The following example shows two drivers with rotationally symmetrical diaphragms in an infinite baffle which differ in their size. The infinite baffle ensures that only the directivity of the diaphragm size comes into play.

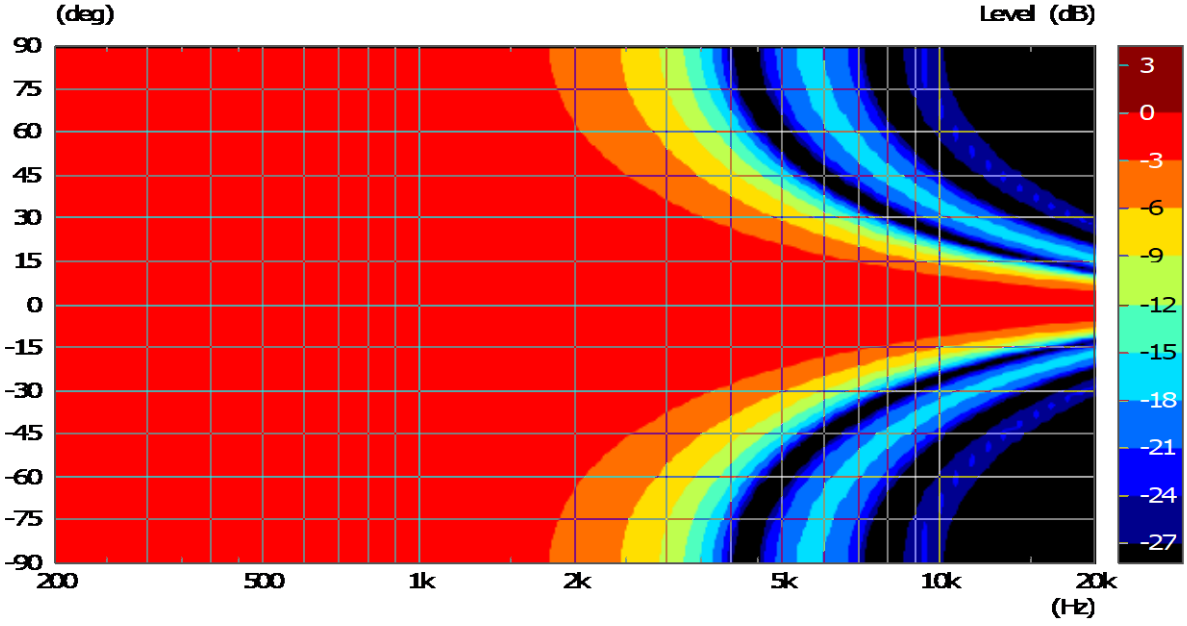


Illustration 1: Dispersion of an ideal driver with a diameter of 10 cm

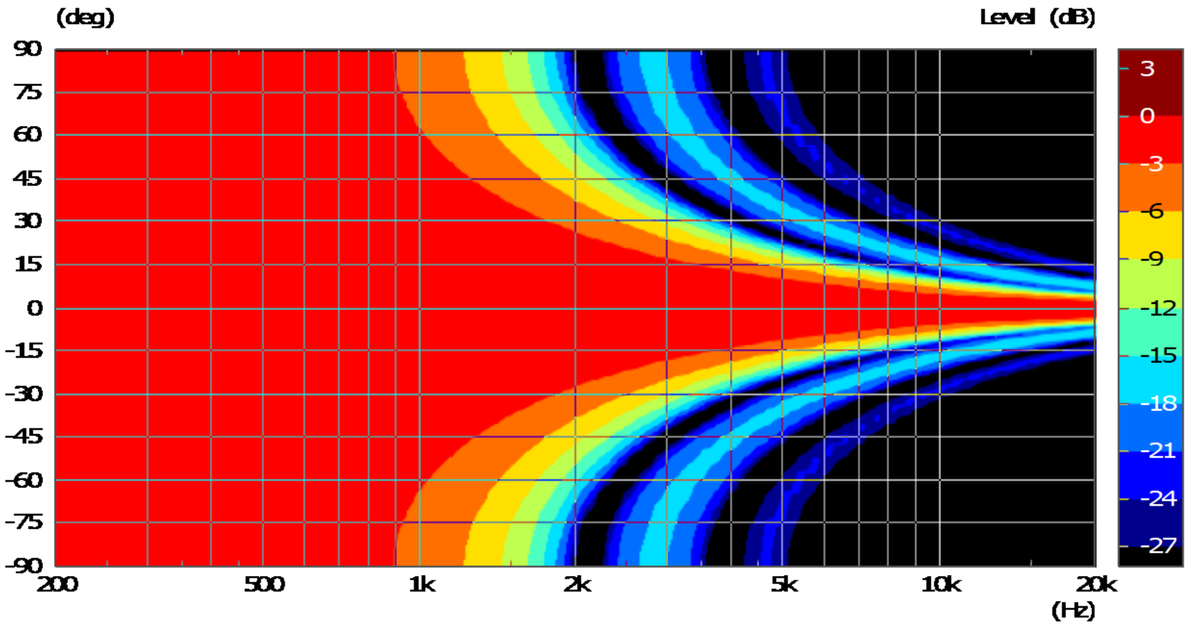


Illustration 2: Dispersion of an ideal driver of 20 cm Diameter

On real cone drivers with an internal voice coil, the outer part of the diaphragm decouples with increasing frequency, so that the effective diaphragm size is reduced. As a result, the directivity usually narrows less than with a dome where the voice coil is located on the outside.

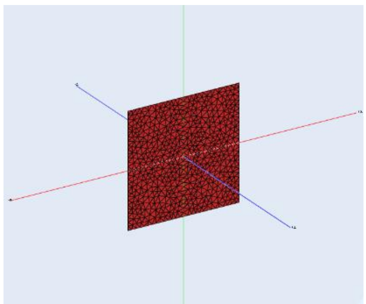
Geometry

The geometry of the diaphragm largely determines how strong the directivity is. This applies to the two-dimensional surface and the third dimension, i.e., the depth. First, the effect of the shape of flat membranes is shown.

The diameter of the examples is 10 cm in both dimensions. The radiation behavior is specified horizontally in each case.

Square

The narrowing of a square-shaped diaphragm begins relatively early in the frequency domain. The reason is that there is the same width across the entire height. Since the width determines the horizontal directivity, it is maximum in relation to other shapes.



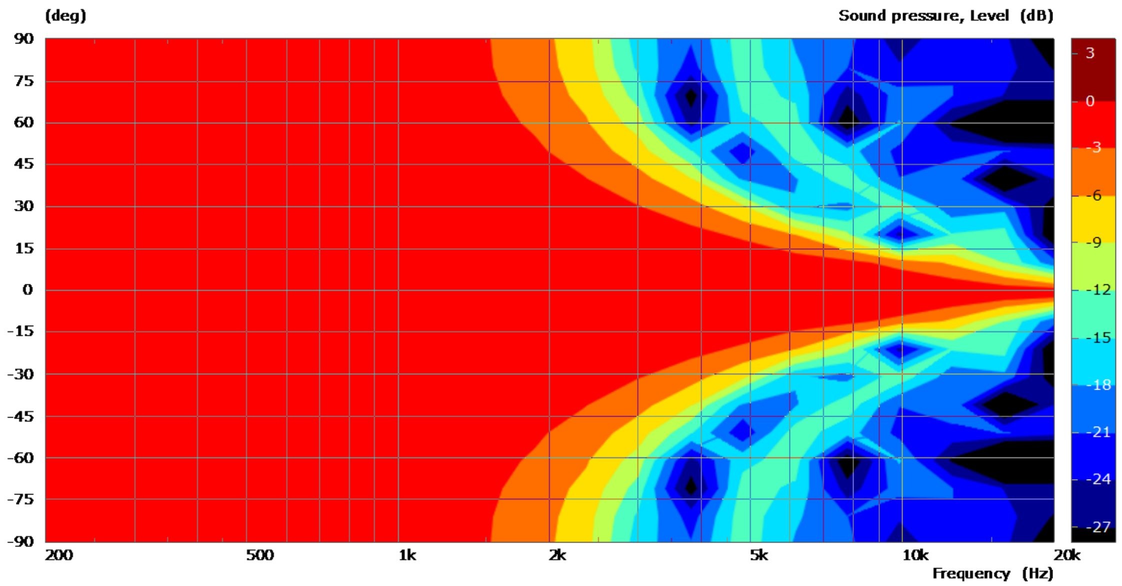
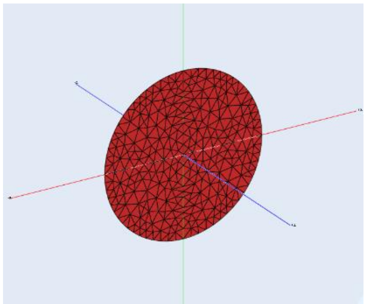


Illustration 3: Horizontal dispersion of a square diaphragm

Circle

In the case of the circular membrane, the width, as opposed to the square, changes over the entire height. It is only maximum in the middle and otherwise follows sinusoidally. As a result, the width is smaller on average than with the square, which results in a lower directivity. In this example, it starts at about 1.7 kHz instead of 1.5 kHz.



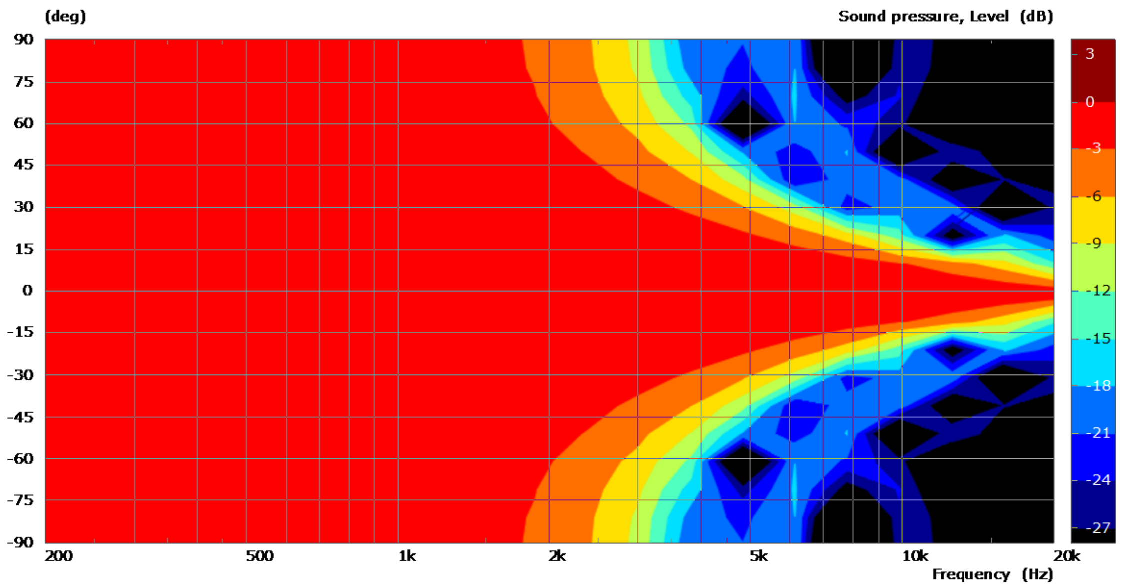
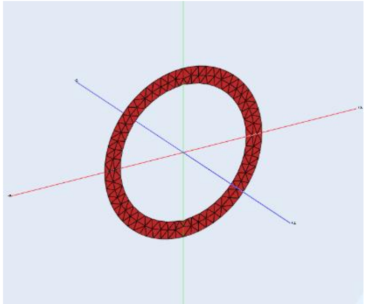


Illustration 4: Horizontal Dispersion of a Circular Diaphragm

Ring

In the case of the ring, the sound-emitting surface is only on the outside, the inside does not contribute to it. As a result, the structure can be divided horizontally into two separate sound sources over a large part of the height. This leads to sidelobes. Accordingly, the directivity begins earlier in the frequency range than in the filled circle and even slightly earlier than in the square.



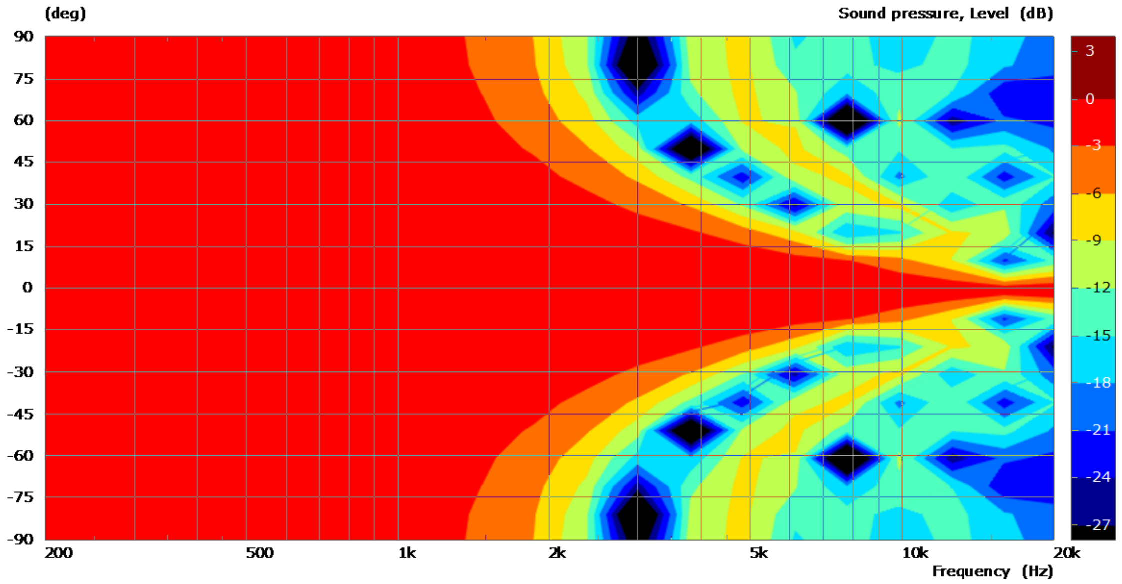
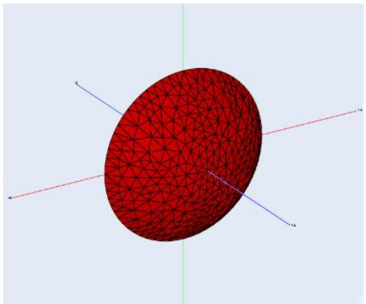


Illustration 5: Horizontal dispersion of a ring-shaped diaphragm

Sphere segment (convex)

In the following, the third dimension (the depth of the membrane) will be considered. In this example, the diaphragm is convex, it bulges out of the surface. The depth was assumed to be half the radius.

As can be seen in the dispersion behavior, the narrowing in the frequency domain begins later than in the flat circle. In the upper frequency range, the radiation even widens again.



