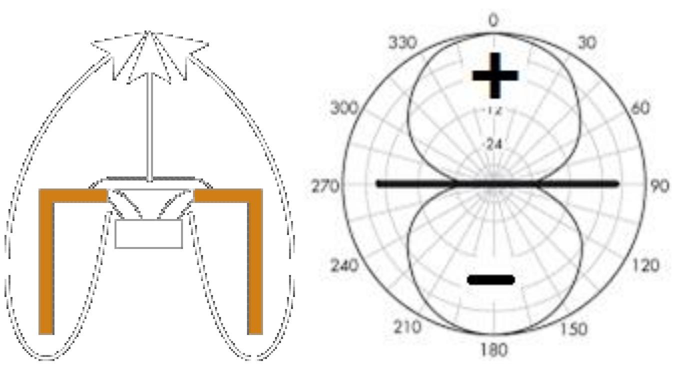
In Pursuit of a 20-20k Dipole Loudspeaker

Charlie Laub / JAN 2019

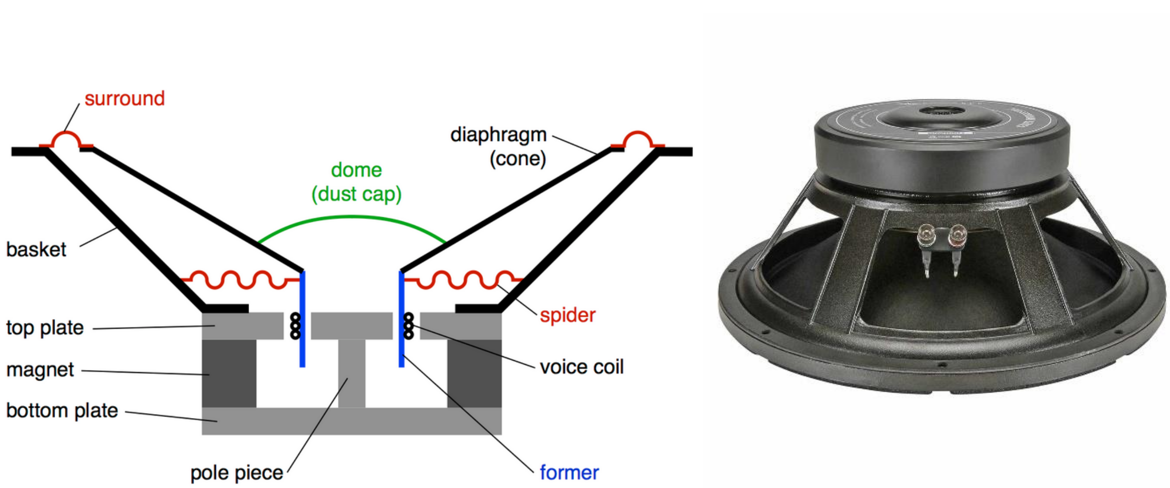
INTRODUCTION:

In the most simplistic sense, getting a loudspeaker driver to produce dipolar radiation is as easy as removing the rear of the "box". The radiation from the rear of the cone can then propagate out into the room and will have reverse polarity compared to the radiation coming from the front of the cone. Where the front and rear radiation meet, and each having traveled the same distance, the two wave fronts will cancel out and a null will form. In general, this occurs "to the sides". The dipole pattern is formed, with a positive pressure lobe to the front, a negative pressure lobe to the rear, and nulls on each side as shown in the images below.



ABOVE: left: open back dipole loudspeaker, right: dipole radiation pattern

This is a very simplistic picture of a dipole speaker that is not very accurate. The behavior becomes more complicated and is influenced by the drivers themselves as you move up in frequency. First let's take a look at whether a driver is a good dipole source, and why or why not.



ABOVE: left: loudspeaker cartoon, right: real loudspeaker showing magnet and basket windows

An example of a moving coil driver (see previous image) is what is commonly known as a “woofer”: a cone, basket, and motor assembly (magnet and voice coil).

