Loudspeaker Free-Field Response

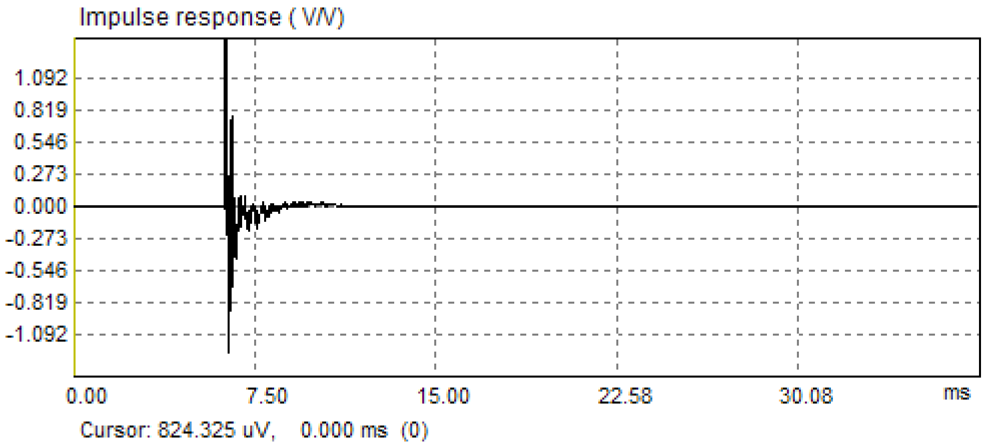
This AP shows a simple method for the estimation of the loudspeaker free field response from a set of measurements made in normal reverberant rooms.

Content

1. Near-Field, Far-Field, Free-Field and Reverberant-Field

When measuring a loudspeaker response we usually denote the measuring conditions as: *near field*, *far field*, *free field* or *reverberant diffuse field*. What does it mean?

To get answer we will have a look at some real measurements of impulse and frequency response.

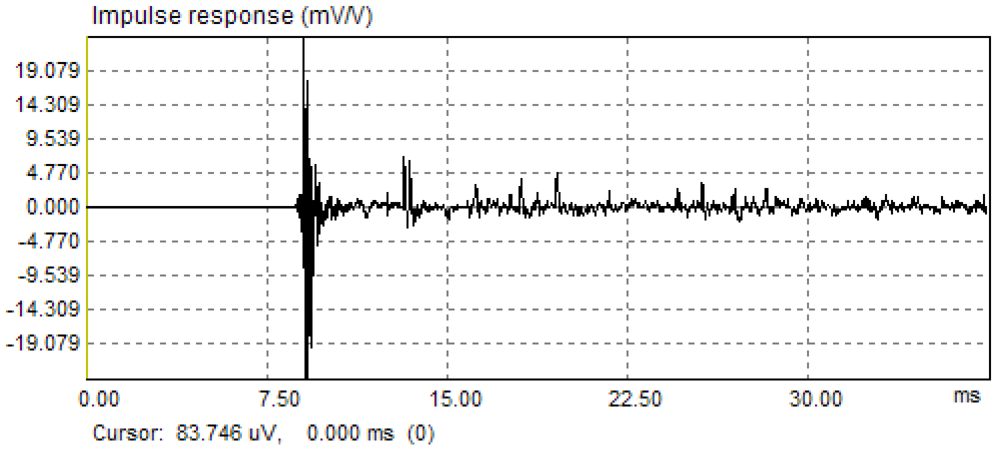


a)

Figure 1. Impulse response of a small loudspeaker box, measured in a living room, a few mm near the center of loudspeaker membrane.

Fig. 1 shows the **near field** impulse response of the loudspeaker. It was obtained by placing the microphone near the center of loudspeaker membrane. We see a sharp impulse followed by the decay of the loudspeaker resonances that lasts a few milliseconds.

Fig. 2 shows the **far field** impulse response of the loudspeaker. It is obtained by placing microphone 96cm from the center of loudspeaker membrane. We see a sharp impulse followed by the decay of the loudspeaker resonances. After a few milliseconds a lot of smaller impulses are following - also with their own decay patterns. These impulses come from wall reflections, and are called **early reflections.** The first impulse is called the **direct wave**. At the tail of the impulse response there is a smooth decay pattern without strong impulses. It represents the response of the diffuse **reverberation field** in which a lot of waves hits the microphone from different directions.



b)

Figure 2. Impulse response of a small loudspeaker box, measured in a living room, 96 cm in front of the loudspeaker membrane

If we make measurements in open space or in a anechoic chamber, with substantial distance from the loudspeaker, we say the measurements are done in **free field**.