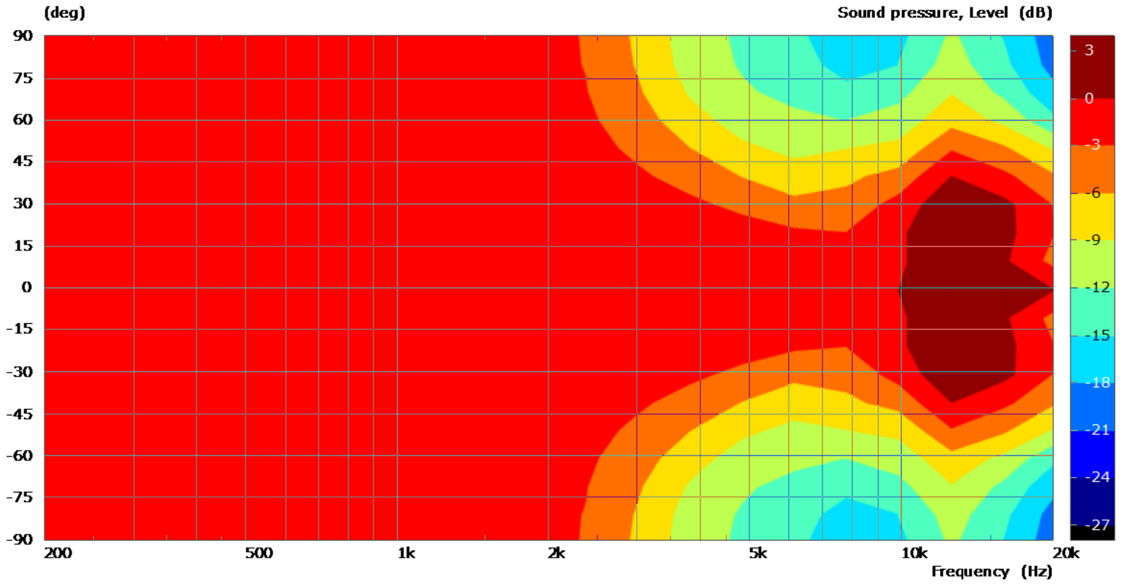
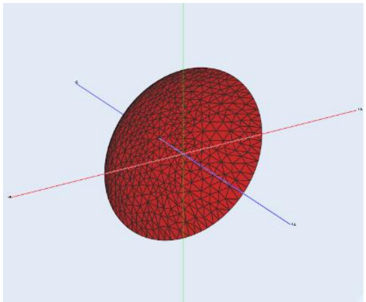


Illustration 6: Horizontal dispersion of a convex diaphragm

Sphere segment (concave)

In the case of the concave diaphragm, the narrowing in the frequency range also begins a little higher. However, the upper frequency range looks chaotic.



Basically, this shape creates a kind of parabolic mirror, while cone-shaped membranes form a kind of horn.

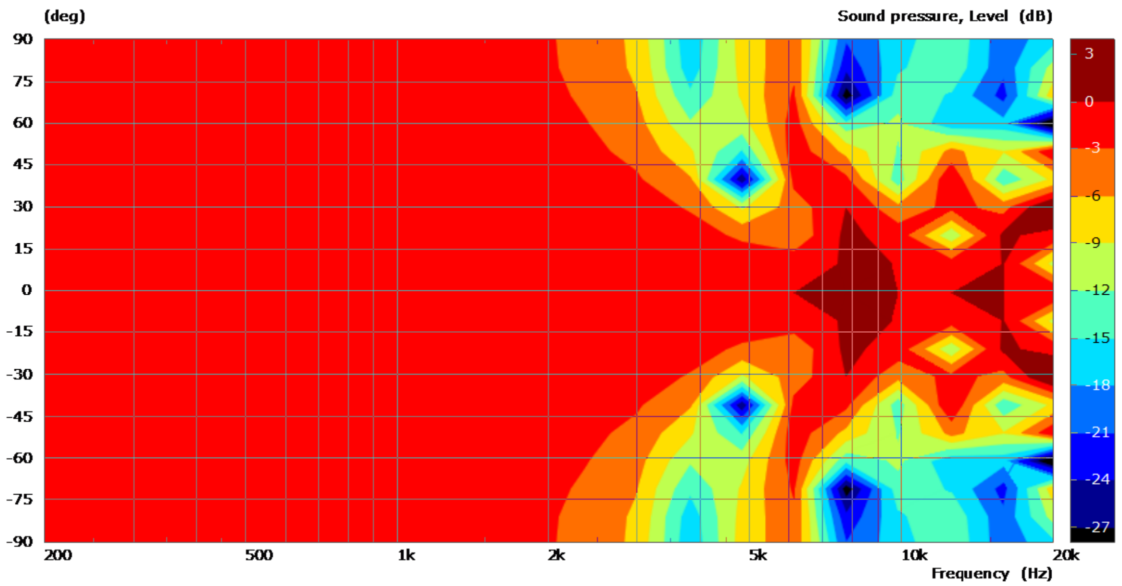


Illustration 7: Horizontal dispersion of a concave diaphragm

Summary

The two-dimensional diaphragm geometry can be understood as a set of infinitely individual sound sources. It is important that only parallel, rectangular membranes can be evaluated and simulated in two dimensions. For all other shapes, the width (or height) is not constant over the entire height (or width), so their beaming is decreased. A three-dimensional simulation is necessary here.

With the third dimension, the directivity can be further influenced. In relation to an infinite number of individual sound sources, this corresponds to a time delay of the external or internal sound sources.

What is missing from the consideration is the breaking of the membrane at a certain frequency. ABEC and AxiDriver do not support this. The diaphragms are always simulated as piston oscillators. The upper frequency range is therefore only applicable to real diaphragms to a limited extent.

Chamber with slot

It is possible to increase the sound-emitting area by placing an object in front of the diaphragm that is larger than the diaphragm itself. A slit is left all around through which the sound can radiate. This significantly increases the directivity. However, analogous to the ring-shaped membrane, sidelobes and resonances also occur in the chamber.

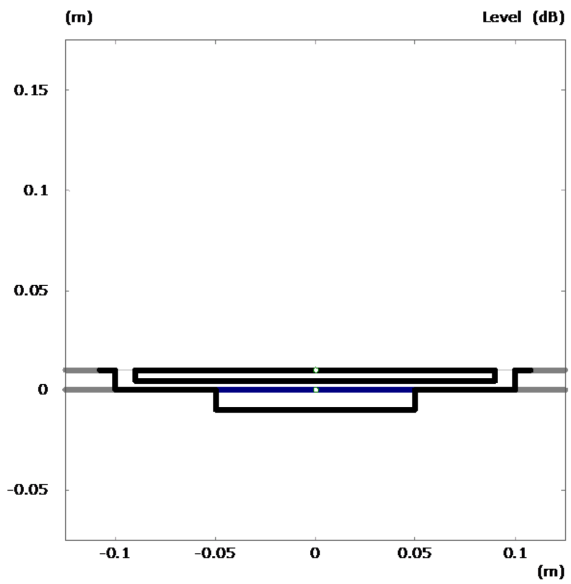


Illustration 8: Chamber with circular slit in front of the diaphragm

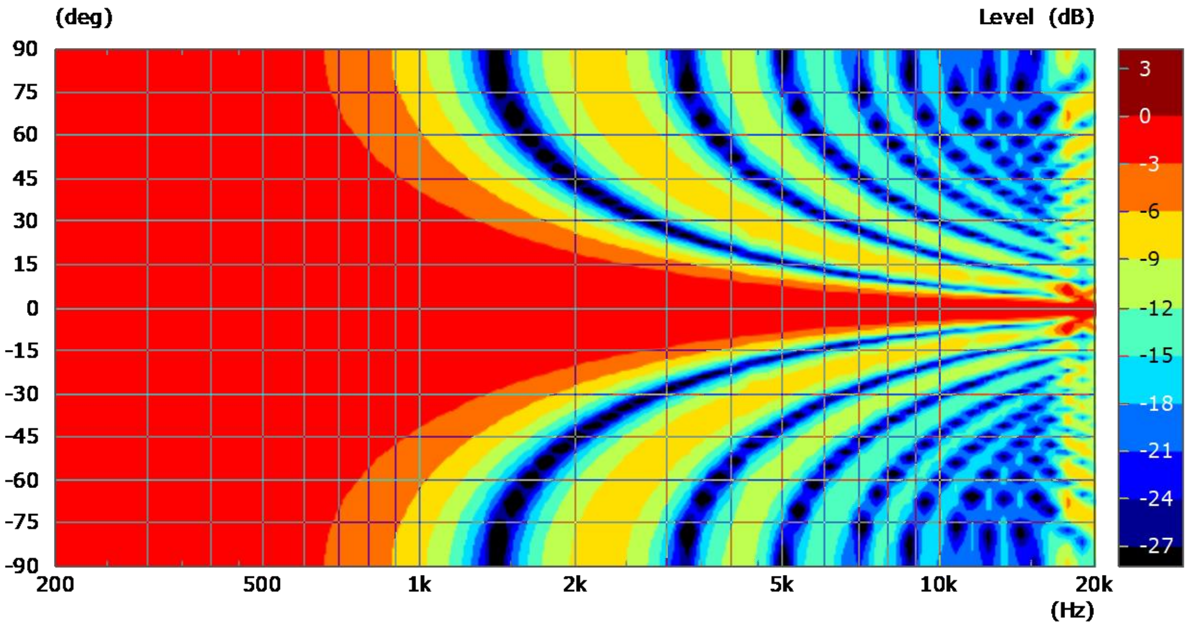


Illustration 9: Dispersion of the chamber with slot

Interference from multiple sound sources

Coherent sound sources

General

As soon as at least two *coherent* sound sources are active, interference occurs. Two sound sources produce a steadily increasing directivity from approximately the wavelength that is a quarter of their distance from each other. As soon as the wavelength comes close to half the distance between the sound sources, sidelobes occur. The larger the distance between the sound sources, the earlier the narrowing begins.

The following example was created with two ideal point sources and a distance of 10 cm. Thus, the first sidelobe occurs in the range of 3.4 kHz.

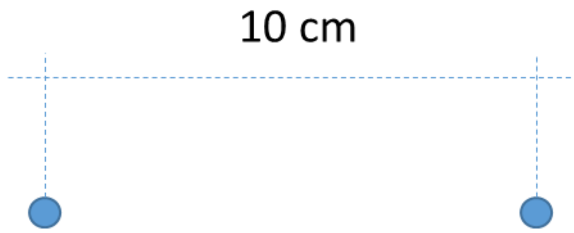


Illustration 10: Two coherent sound sources

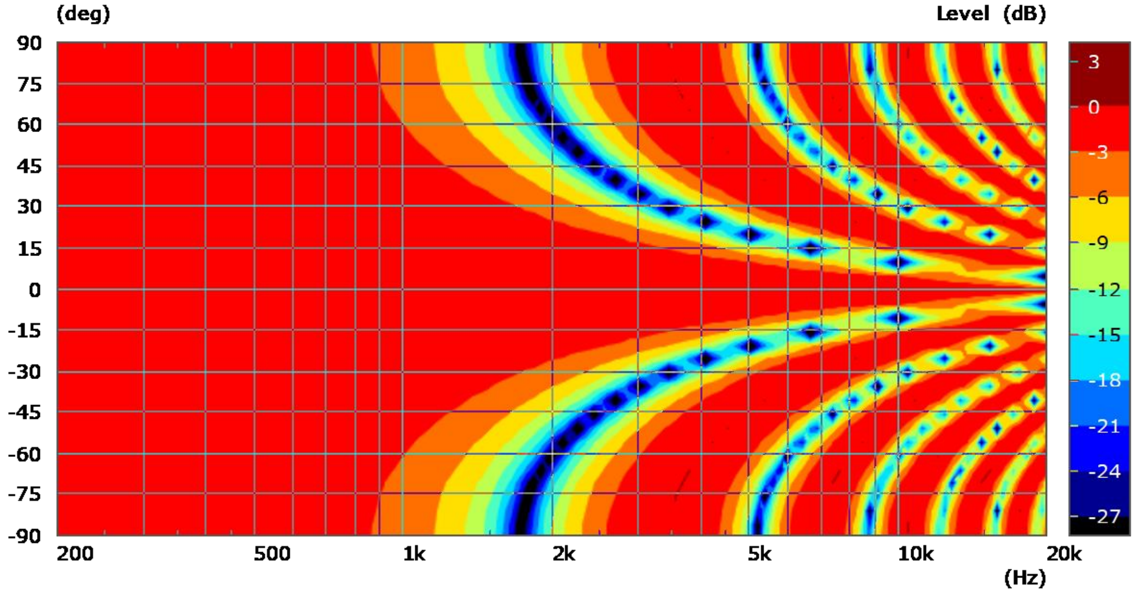


Illustration 11: Dispersion of two ideal point sound sources

Attenuation of sidelobes

Sidelobes occur to a lesser extent if the individual sound sources have a narrow directivity. This can be realized, for example, by increasing the diaphragm size or by attaching a horn. The following example shows the reduced sidelobes due to a directivity of two individual sources.

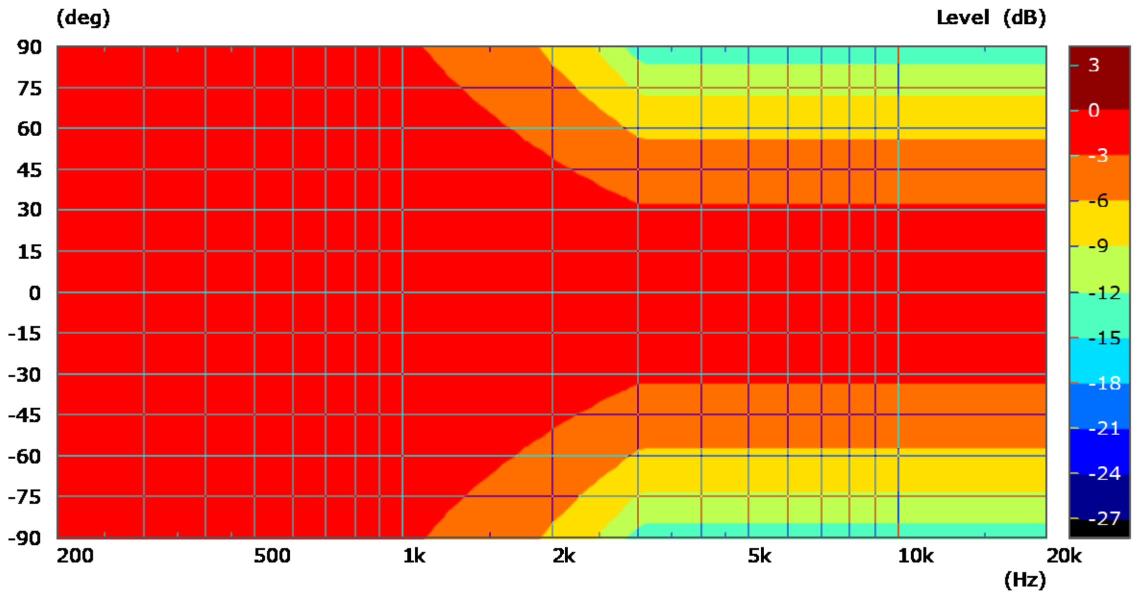


Illustration 12: Dispersion behavior of the individual sound sources

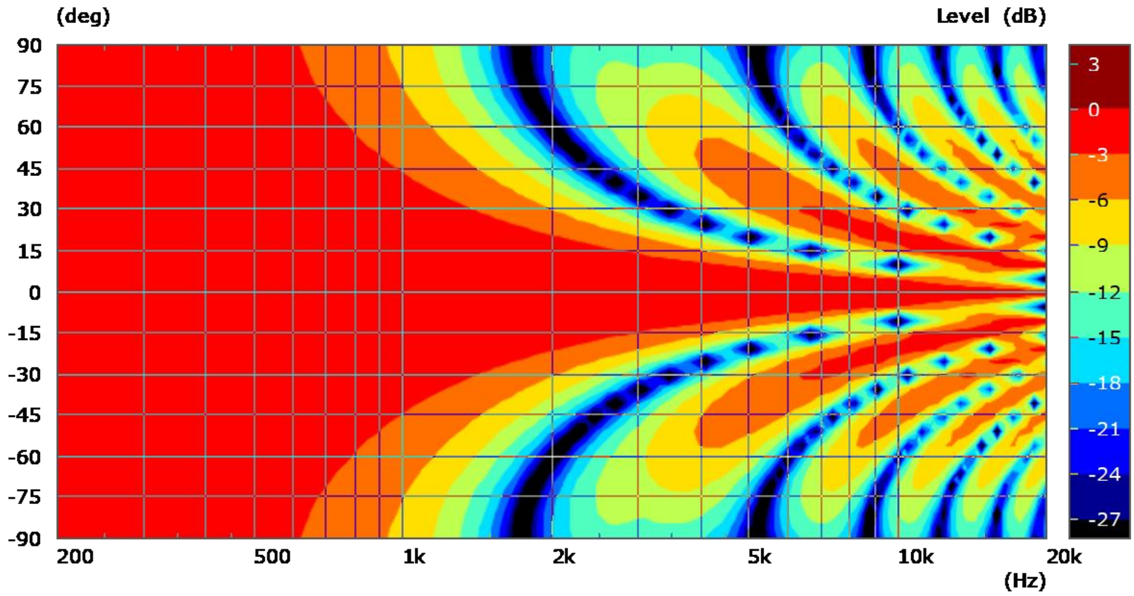


Illustration 13: 2 Two directivity sound sources with reduced sidelobes

Impact of supporting sound sources

An increase in the number of sound sources while maintaining the same overall length of the array does not produce a higher directivity, but rather a shift of the sidelobes in the frequency domain. However, the additional sound sources allow the directivity to start at a slightly higher frequency. The result is a line radiator whose sound pressure level decreases by 3 dB per doubling of distance, depending on length and frequency [3].