At low frequencies the front and rear acoustic radiation is very similar, but at higher frequencies the basket and magnet tend to act as an acoustic resonator and a low pass filter to the rear cone radiation. This influences how high in frequency this type of driver can be used as a true dipole source, and even the best examples are less and less ideal above 2kHz. Although to the front a small diameter driver might have on-axis response to 10kHz and higher, the back will be very different situation and most moving coil drivers are not a good candidate for producing dipole radiation above about 2kHz or 3kHz.

This effect is usually worst in smaller diameter (e.g. <5”) moving coil drivers actually because the motor is similar in size to the cone and blocks the rearwards path. Also, the basket windows of small drivers tend to be smaller and open only to the side and not to the rear. This sometimes results in strong resonances as low as 1kHz, and the low pass filter effect rolls off the rear radiation at higher frequencies. While the dipole peak for smaller drivers will be higher in frequency, the peak shape is often relatively narrow and “higher Q” in shape, dropping steeply above the peak. This creates some serious challenges for crossover development (even for active crossovers) if the goal is a smooth frequency response on and off axis.

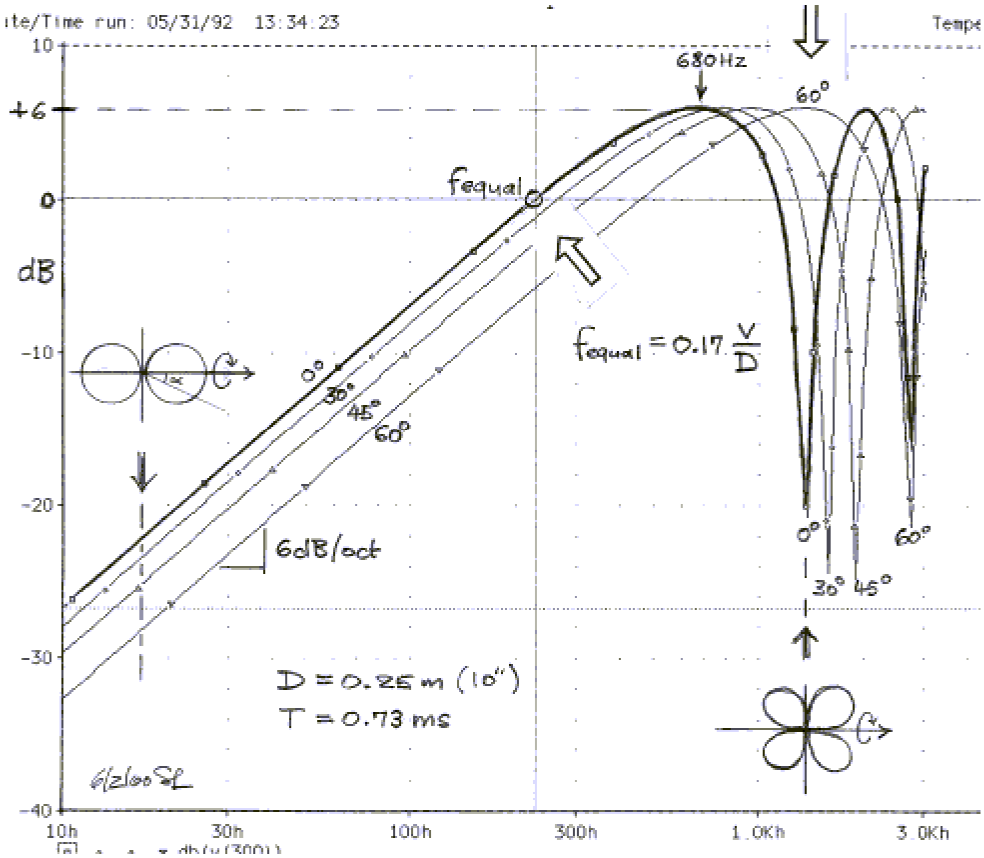
Using larger diameter (e.g. >8”) drivers solves some of these problems, however, some new ones are created that prevent the driver from operating to a high frequency. Larger cones undergo breakup at lower frequencies and have a narrowing dispersion pattern (e.g. beaming) as frequency increases. The larger voice coil may have an inductance that is problematic (too high). The larger diameter shifts the “dipole peak” to a lower frequency. It is helpful that the basket windows tend to be larger and the rear of the cone can be seen from behind the motor. If the motor is also small (e.g. because it is a neo motor), and the part of the basket where the suspension is attached is not too large, resonances and the low-pass filter effect may be absent.