We can obtain **quasy-free field** measurements from a impulse response, that is measured in a normal living rooms, if we remove the tail of the impulse response beginning at the first early reflection. The remaining part of the impulse response, which is left for the analysis, we call the **gated impulse response**.

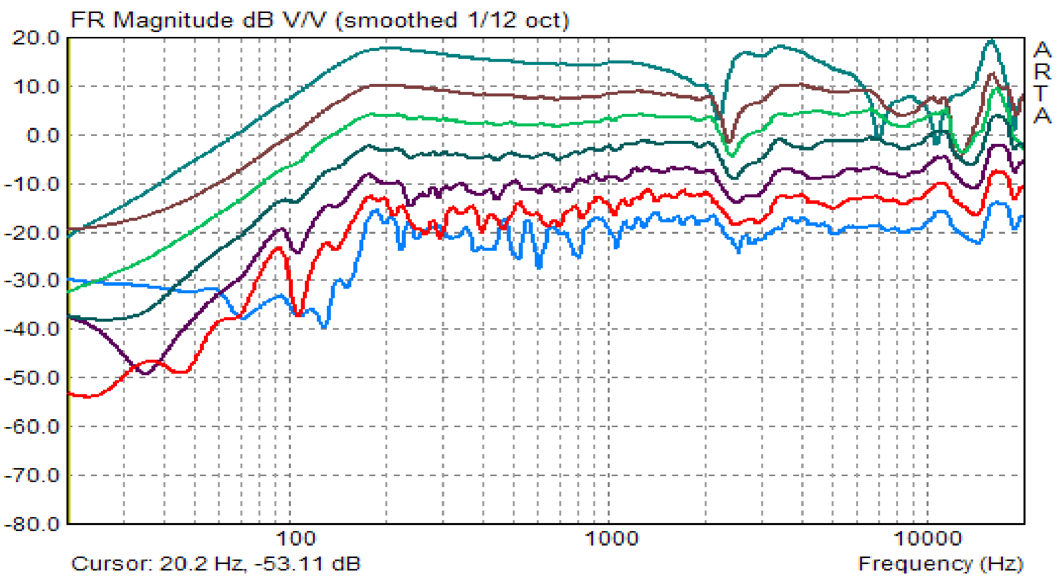


Figure 3. Frequency response of a small loudspeaker box, measured in a living room. Measuring distances are: 0 cm, 3 cm, 6 cm, 12 cm, 24 cm, 48 cm, 96 cm (from upper to lower curve).

Figure 3 shows a frequency response measured in a normal living room at the following distances from the loudspeaker: 0cm, 3cm, 6cm, 12 cm, 24cm, 48cm and 96cm. The near field frequency response has the smoothest pattern, but with several notches at higher frequencies. At larger measuring distances the frequency response has lot of ripples. It is absolutely normal that ripples in a reverberant field are larger than ±5dB.

2. Near-Field to Far-Field Transition in Half Space

To get insight why there are notches in a near field response we take a look on the theoretical analysis of the response of a loudspeaker which is mounted in an infinite baffle and radiates into half space (2π space angle).

Figure 4 shows the normalized sound pressure at the distance *r* on axis of a circular membrane, which has a velocity *v*. We got it from the solution of the Rayleigh integral for the radiation of a circular disc:

$$|p(r)| = 2\rho_0 cv \, \sin\left(ka\frac{(r^2/a^2+1)^{1/2} - r/a}{2} \right)$$

a = radius of the membrane, k = wave constant = $\omega/c = 2\pi/\lambda$, ω = frequency = $2\pi f$,
c = speed of sound, ρ_0 = density of air

We see that in region where the distance r is smaller than 6 times the radius of the membrane the sound pressure depends strongly on the directional factor $ka = 2\pi a/\lambda$. For some values of ka and r the sound pressure can be zero. For distance $r > 6a$ the sound pressure is independent of the directional factor, and we get the far field response in half space ($p_{2\pi}$):

$$|p_{2\pi}(r)| = \frac{\rho_0 \omega a^2 \pi v}{2\pi r}, \quad \text{far-field response in a half space } (r > 6a)$$