In the following example, the total distance has not been changed and two additional sound sources have been added equidistantly between the two existing ones. This reduces the distance between two adjacent sound sources to one-third of the previous example. As a result, the directivity now only starts at 1.2 kHz and the sidelobes are shifted from 3.4 kHz to 10.2 kHz (by a factor of 3).

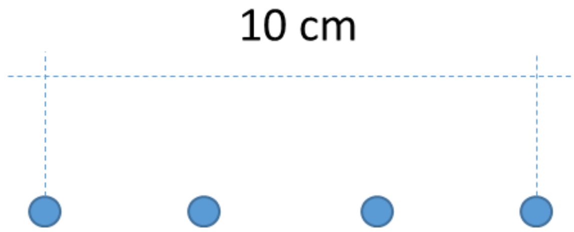


Illustration 14: Four equidistant coherent sound sources

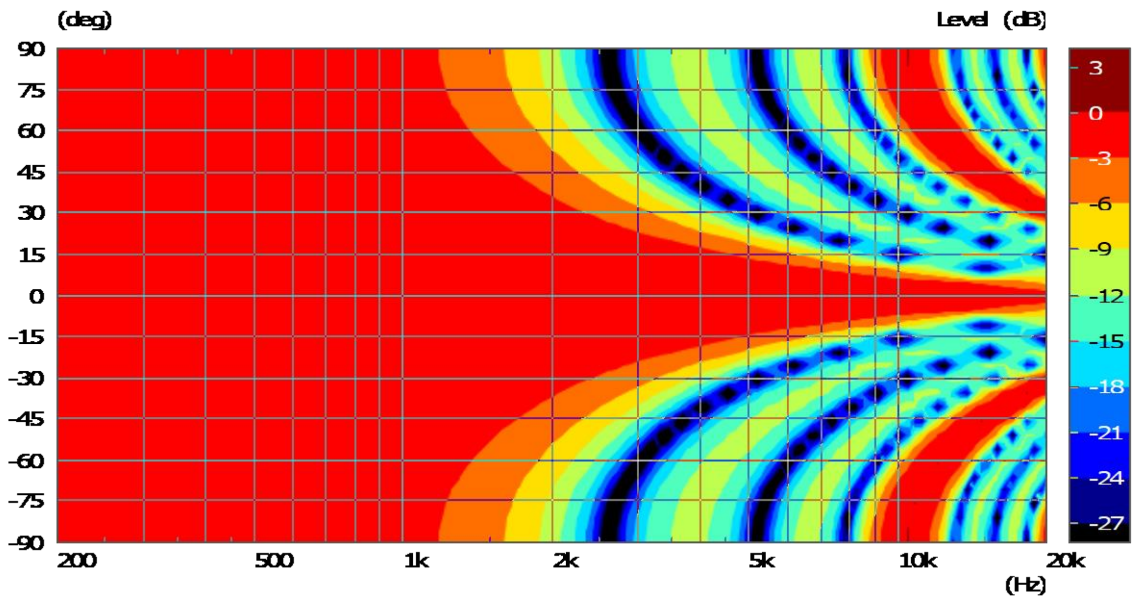


Illustration 15; Dispersion characteristics of four ideal point sound sources with a total length of 10 cm

Muilti-way system by Horbach and Keele

Horbach and Keele have shown [1] that with coherent pairs of drivers at a certain distance and special FIR filters, an almost constant dispersion behavior can be produced if enough ways are used. Each pair of drivers is only active in a narrow frequency range and superimposes its increasing directivity with the next lower way which radiates wider there. Overall, the directivity thus remains almost constant.

The prerequisite is that the spacing of the drivers follows a certain pattern and that the filter functions used follow a special, asymmetrical shape (linear-phase subtraction filters).

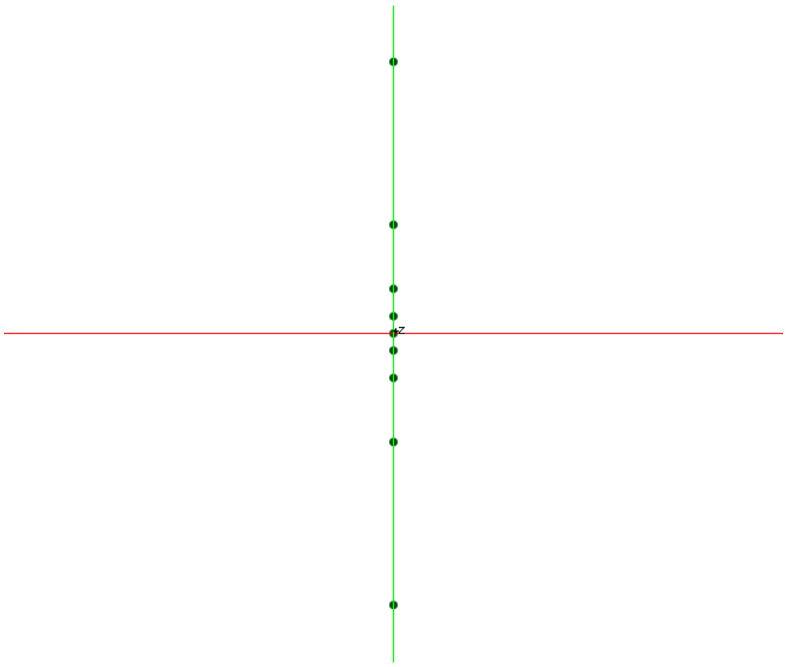


Illustration 16: Coherent Driver Pairs as reusable to Horbach and Keele

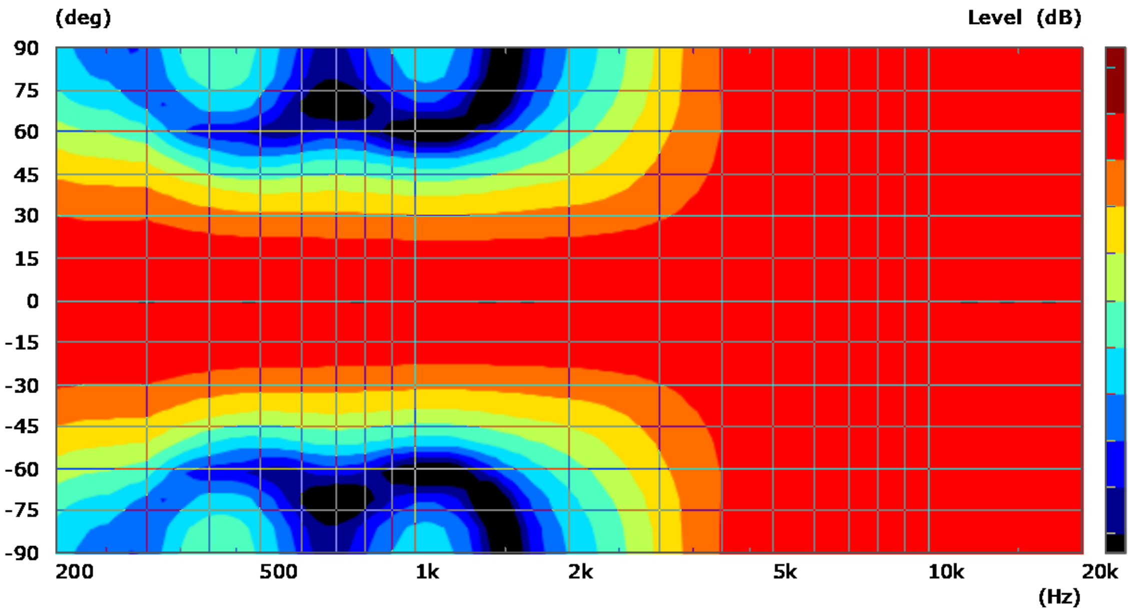


Illustration 17: Vertical dispersion of the reusable

The tweeter in the middle does not have a partner and therefore does not produce sufficient directivity, which explains the strong expansion from about 3 kHz. The tweeter must therefore produce the directivity in another way (e.g., by means of a vertically extended diaphragm or by means of a horn).

Incoherent sound sources

Multiple sound sources can differ in their polarity, level, and delay. Since the possibilities are very complex and almost unlimited, only a few examples will be shown.

Dipole

The dipole consists of two adjacent sound sources that have an inverted polarity to each other. In the simplest case, it can be realized by a driver without a housing. It does produce a directivity by cancelling out the inverted signal from the rear, but only on the sides in the range of 90°. The dispersion is symmetrical at the front and rear (figure-of-eight pattern). Furthermore, the cancellation creates the effect that the sound pressure level falls with 6 dB/octave below the frequency whose wavelength corresponds to the propagation time difference of the two sound sources. As a result, the dipole is very inefficient in the bass range.

The following example was simulated with ideal point sources and without housing. In a real housing, the dipole effect no longer exits when the wavelength becomes small compared to the housing width or height.

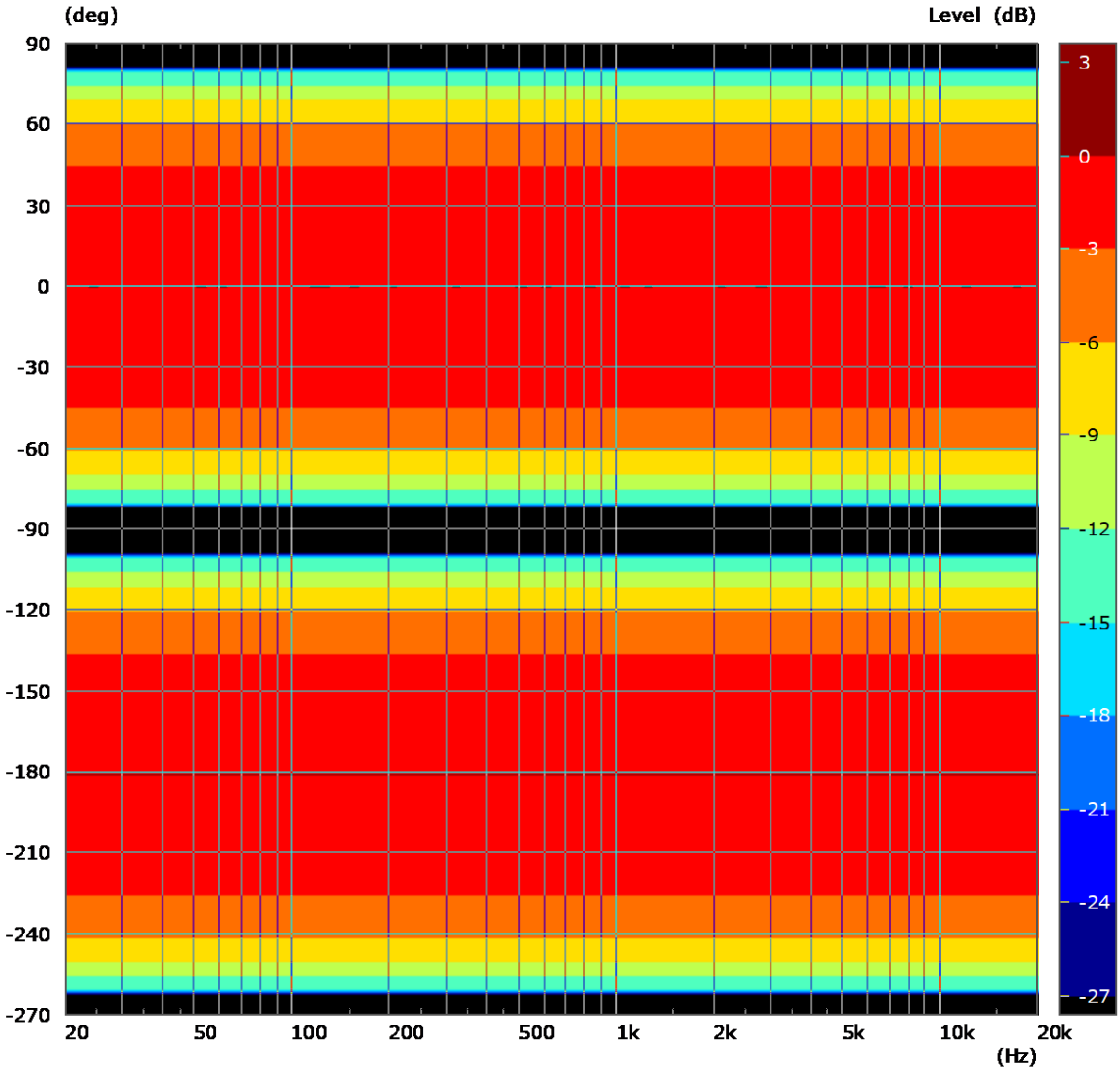


Illustration 18: Dispersion of an ideal dipole

Cardioid

With two drivers placed opposite to each other in a housing, a cardioid radiation behavior (cardioid polar pattern) can be generated. To do this, the rear driver must be inverted and delayed by the amount of time it takes for the sound to diffract around the enclosure. The cancellation is limited to the rear hemisphere, which has the lowest sound pressure level at 180°.

The following example shows the radiation behavior of an ideal cardioid with a rear attenuation of 30 dB.