The greatest challenges are to find driver that will operate as a true dipole source to a high enough frequency, and to suitable dipole tweeters. Moving coil type drivers just simply cannot work as a dipole to more than a few kHz, so a dipole tweeter must be capable of crossing over around 2-3kHz. Typically, dipolar ribbon drivers are used, with some possible exceptions that will be discussed later in this text.

Let’s look at some models of an acoustic dipole and see what we can learn. Then we will return to look at some real world drivers and to consider a few other practical details.

THE DIPOLE PATTERN MODEL

The classic response pattern of the dipole (modeled via two monopoles) looks like this (source: linkwitzlab.com)



Source: http://www.linkwitzlab.com/images/graphics/2pt-src2.gif

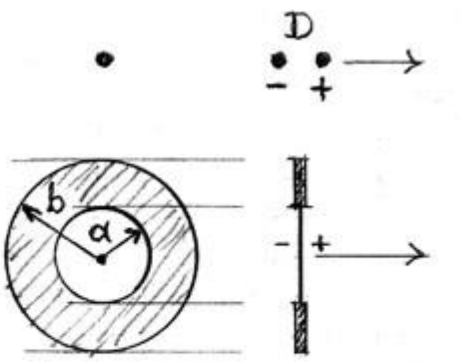
Features of the dipole model include:

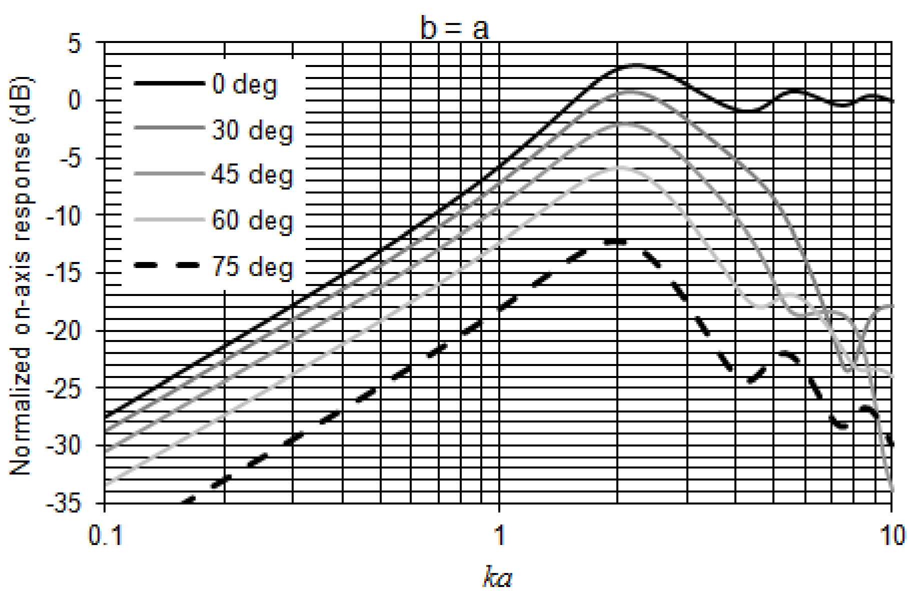
- The “dipole peak” (at 680Hz for the on-axis position in the figure). Here the front and rear radiation are in phase due to the pathlength difference to the measurement location and the SPL is +6dB compared to a single monopole (+3dB because there are two sources, front and rear, and +3dB because the sources are in phase at the dipole peak). Note that the dipole peak shifts to a higher frequency as you move off axis.
- A frequency region below the dipole peak which has a 6dB per octave downwards slope in the sound pressure. This 6dB per octave decrease in SPL is created because there is a fixed distance D between the front and rear sources. At lower and lower frequencies the relative phase angle of the front and rear wave at any given position is getting closer and closer to 180 degrees as frequency decreases because the wavelength is getting longer and longer and is much larger than D. Another way to think of it is that, relative to the wavelength λ, the source separation D is getting smaller and smaller and you essentially have two out of phase sources that are acoustically “close” to each other. This produces increasing cancellation.
- A region “above” (higher in frequency than) the dipole peak(s) (not shown in the plot). For two monopoles, this region is characterized by a series of peaks and nulls. The exact frequency of each is different as you move off axis. Where you have an on-axis null you can have a peak at some off-axis angle. The response is somewhat chaotic.