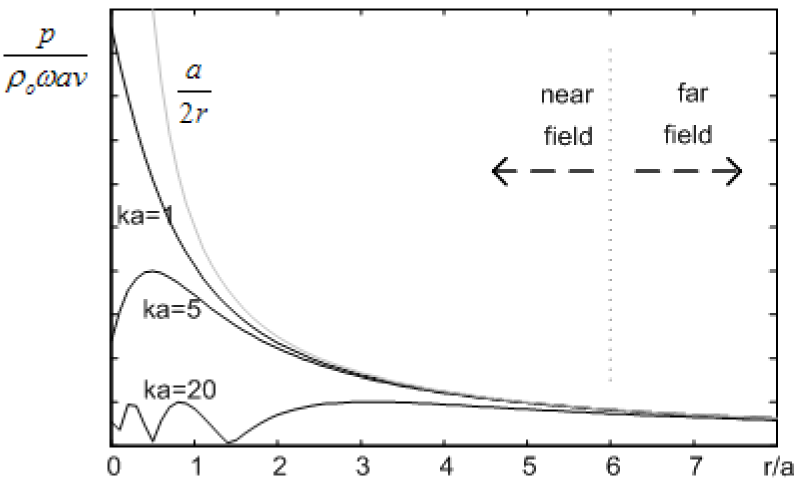


Figure 4. Normalized loudspeaker response at different frequencies (ka = 1, 5, 10) in a transition region from near-field to far-field.

In the vicinity of the membrane ($r << a$) we have a near filed response p_N:

$$\left|p_N\right| = \rho_0 \omega a v \frac{\sin\left(ka/2\right)}{ka/2}, \quad \text{(on axis near-field response)}$$

A near field response has dips at frequencies where ka/2 = π/2, 3π/2, .. i.e. at $f_n = (2n+1)\, c/4a$.

In our example, a loudspeaker with a membrane radius a=3.2 cm should have dips in the frequency response at 2687 Hz, 8062 Hz and 13437 Hz, nearly as shown in Fig. 2.

The ratio of sound pressures at the distance r in far field to the sound pressure in the near field is:

$$\left|\frac{p_{2\pi}(r)}{p_N}\right| = \frac{a}{2r}\frac{ka/2}{\sin\left(ka/2\right)}$$

At low frequencies, where $ka << 1$, $\sin(ka/2) \cong ka/2$, we can use simplified equation:

$$\left|\frac{p_{2\pi}(r)}{p_{NF}}\right| = \frac{a}{2r}$$

This expression is important as it is used normally for the transition of the measured near field response to the far field response in half space. This expression gives a very small error in the range below 200Hz for any practical size of loudspeaker membranes.

The measurement procedure is as follows:

1. Put the measuring microphone a few millimeters in front of the center of the loudspeaker membrane / dust cap and measure the near field impulse response.
2. Scale the impulse response with the factor $a/2r$ to get the half space far field response at the distance r. (ARTA Impulse Response Window - menu command **'Edit->Scale'**)
3. Save impulse response under appropriate name.

3. Half space to Full Space Free-Field Loudspeaker Frequency Response Estimation

A more real case is when the speaker is mounted in a small box and radiates in a full space (4π). To get more insight, how a small box baffle diffracts acoustical waves, we compare the response of a loudspeaker that is mounted in a infinite baffle ($p_{2\pi}$) to the response a loudspeaker that is mounted in a spherical box ($p_{4\pi}$).

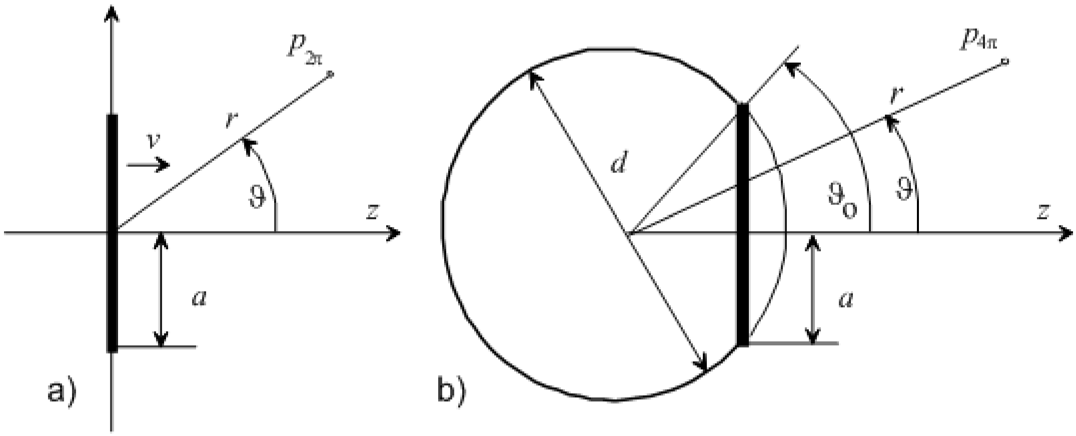


Figure 5. a) Loudspeaker with radius a, mounted on an infinite baffle
b) Loudspeaker mounted in a spherical box of diameter d.