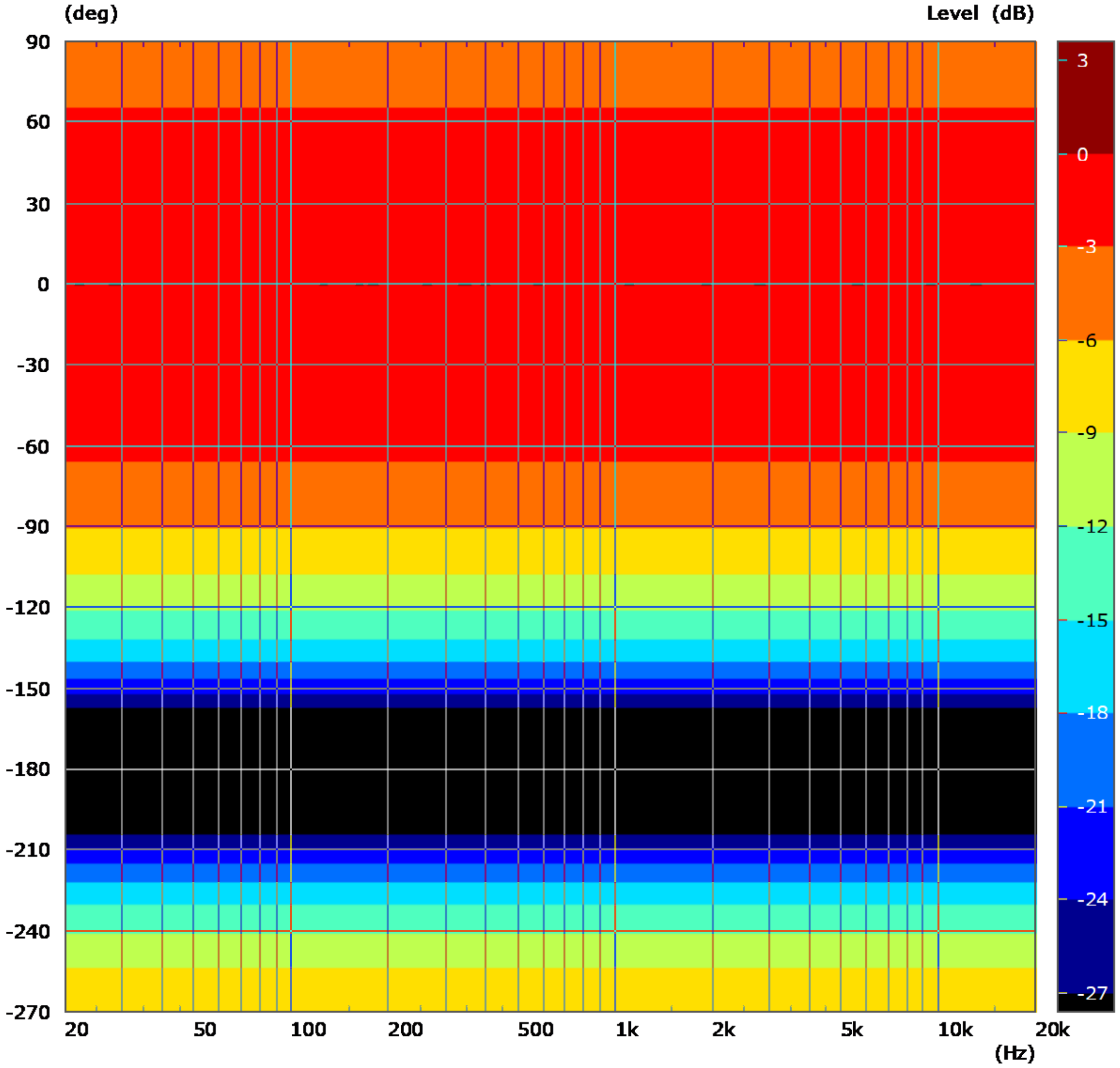


Illustration 19: Dispersion of an ideal cardioid

Constant Beamwidth Transducer (CBT)

In addition to various cardioid radiations, there are also more complex ways to influence the radiation behavior. In so-called beamforming, the wavefront is formed by several sound sources, which differ in delay and level. As an example, here is the Constant Beam Width Transducer (CBT) from Keele [2], which produces an almost constant dispersion pattern through a vertical arrangement of delay and level-adjusted drivers of identical size. The strength of the directivity can be parameterized within large limits. Legendre shading is used.

In contrast to line emitters with coherent sound sources, the sound pressure level of a CBT decreases by 6 dB per doubling of distance.

A CBT only works up to the frequency up to which sidelobes do not occur. This means that the drivers should be as small as possible. Another disadvantage is the high number of drivers necessary. In the following, the distance between the sound sources was 4 cm, which can be achieved in reality.

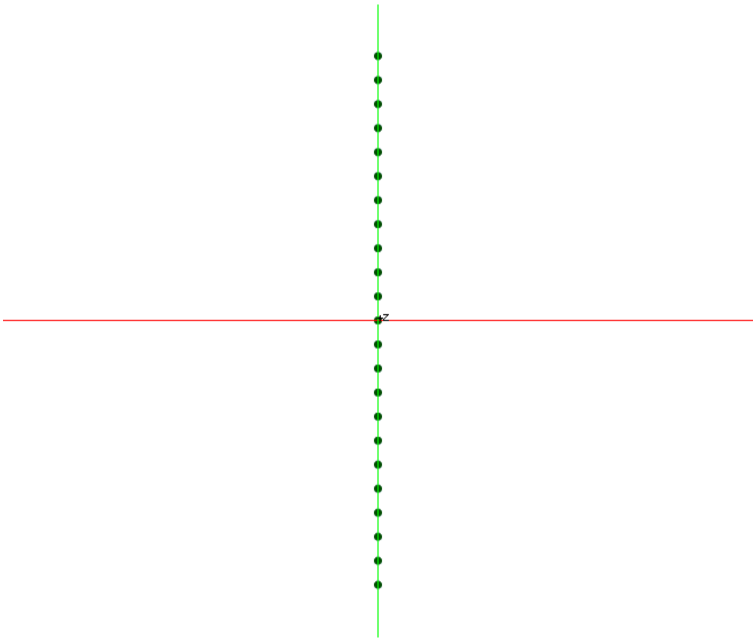


Illustration 20: CBT from ideal point sound sources with a distance of 4 cm

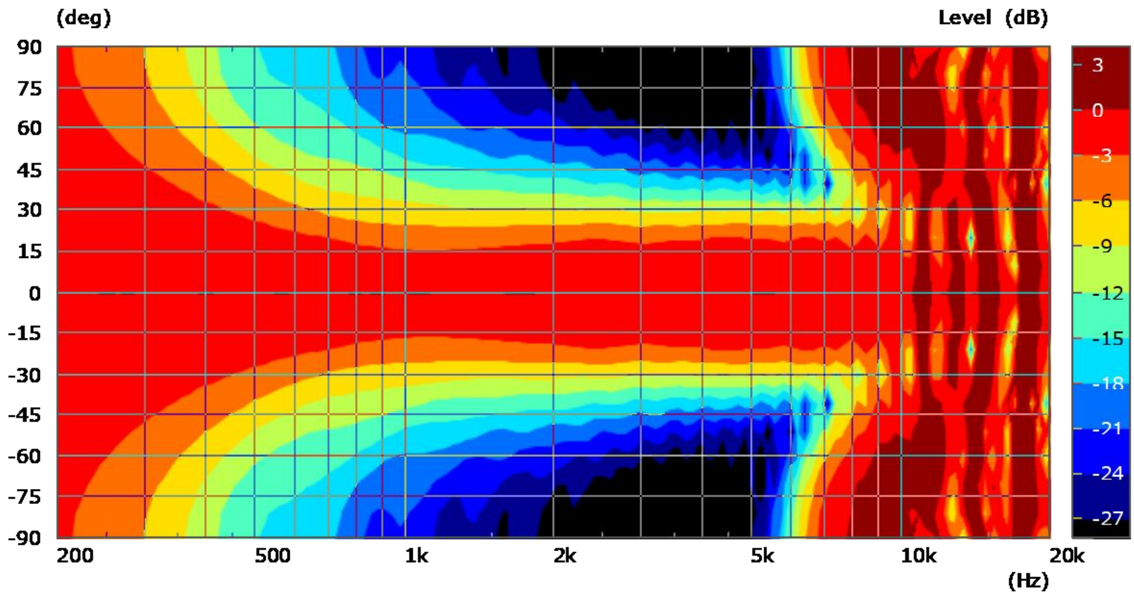


Illustration 21: Vertical dispersion of the CBT with a distance of 4 cm between the sound sources

Enclosure

Baffle Step

Depending on its dimensions, the enclosure in which the driver is installed creates a directivity by covering the sound from the front to the rear. This only works for wavelengths that are small compared to the dimensions of the baffle and are not deflected to the rear.

The directivity of covering is limited to the rear hemisphere. A wall installation thus produces the same effect, but for the entire frequency range. When installed in a wall, sound is only emitted in the front hemisphere. The sound pressure increases at 0° by a maximum of 6 dB and the directivity index as well. In finitely large enclosures, the so-called baffle step occurs in the region where the wavelength is similar to the baffle dimensions. It marks the transition frequency range between a full-space and a half-space radiator.

The following example shows the comparison between a sphere enclosure with a diameter of 10 cm and one with a diameter of 20 cm. The diameter of the driver is only 8 mm. Due to the spherical housing, there are no edge diffractions. It only covers the sound towards the rear.

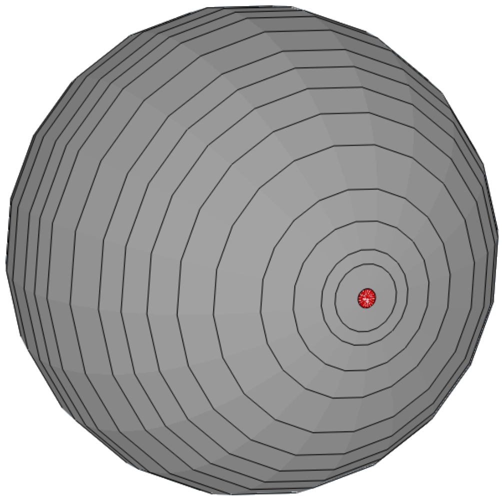


Illustration 22: Sphere enclosure

The examples show that doubling the diameter shifts the transition range of diffraction in the frequency domain downwards by a factor of two.

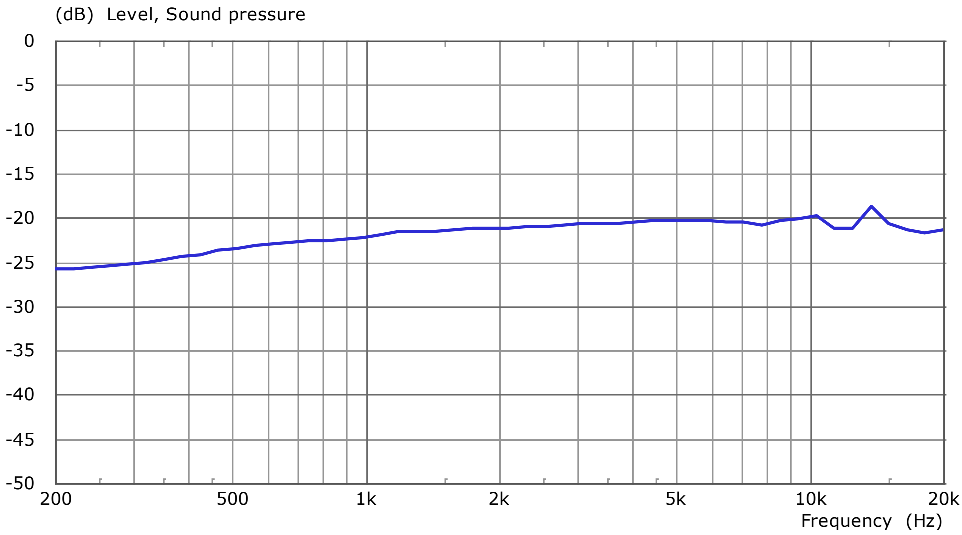


Illustration 23: Amplitude response below 0° with broad baffle step of the 20 cm sphere

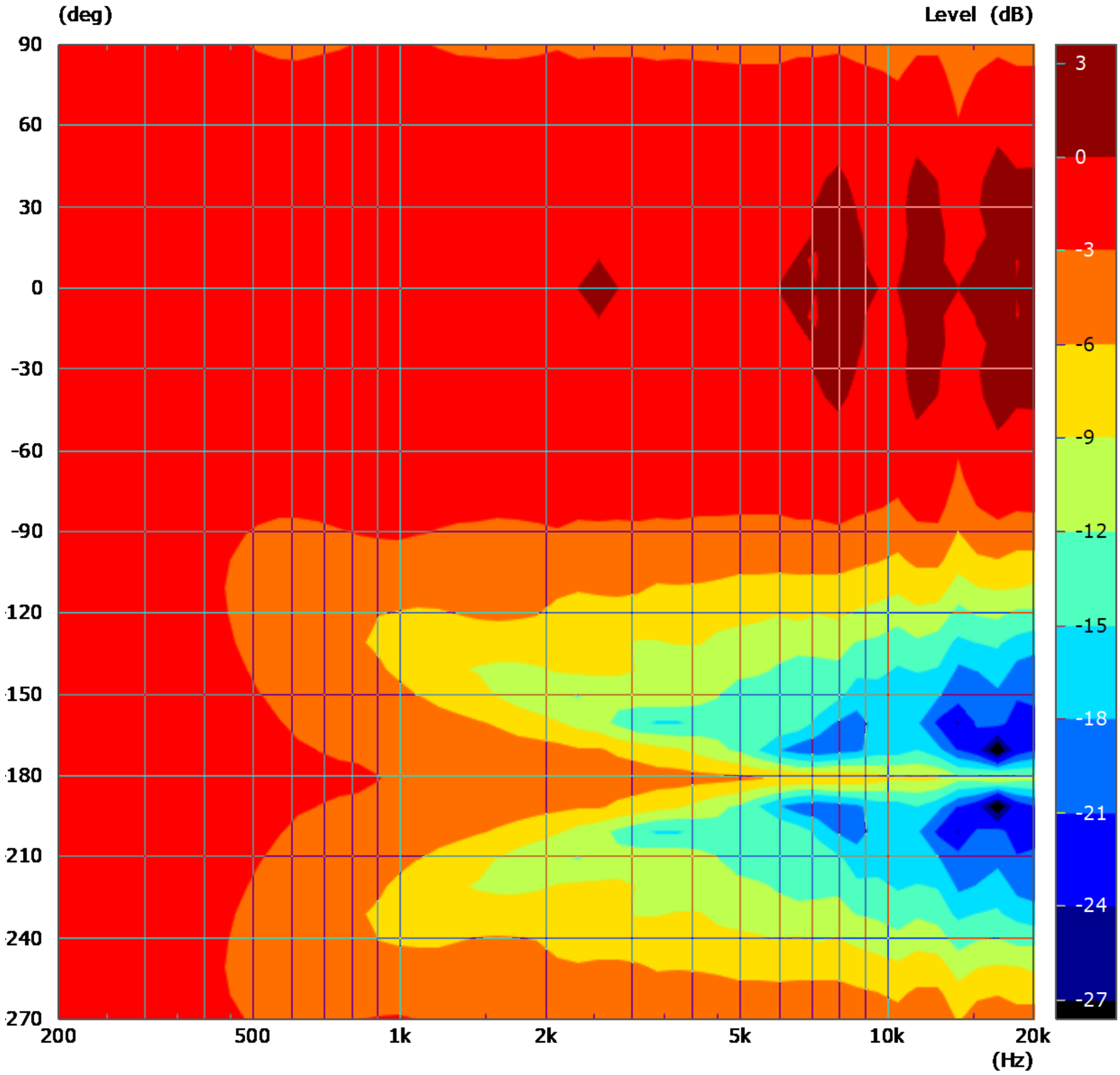


Illustration 24: Rear covering by a sphere enclosure with a diameter of 20 cm

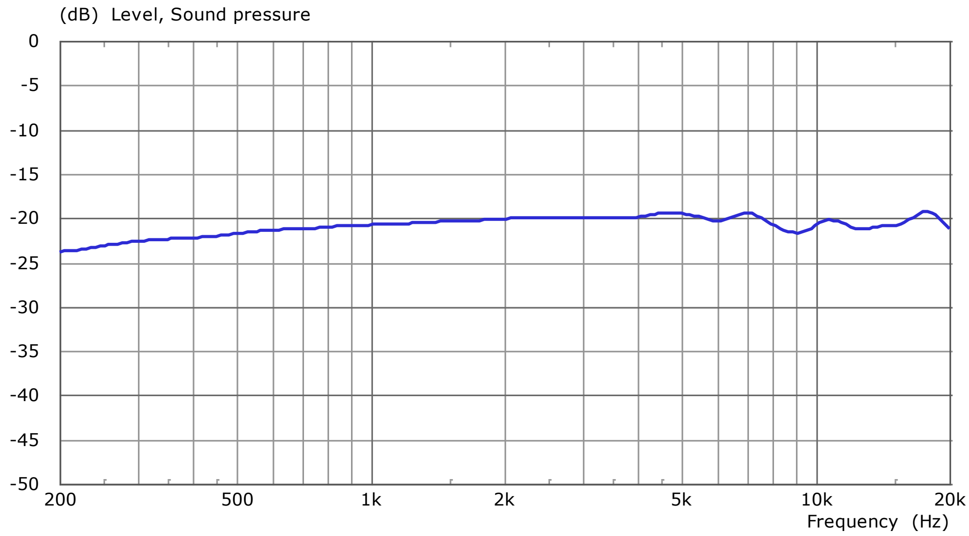


Illustration 25: Amplitude response below 0° with broad baffle step of the 40 cm sphere