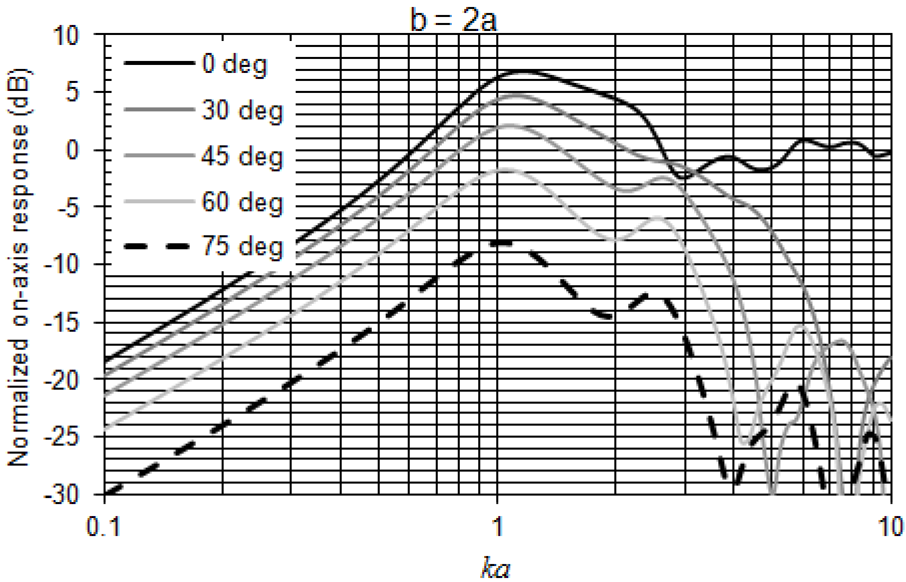
This “two monopole dipole” model captures the 6dB down-sloping low frequency region well, however, it is not a good representation of real world drivers around the dipole peak, and above.

A MORE ADVANCED DIPOLE MODEL

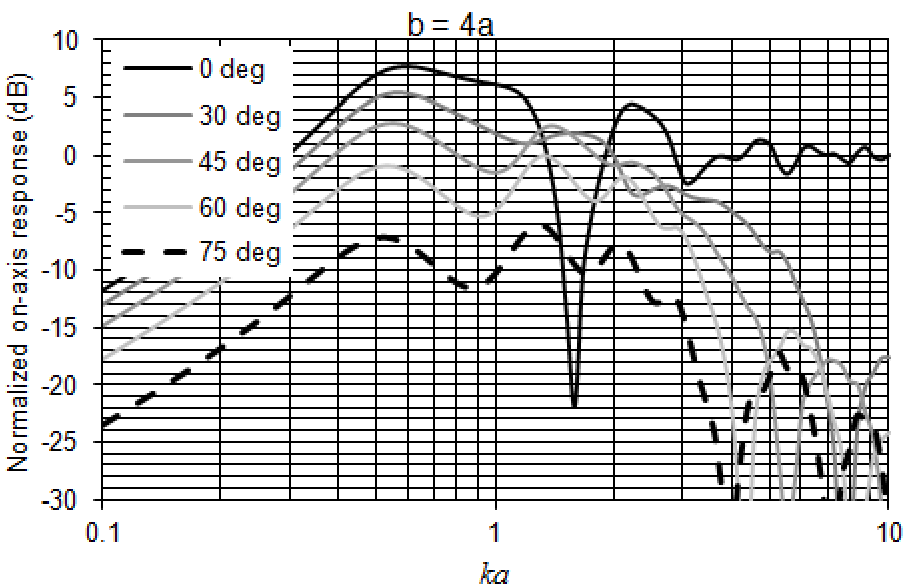
Using some much more sophisticated modeling and mathematics in which the driver is represented as a piston in a round planar baffle, Leo Beranek & Tim Mellow calculated the response for various ratios of the piston radius, a, and baffle radius, b. Below I present several plots from their work in which the diameter, b, of the circular baffle increase from b=a to b=8a (source linkwitzlab.com):