A well known analytical solution for the radiation of the spherical loudspeaker box gives us the ratio of response in free space ($p_{2\pi}$) to response in half space ($p_{4\pi}$):

$$\frac{p_{4\pi}}{p_{2\pi}} = \frac{e^{-jkd/2}}{\left(\frac{kd}{2}\sin\vartheta_0\right)^2}\sum_{n=0}^{\infty} C_n \frac{e^{j(\delta_n + n\pi/2)}}{B_n(ka)}$$

where C_n are Legendre polynomials, B_n and δ_n are magnitude and phase of spherical Bessel functions. This solution is valid for on axis radiation (ϑ=0).

The evaluation of this expression needs a large computing power, so we define an approximate solution. It is of practical interest to analyze the case where the membrane occupies 1/40 to 1/10 of the spherical surface (i.e. for angles ϑ_0 from 5^o to 20^o). In that case the on axis response (ϑ=0) of the flat loudspeaker that is mounted in a spherical box, can be approximated, with an error less than 0.5dB, by the expression:

$$\frac{p_{4\pi}}{p_{2\pi}} = \frac{1 + j\,f/f_0}{2 + j\,f/f_0}$$

with $f_0 = 42.70 / d$ for a spherical box of diameter d or with $f_0 = 34.16 / d$ for a box with squared baffle of width d. For a rectangular box, that has front baffle width w and height h, ARTA currently uses - as an approximation - an equivalent squared box of width $d = w\,(h/w)^{1/3}$.

This equation defines a "baffle step equalizer". Examples of responses are shown in Fig. 6.

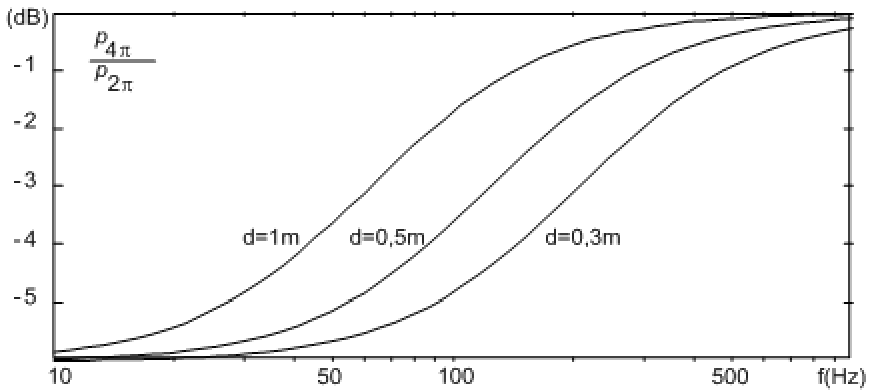


Figure 6. Frequency response of a baffle step equalizer for three spherical boxes with diameters of 0,3 m, 0,5 m and 1,0 m.

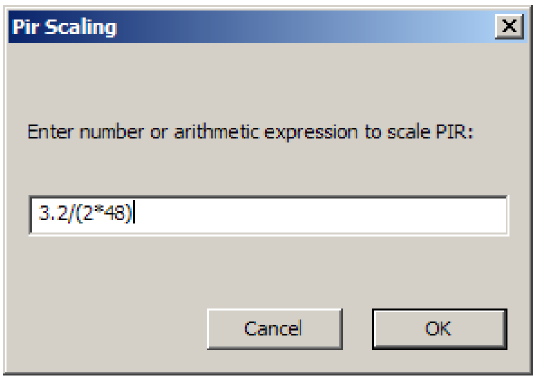
Figure 6 shows that at very low frequencies the response in free space is half (-6dB) than the response in half space, but it tends to be the same at higher frequencies.

Note: *ARTA and STEPS uses the previous expression for the estimation of the diffraction for spherical or rectangular baffled boxes. Some CAD and simulation programs are using a high-frequency geometrical model for the estimation of box diffraction at low frequencies. Such models can give larger errors on low frequencies than the simple model that is presented here.*