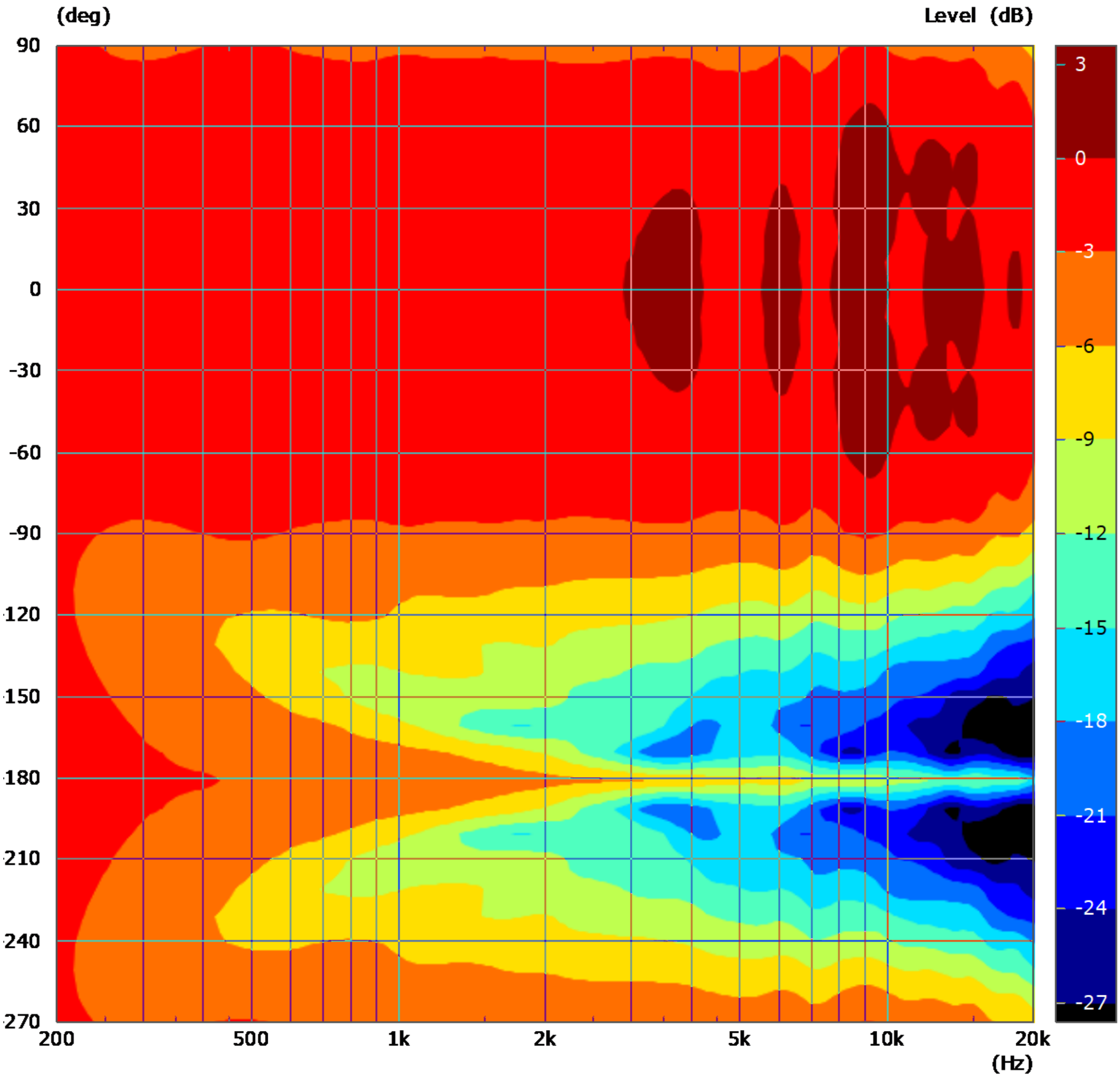


Illustration 26: Rear covering by a sphere enclosure with a diameter of 40 cm

Edge diffractions

Furthermore, hard edges on the baffle create secondary sound sources that interfere with the direct sound. These edge diffractions create an additional narrowing of the directivity in the region of half the wavelength which corresponds to the distance between the driver and the edge. At the whole wavelength there is a widening. Again, a distinction can be made between horizontal and vertical if the height and width of the baffle differ.

Subsequently, a cylinder housing with hard edges was simulated. The circular baffle in combination with the centrally placed driver produces the same rotationally symmetrical edge diffractions.

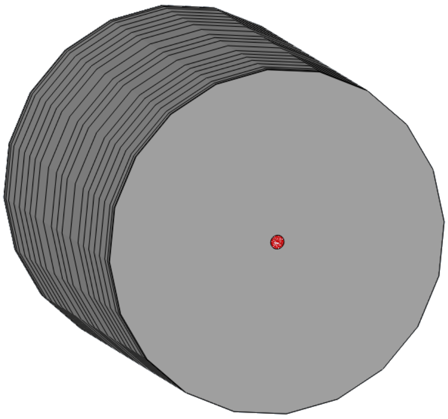


Illustration 27: Cylinder housing

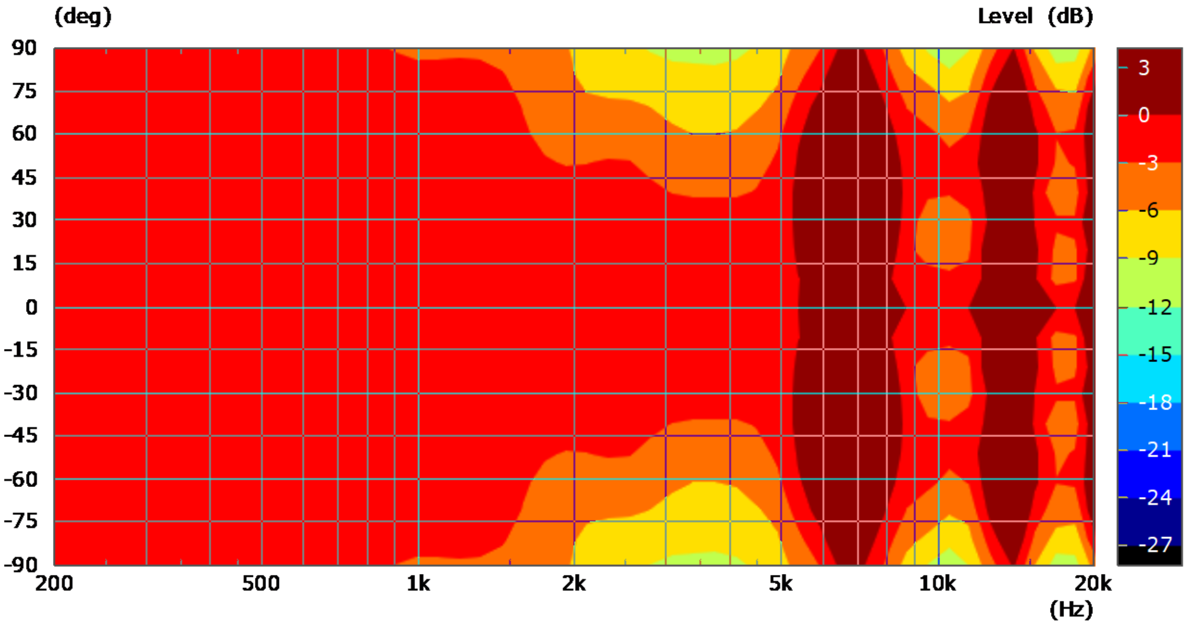


Illustration 28: Dispersion of a circular baffle with a diameter of 10 cm

Doubling the diameter of the baffle pushes the interference pattern down in the frequency domain by a factor of two.

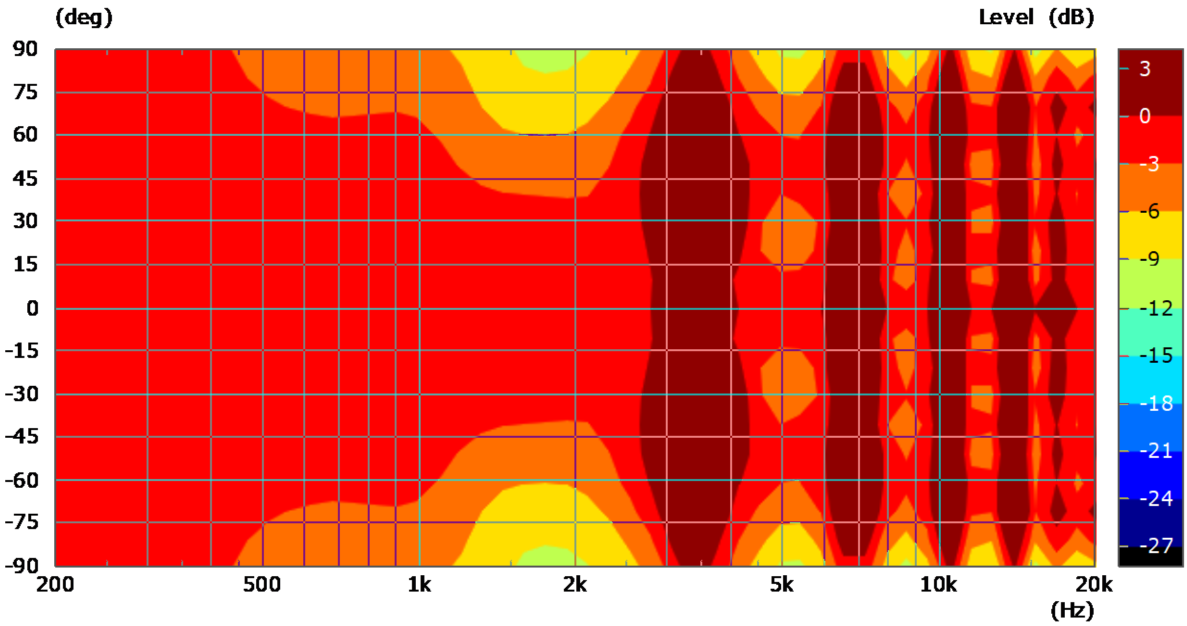


Illustration 29: Dispersion of a circular baffle with a diameter of 20 cm

The edge diffractions create an interference pattern in the amplitude response at 0°. This results in dips and elevations with a maximum of +/- 3 dB (comb filter). In practice, the aim is often to distribute all edge diffractions over different frequency ranges as far as possible by cleverly designing the baffle and placing the drivers.

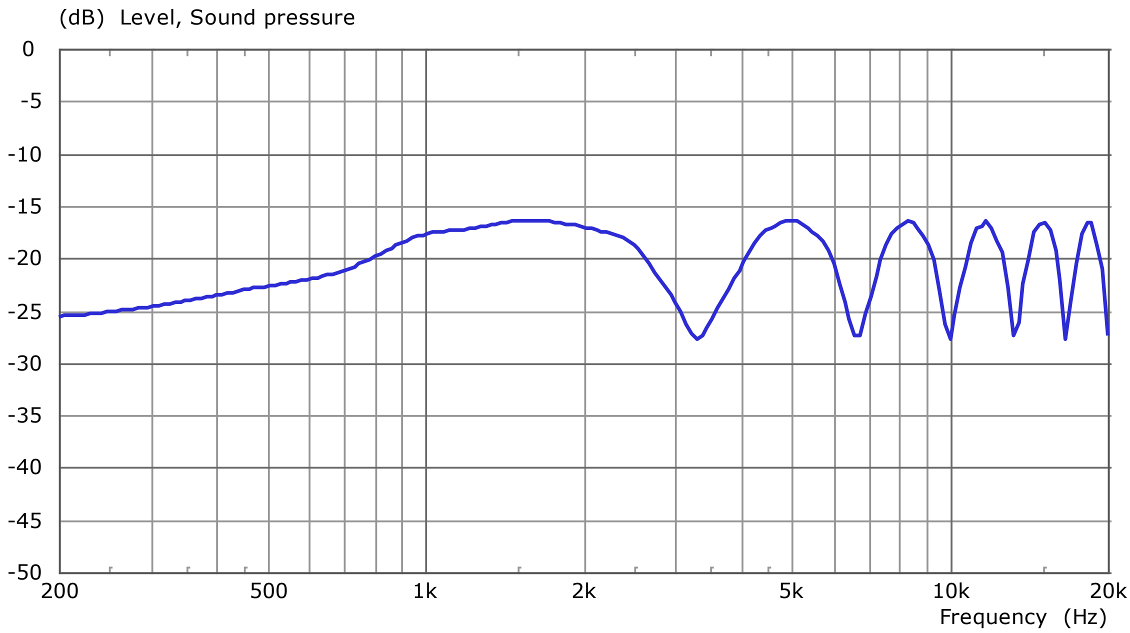


Illustration 30: Interference pattern at 0° due to edge diffractions

The edge diffractions only have a directivity effect if the loudspeaker stands free. This means that an in-wall installation completely removes this directivity effect.

Furthermore, the strength of the directivity is limited to a minimum beam angle of approx. 120° (-6 dB). It is not possible to shape the radiation pattern arbitrarily narrow with this operating principle.

Horns / Waveguides

General

Horns create directivity by directing the sound wave through a steadily opening contour. This directs the sound energy forward and increases the amplitude level at 0°. However, a horn can also widen the directivity at high frequencies, which then reduces the sound pressure level at 0°.

The following is an example of the amplification or attenuation of the sound pressure below 0°, which is created by a waveguide with a beam angle (-6 dB) of approx. 100°. Up to about 12 kHz there is amplification, above that there is attenuation. This means that the waveguide no longer narrows above 12 kHz, but *widens*. In this way, an almost constant dispersion behavior over a very wide frequency range can be realized.

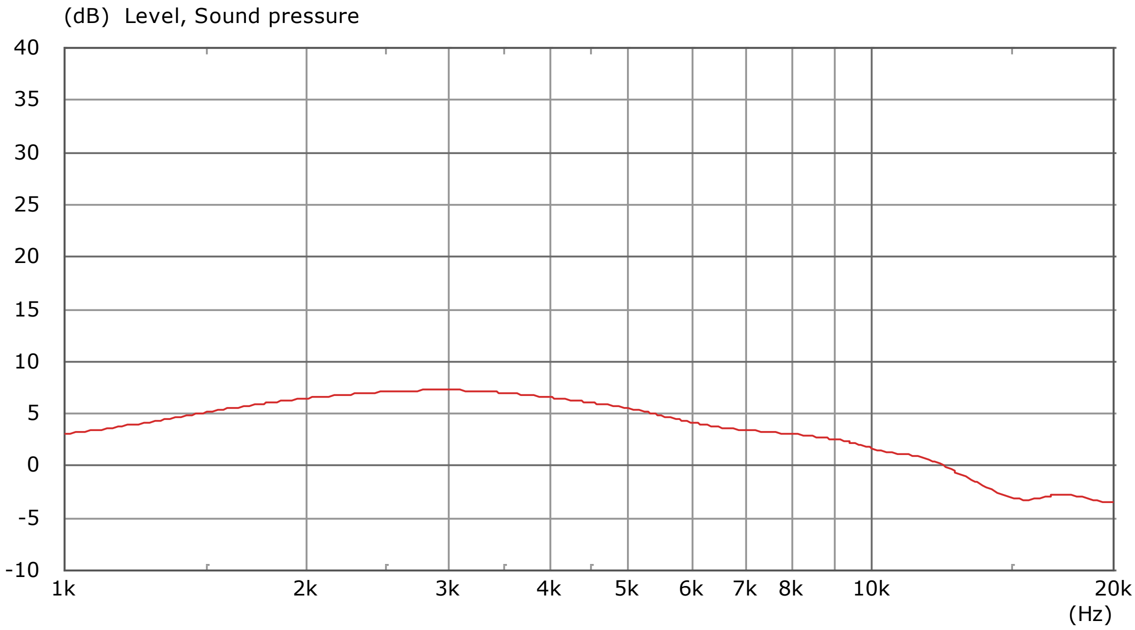


Illustration 31: Amplification/attenuation of the sound pressure level below 0° by a waveguide (normalized)

In order to observe only the directivity of the horn, it must be installed in an infinite baffle. Otherwise, the directivity of the diffraction on the mouth’s edges would overlap with that of the contour. Unfortunately, measurements of real horns are almost always done without a baffle, so that the directivity of the contour can hardly be assessed in isolation in practice.