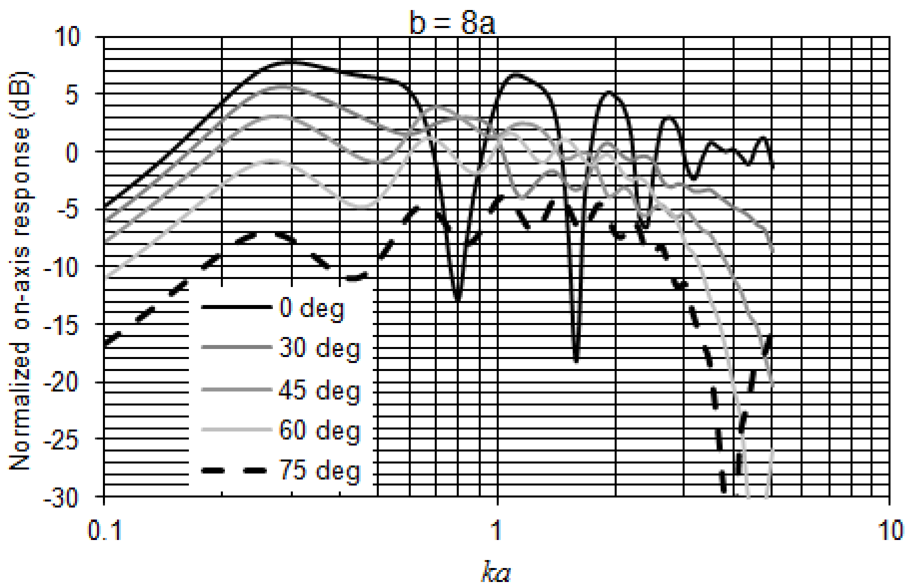




b = 2a
0 deg
30 deg
45 deg
60 deg
75 deg
Normalized on-axis response (dB)
10
5
0
-5
-10
-15
-20
-25
-30
0.1
1
10
ka



b = 4a
0 deg
30 deg
45 deg
60 deg
75 deg
Normalized on-axis response (dB)
10
5
0
-5
-10
-15
-20
-25
-30
0.1
1
10
ka



For more information please see http://www.linkwitzlab.com/models.htm, entries A through A3.

One trend that can be seen in these plots is that the model-predicted on and off axis responses remain relatively similar and track each other (do not cross over one another) around the dipole peak for all cases. This is significantly different than the “two monopole dipole” model. Above the dipole peak, as the baffle diameter b increases the on and off axis responses begin to merge and cross, and some edge diffraction effects cause nulls to form in the on axis response.

In my experience, the modeling by Beranek and Mellow capture much of the real-world-driver behavior that you can measure yourself, and that I have measured myself when doing mockups with dipole systems using a baffle. I will show some real world measurements a little later.

What insights can be obtained from these results? They seem to suggest that very small baffles or no baffle will result in a smoother and more consistent dipole response pattern thru the dipole peak and above it. When using no baffle the dipole peak frequency is moved up in frequency as much as possible and this might help the driver operate as a dipole to frequencies where it can be crossed over to a dipole tweeter. One consequence of the baffle-less (nude) mounting is that the low frequency dipole losses are increases (the 6dB downward slope towards low frequency). This can have some real world consequences in terms of SPL losses, higher power input requirements, and increased driver excursion requirements. At some (low) frequency the driver will no longer be capable of producing the desired SPL target and the designer must cross over to another, larger, driver. This tends to increase the number of bands (drivers) in an open baffle nude dipole system to at least 3 or 4 bands.