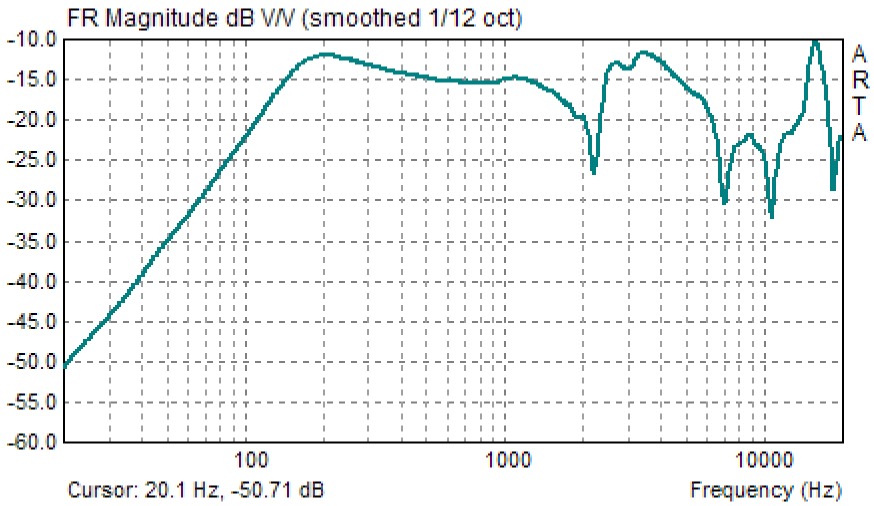
4. Estimation of the Low Frequency Free-Field Response

Now we give the procedure for the estimation of the low frequency free-field loudspeaker response:

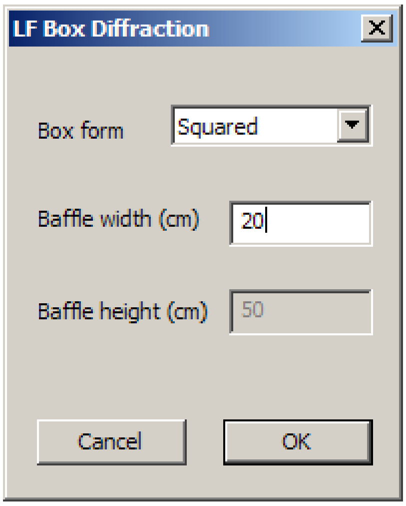
1. Measure near-field response and estimate half space response as explained in preceding section, i.e. for our speaker with a radius of 3.2 cm, we scale a half-space near field response, to far-field half-space response on 48cm, by menu command '**Edit->Scale**' and entering the scaling factor $a/2r$ into the dialog box '**Pir Scaling**';



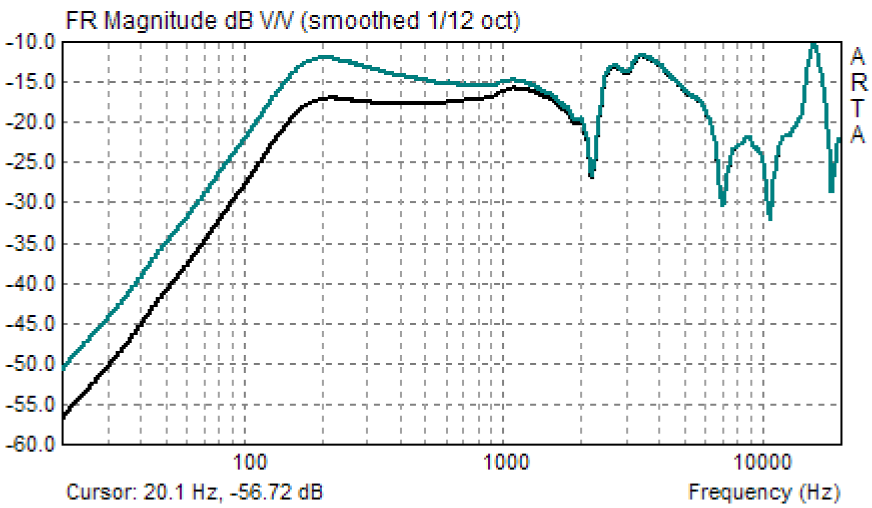
2. Execute command '**Analysis->Smoothed Frequency response**'. Activate in Smoothed FR window command '**Overlay->Set as overlay**'. You will get following figure:



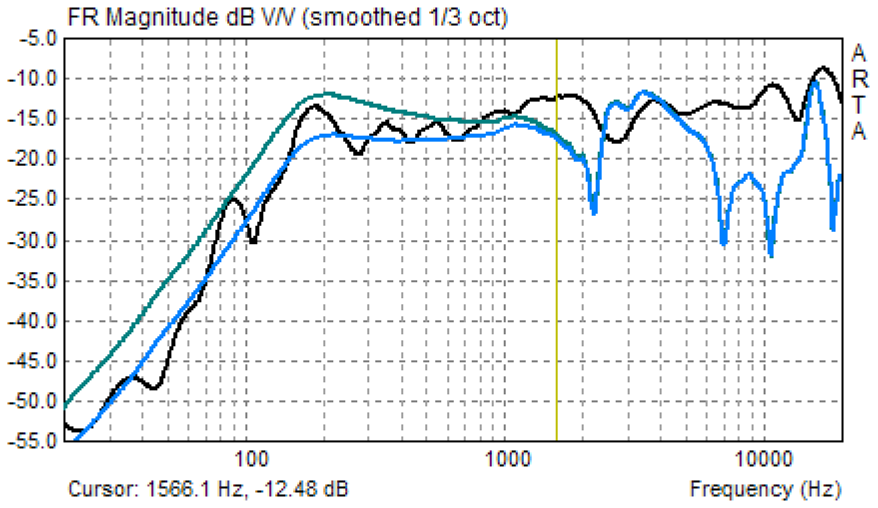
3. Execute menu command **'Edit → LF box diffraction'**, to get following dialog box:
4.



Here you should enter the width and the type of the box (spherical, squared or rectangular). Now you will get the following graph:



5. Save this curve as overlay.
6. Return to PIR window and load loudspeaker response that is measured at the distance of 48cm. Set cursor and execute command '**Analyze->Smoothed frequency response**'. Finally, you will get the following graph:

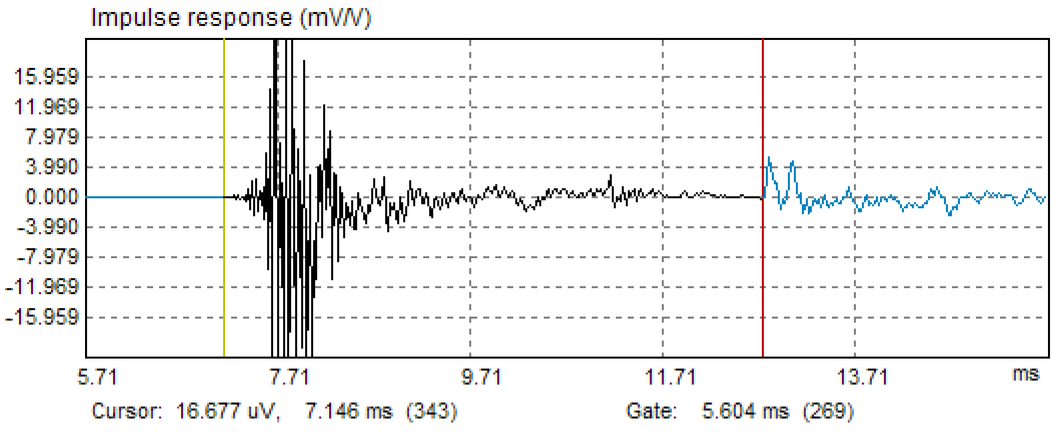


We see that the frequency response measured at 48 cm (black) has high ripple, due to room resonances, but generally it is very close to the estimated free-field response (blue).

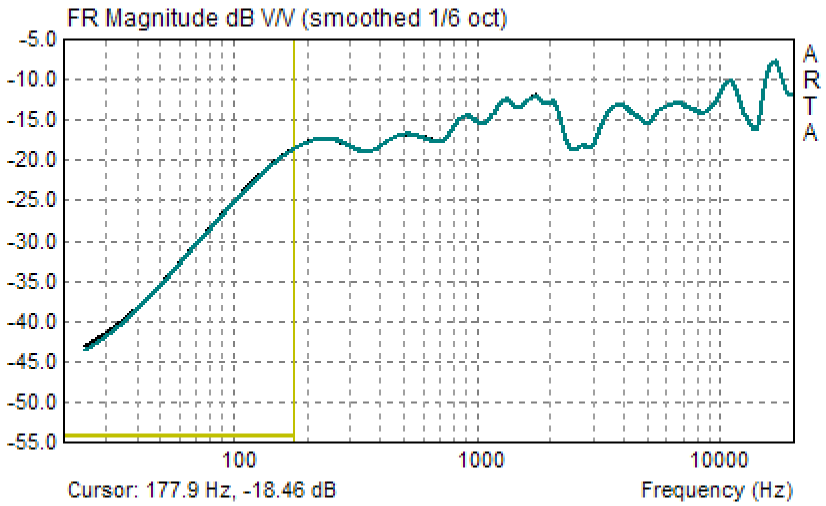
5. The Estimation of the Wideband Free-field Response

We can make a good estimation of free-field response if we combine the low-frequency near-field response and the gated quasi-free-field wideband response.