The contour determines the frequency-dependent directivity. Roughly, the following rule applies: the steeper the contour, the stronger the directivity. The following example shows a small horn with a beam angle (-6 dB) of approx. 60°. An idealized 1" piston radiator was simulated which in practice is usually replaced by a compression driver.

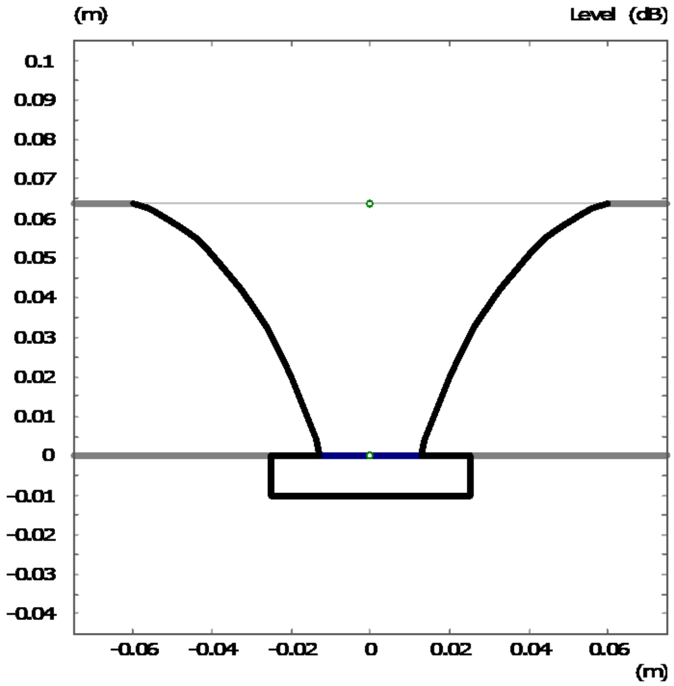


Illustration 32: Horn contour

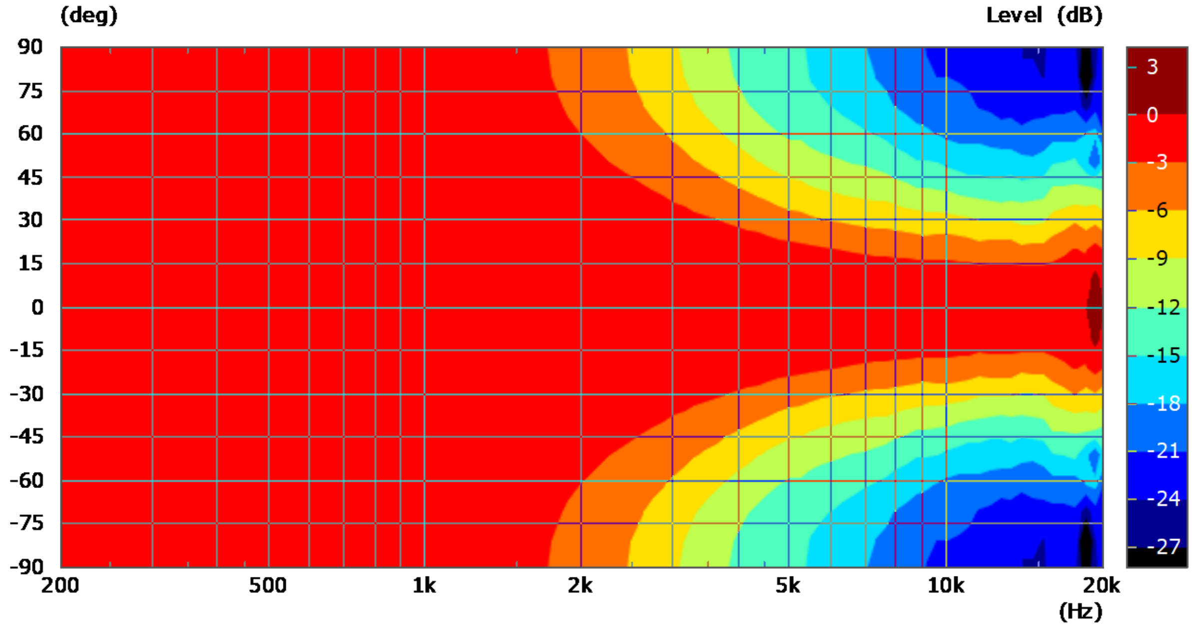


Illustration 33: Dispersion Behavior of a rotationally symmetrical horn in infinite baffle

Influence of horn depth

The depth of the horn largely determines the slope of the contour. This means that a reduction in depth leads to a broadening of the directivity and vice versa. In the following, the depth has been reduced to half the depth of the previous example.

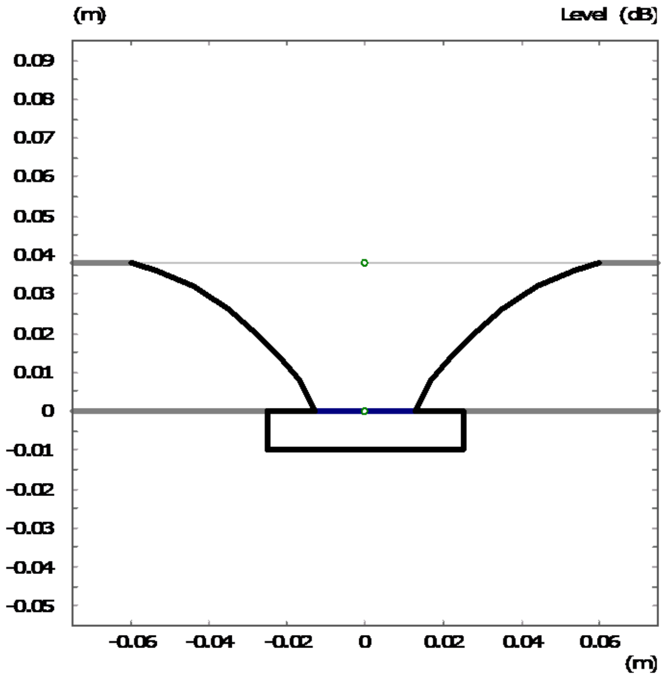


Illustration 34: Horn with halved depth

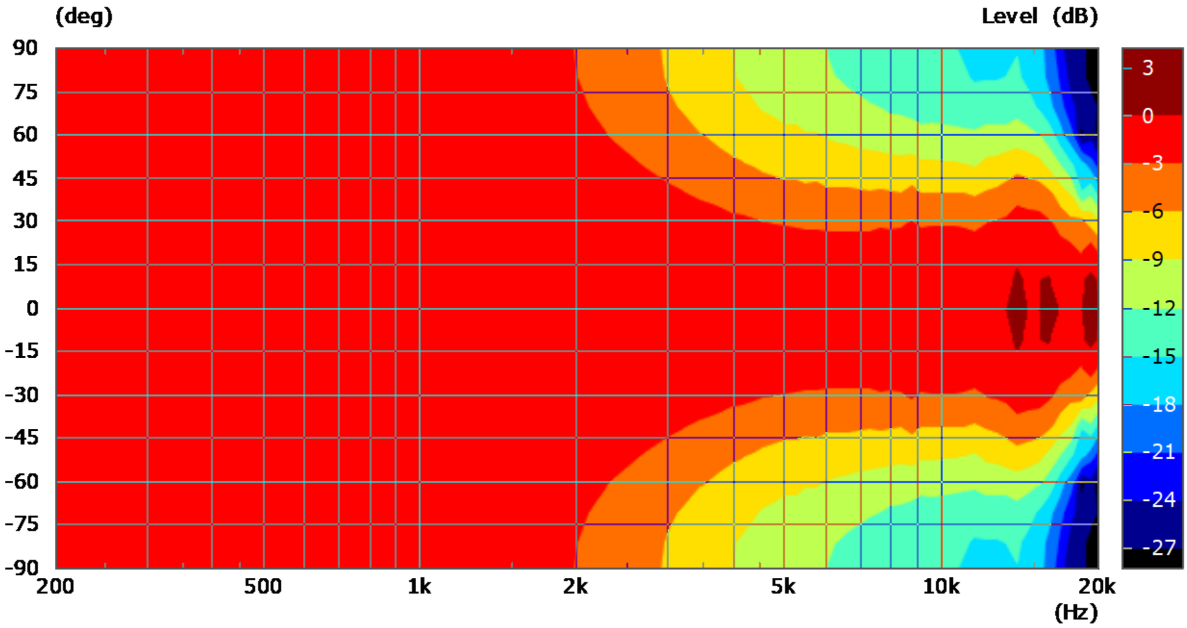


Illustration 35: Dispersion of the horn with halved depth

Influence of mouth diameter

The *mouth* is the large opening where the driver is not located. The diameter of the mouth is largely responsible for the lower cut-off frequency of the directivity. The larger the diameter in a dimension, the earlier the directivity begins there.

The following example shows a doubling of the mouth diameter compared to the first example. Since this also causes a reduction in steepness, the directivity widens in line with the halving of the depth. In addition the lower cut-off frequency decreases.

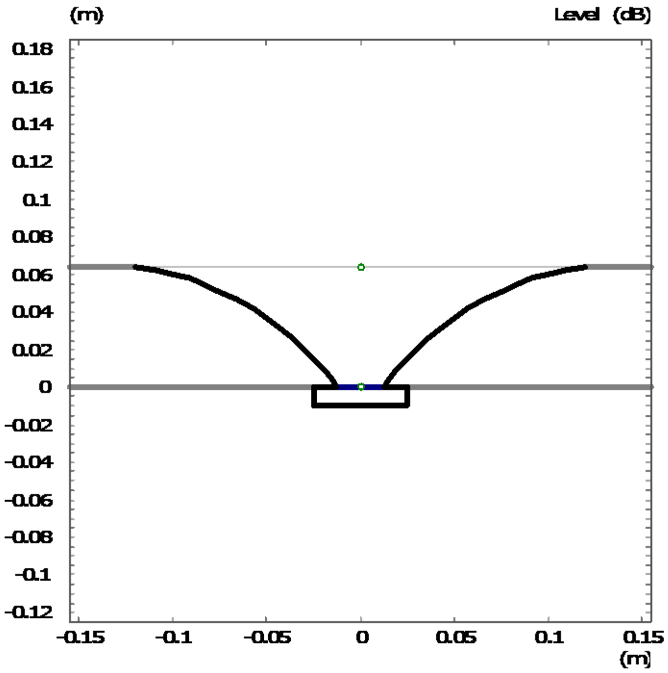


Illustration 36:Horn with doubled mouth diameter

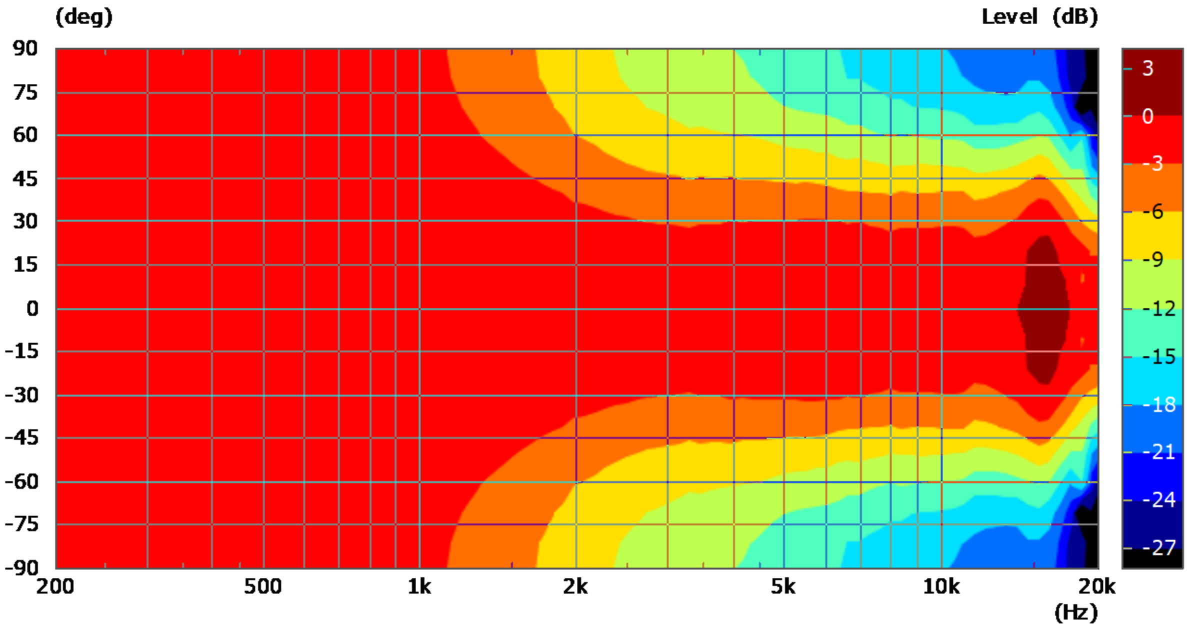


Illustration 37: Dispersion of the horn with doubled mouth diameter

Summary

The following table compares the basic properties of the various active principles. In the *column Sound pressure (0°)*, the effect is compared with an ideal spherical radiator.

	Directivity	**Frequency Dependence**	**Sound pressure (0°)**
Diaphragm size	strong medium (real cone)	steadily increasing	-
Chamber with slot	very strong	steadily increasing, weak sidelobes and resonances	very unsteady due to resonances
Coherent sound sources	very strong	steadily increasing, side lobes, constant possible via multi-way	Addition of all individual sources
Incoherent sound sources	any	arbitrary (constant possible)	variable
Covering by enclosure	limited to the rear hemisphere	Low (Baffle Step)	Gain (3 dB)
Edge diffractions	small	strong	Amplification / Attenuation
Horn / Waveguide	any	arbitrary (constant possible)	Amplification / Attenuation

Combinations based on practical examples

The different ways of creating directivity can be combined almost arbitrarily. Here are some practical examples.

Free-standing horn

In the following, it is shown how the directivity of the diffraction on the housing and that of the waveguide overlap. In an infinite baffle, the dispersion only narrows from approx. 2 kHz. The diffraction on the horn body produces a (weaker) directivity from approx. 1 kHz.