We start by analyzing the wideband impulse response as shown in Fig. 1. We conclude that we can obtain an estimation of the free field response if we remove the first reflection that is 5.6ms apart from the start of the impulse response. We make a “gate” in the ARTA PIR window by placing gate marker (a red line) just before the first reflection, as in following figure:

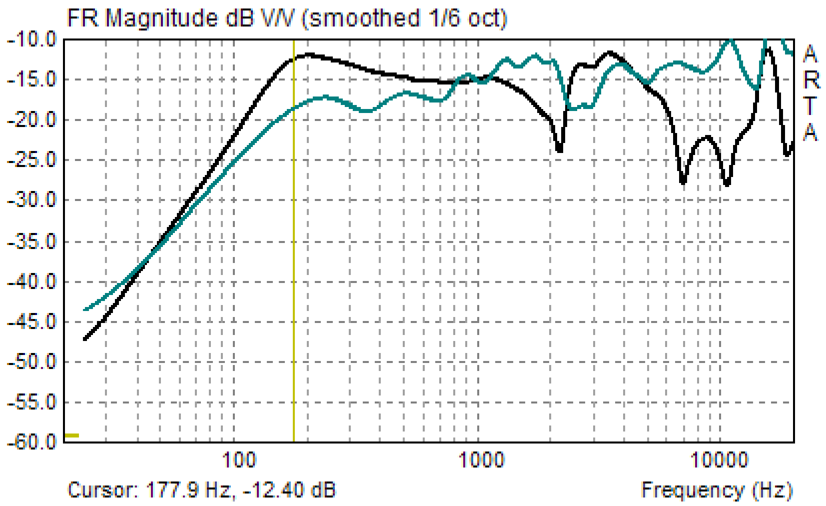


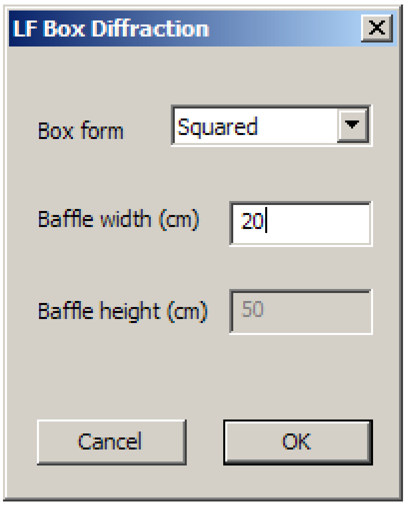
After execution of the command '**Analysis->Smoothed frequency response**' we get the following frequency response:



We save this curve as overlay. Cursor and yellow line at the bottom of the graph denote that the time-bandwidth requirement is satisfied on frequencies above 177.9Hz. *(Note: 1/gate = 1000/5.604 = 178.4)*

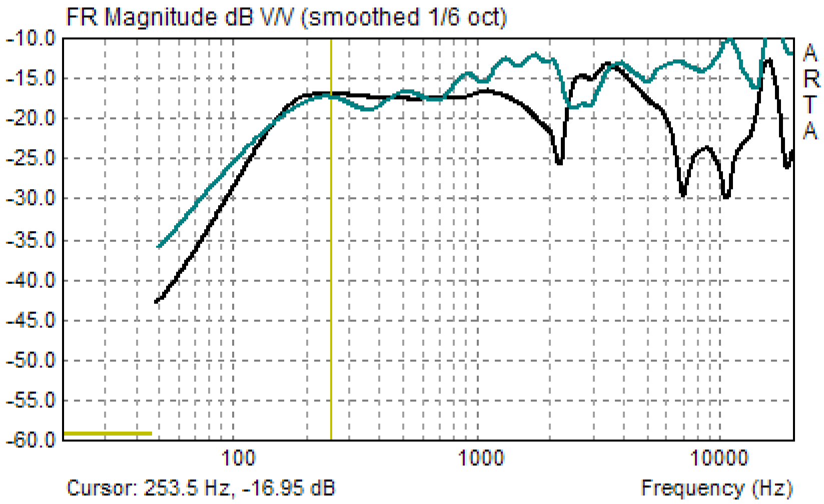
Now we load near-field response, scale it by factor $a/2r$ = 3.2 / (2*48), and calculate frequency response, as explained in preceding section. We get:





Now we apply LF diffraction correction by the command '**Edit->LF box diffraction**' and following dialog box.

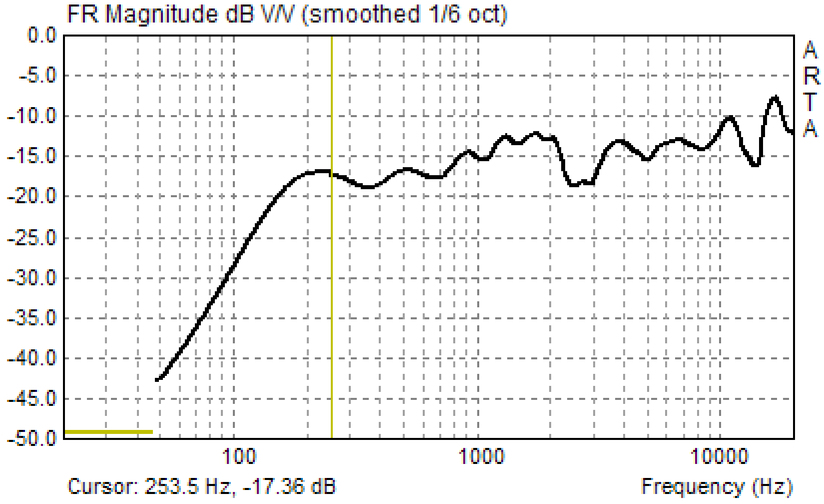
In this dialog we enter box form type (squared or rectangular baffle), box width and box height for rectangular baffle. The corrected response and gated response are now closely related.



At 235 Hz both responses have same level so we will choose this frequency as a point for joining the two curves. We execute now two commands

1) **Edit -> Merge overlay above cursor**
2) **Edit -> Delete all overlay**

and we get finally the estimation of the free field response:



Note: *Usually both curves do not match ideally, and additional scaling of 1-2 dB may be necessary in practice.*

We can save values of this curve with command '**File->Export ASCII**'.

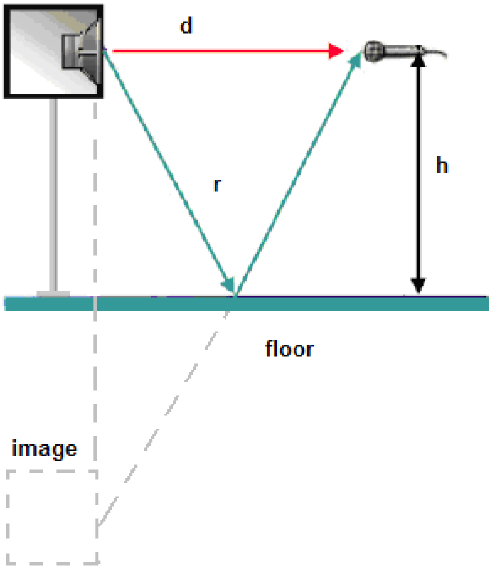
6. Discussion

For the estimation of the loudspeaker free-field response, from measurements that are done in a normal living room, we need following data:

1) effective membrane radius *a* (a membrane radius plus 1/3 width of the surround)
2) near-field-response measured at a distance from the center of the membrane less than $d < a/20$
3) gated far-field-response measured at distance from membrane $d > 6a$

The best estimation we get if the gated impulse response is without any wall reflections. It is recommended that the gate length should be 5ms or more (dictated with a time-bandwidth requirement for correct frequency response estimation on frequencies above 200Hz). Practically this means that for a correct measurement setup we must place the microphone at the distance *h* from the nearest wall or floor so that time delay of first reflection would be larger than 5ms.

The following picture illustrates the method of images that help us find the path of wave reflection from the floor. We will assume that floor is nearest reflecting surface.



From the direct wave path length *d* and the distance h from floor we get the path length of the first reflection

$$r = 2\sqrt{(\frac{d}{2})^2 + h^2}$$

and the delay of the first reflection

$$\Delta t = \frac{r-d}{c} = \frac{2\sqrt{(\frac{d}{2})^2 + h^2} - d}{c}.$$

Now we can express requirement for the loudspeaker distance from the floor (*h*) with following equation

$$h = \sqrt{(\frac{d + c\Delta t}{2})^2 - (\frac{d}{2})^2}$$

In our case, for the delay of 5ms and d=48cm we get h=1.08m. This means that we must place loudspeaker and microphone 1.08m above the floor, to get the first reflection delay larger than 5ms. Of course, the loudspeaker have to be placed distant from all other walls appropriately.

7. Literature

Mateljan I., Models for the Estimation of the Loudspeaker In-Room Response, *Int. Journal for Engineering Modeling*, vol. 6., No.1-4, 1993, ISSN 1330-1365

Kinsler, Frey, Coppens, Sanders: Fundamental of Acoustics, J. Wiley, New York, 2000.