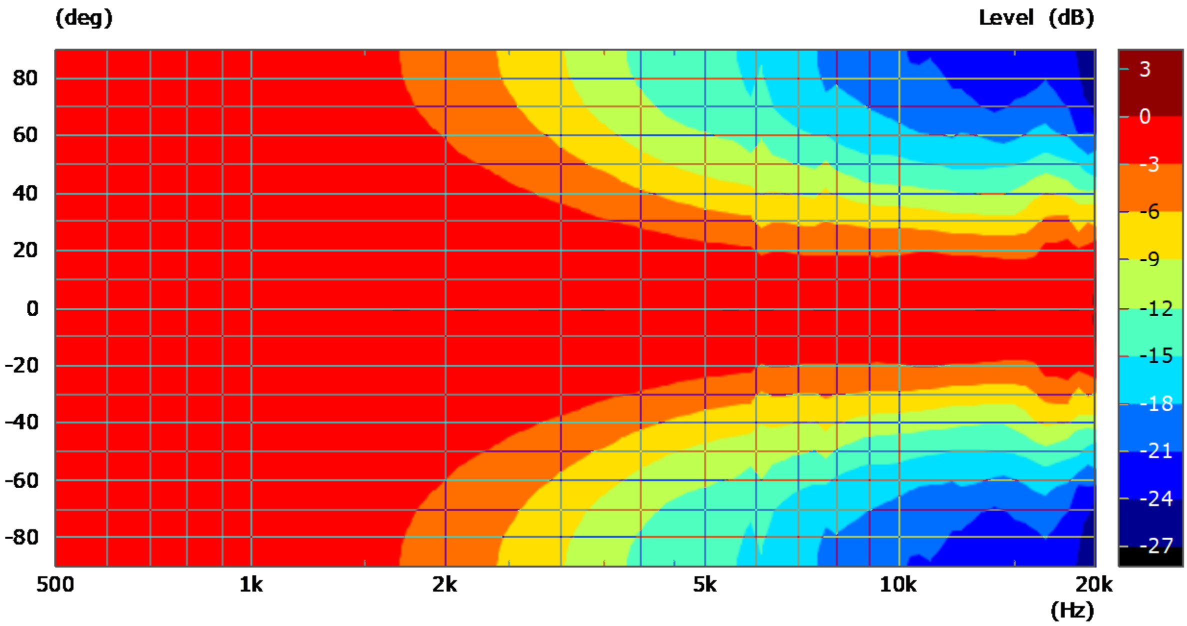


Illustration 38: Horn in infinite baffle with mouth surface of 12 x 12 cm

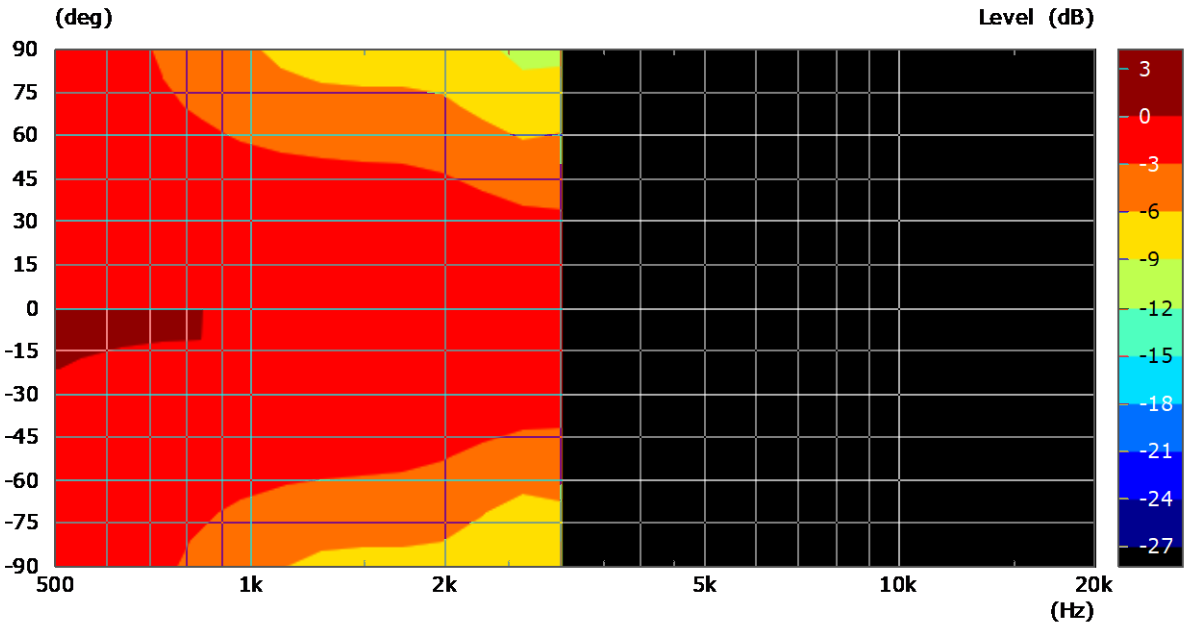


Illustration 39: Dispersion of a 3 cm deep enclosure with baffle dimensions 12 x 12 cm

The following measurement was made on a real horn created using a 3D printer. It is easy to see that the diffraction on the mouth’s edges extends the directivity downwards in the frequency domain. Both active principles overlap.

Illustration 40: 3D printing of the simulated horn

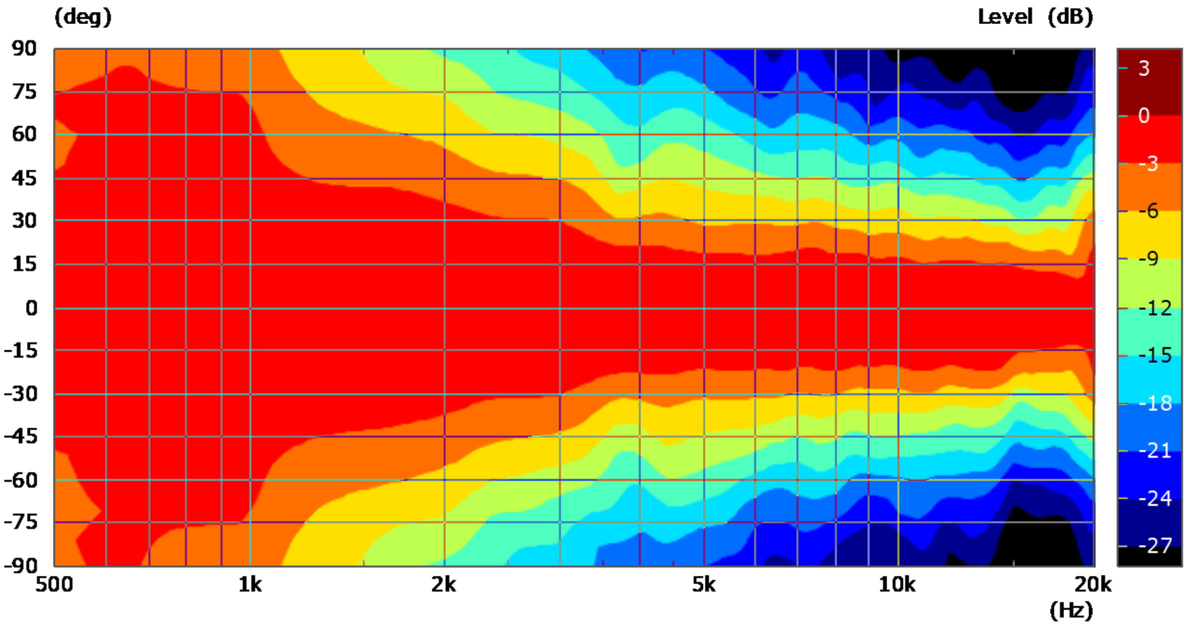


Illustration 41: Measurement of the free-standing horn

Large planar speaker

Large planar speakers use two main operating principles to create a directivity. On the one hand, it is the large surface area and on the other hand, the dipole characteristic due to the open back of the speaker. The simulation was only performed up to 6 kHz, otherwise the calculation time would have been too long.

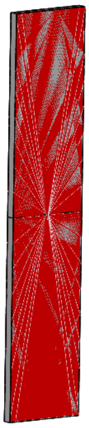


Illustration 42: Large planar dipole speaker (140 x 30 cm)

First of all, here is the horizontal dispersion without driving the rear diaphragm. The diffraction through the housing and the directivity of the 30 cm wide diaphragm overlap.

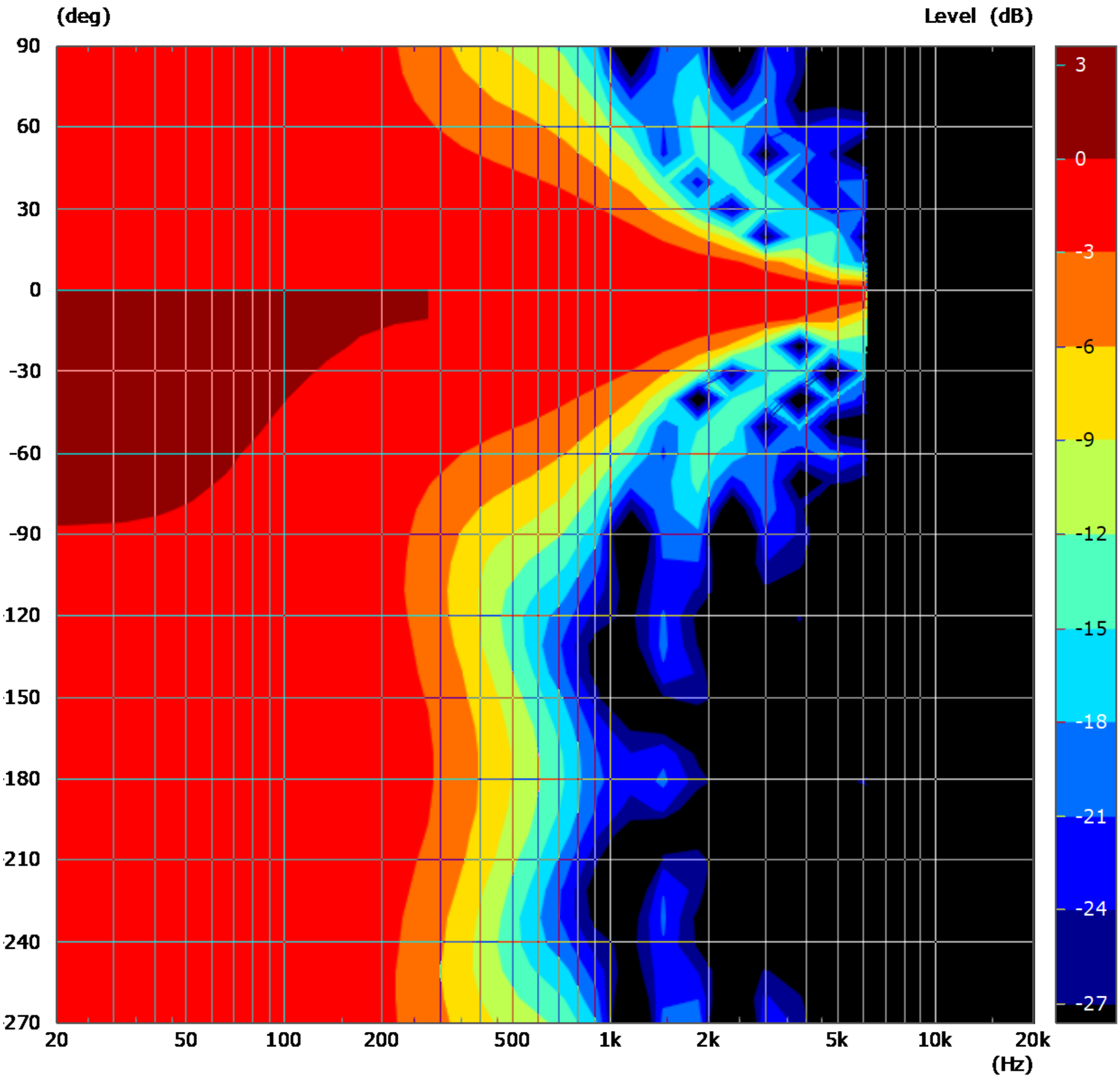


Illustration 43: Horizontal dispersion as a monopol

If the rear diaphragm is added with inverted polarity, the dipole pattern is created. Furthermore, the frequency range with narrows dispersion is radiated the rear with inverted polarity, too.

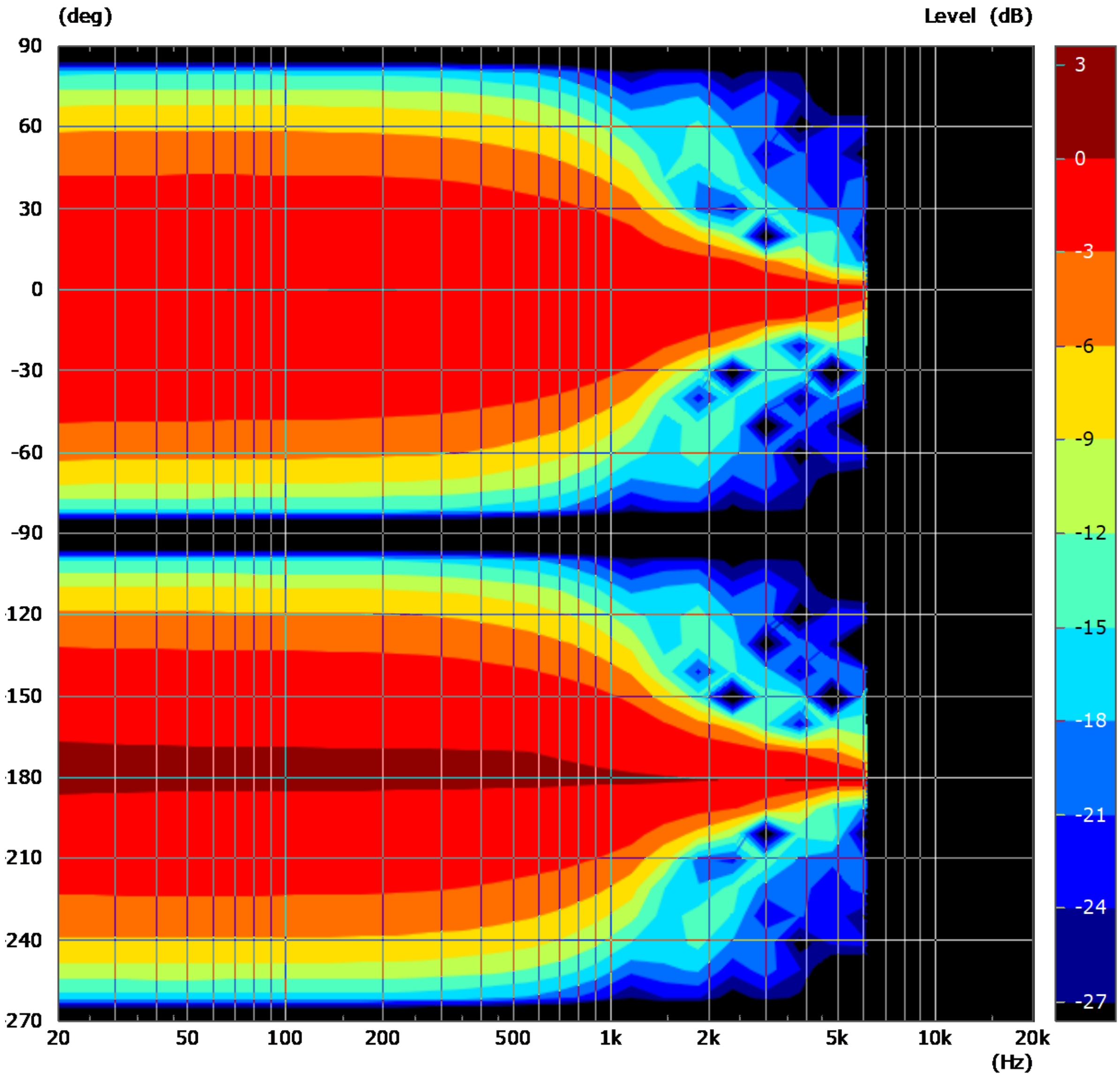


Illustration 44: Horizontal dispersion as a dipole

Cardioid Subwoofer

The following example shows a subwoofer with a 30 cm diaphragm that produces cardioid dispersion through a second driver on the back. This driver is driven with a delayed and inverted signal.

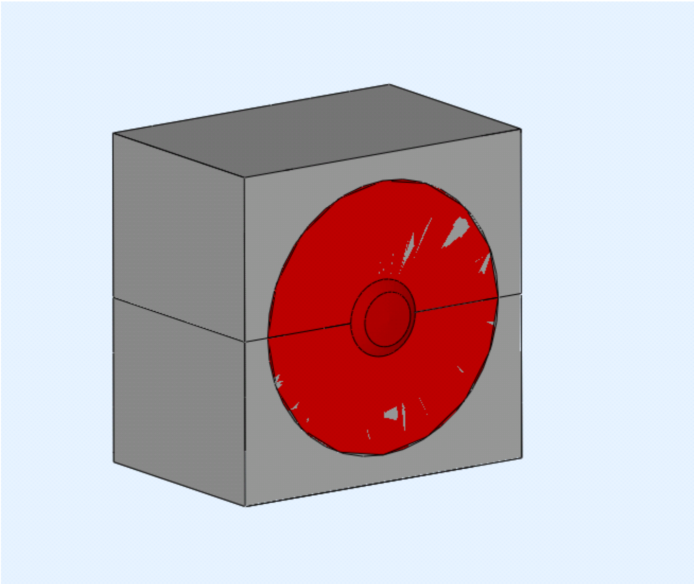


Illustration 45: Cardioid subwoofer with two drivers

The cardioid radiation behavior can no longer be maintained above a certain wavelength and changes to that of a dipole. On the one hand, this is due to the narrowing by the diaphragm size and to the decreasing diffraction of the baffle.

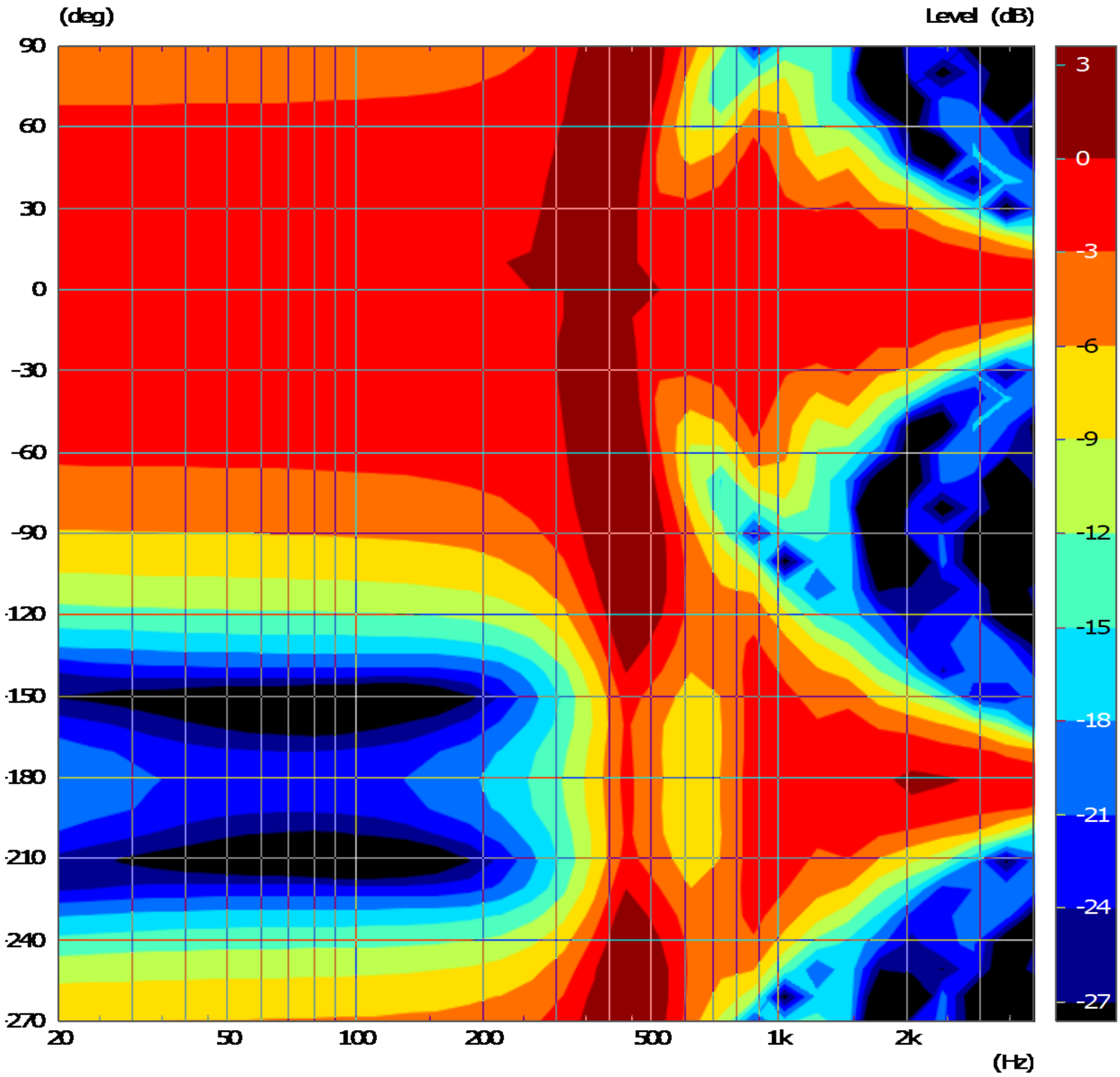


Illustration 46: Dispersion behavior of a real cardioid

The transition to dipole behavior can be prevented by setting a low-pass to the rear driver. Ideally, this should be linear-phase to avoid phase problems with the front driver.

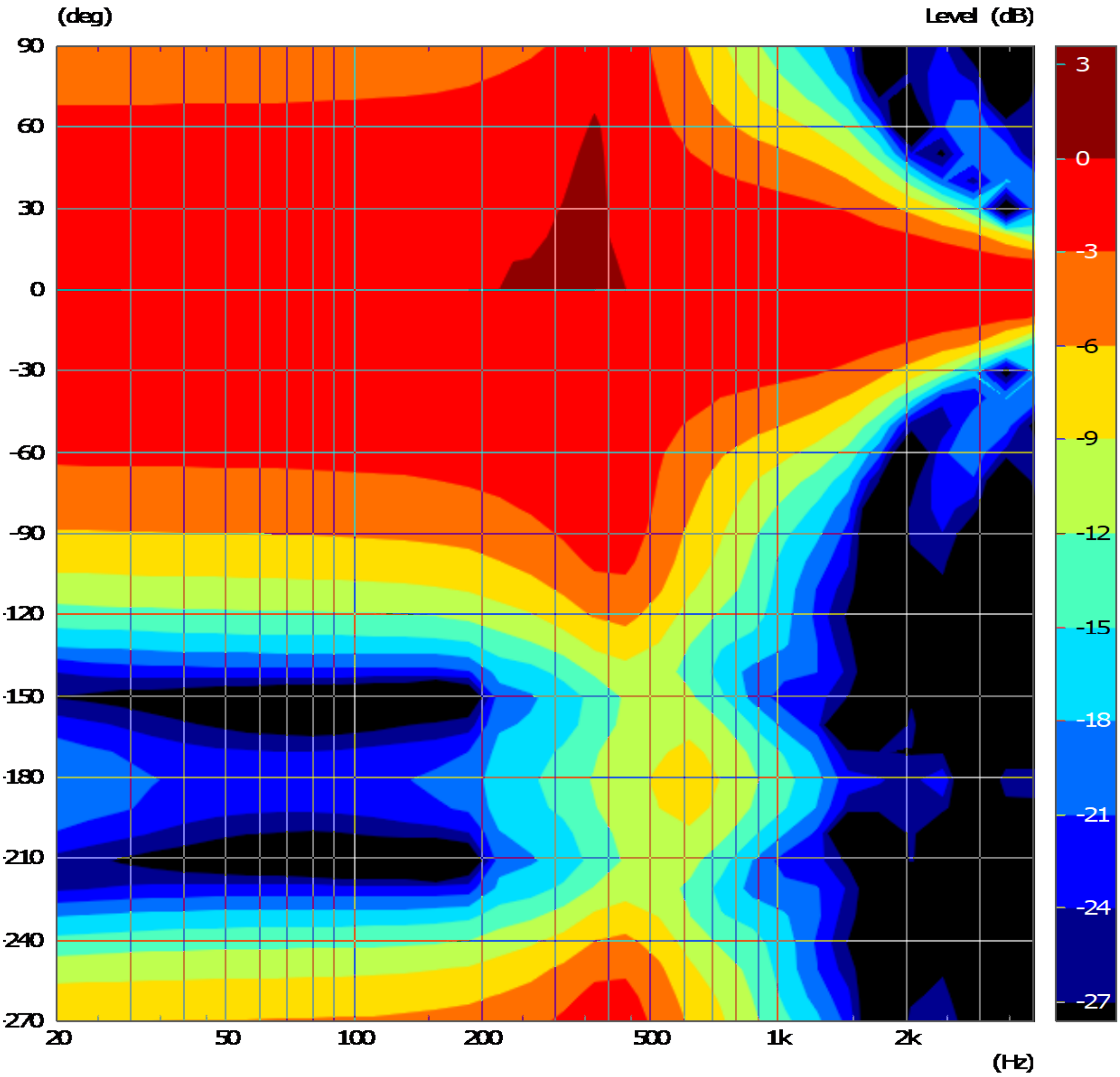


Illustration 47: Cardioid subwoofer with low-pass at the rear driver

2-Way PA Top

In addition to the directivity of the waveguide and the enclosure, a typical PA top with a horn uses a third operating principle, namely the interference of the two ways in the crossover area. The following example shows a speaker with a 12" woofer and a 1" driver on a horn with a vertical beam angle of approximately 40°.

Illustration 48: 2-Way Speaker with Horn

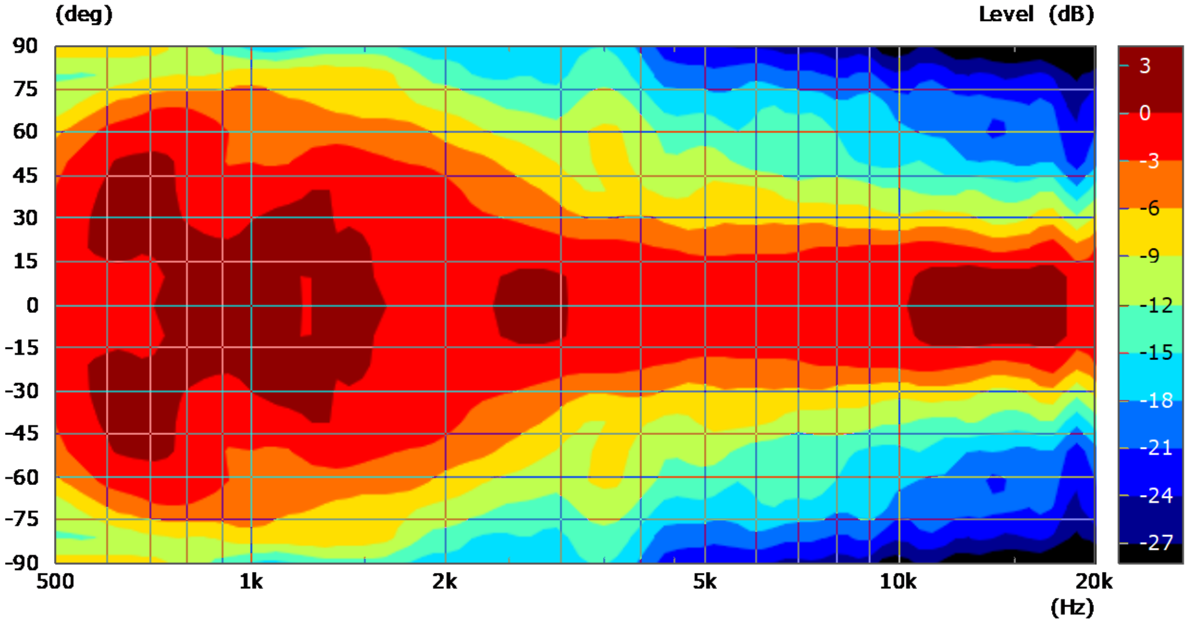


Illustration 49: Vertical dispersion of the horn in the enclosure

With a crossover frequency of 1.2 kHz, a directivity is achieved in the frequency range in which both drivers overlap. The directivity is thus extended downwards.

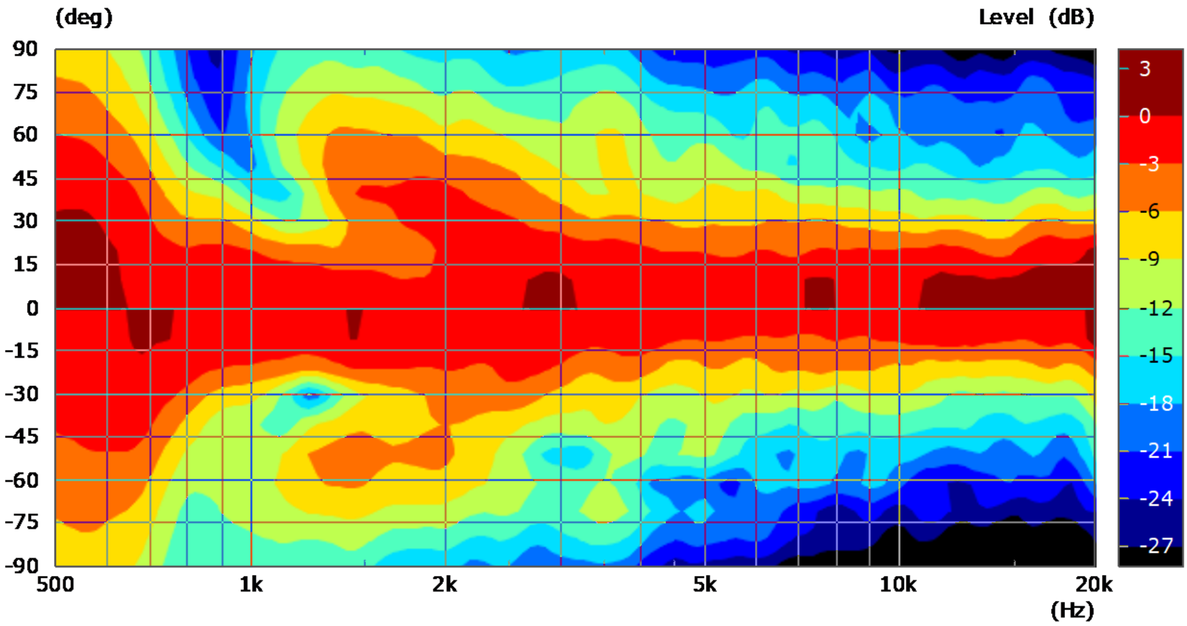


Illustration 50: Vertical dispersion of the entire speaker with separation at 1.2 kHz

References

1. Ulrich Horbach and D.B. Keele, Application of Linear-Phase Digital Crossover Filters to Pair-Wise Symmetric Multi-Way Loudspeakers Part 1, Part 2
2. D.B. Keele, Jr. *Implementation of Straight-Line and Flat-Panel Constant Beamwidth Transducer (CBT) Loudspeaker Arrays Using Signal Delays*
3. James R. Griffin, Design Guidelines for Practical Near Field Line Arrays