Keep in mind that the model here was only a piston in a baffle – there is no modeling of the basket or magnet assembly that I mentioned earlier, since this is driver-dependent. This will cause additional changes to the rear radiation pattern that will further limit the use above the dipole peak.

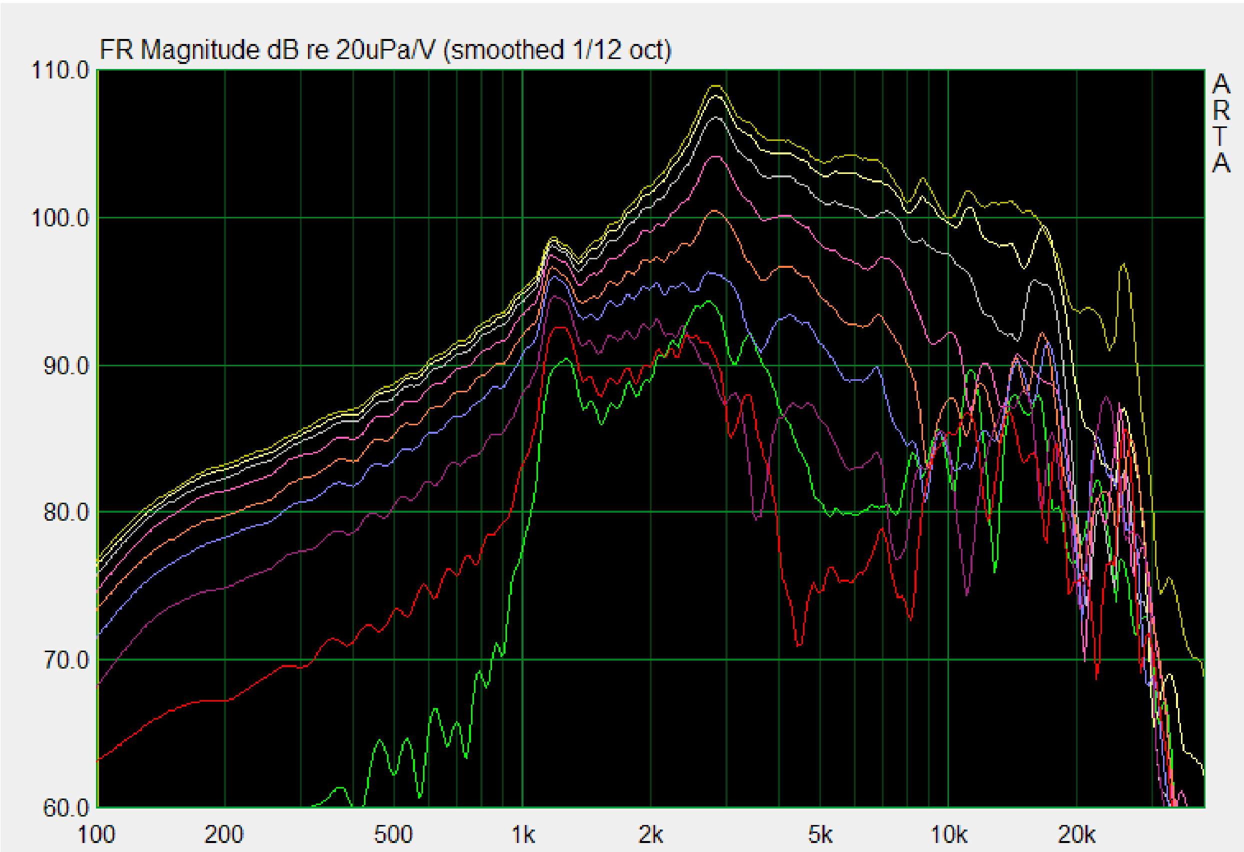
REAL WORLD MOVING COIL DRIVER RESPONSES

It will be more instructive to look at some real world data taken on moving coil drivers to show this effect for a range of driver sizes.

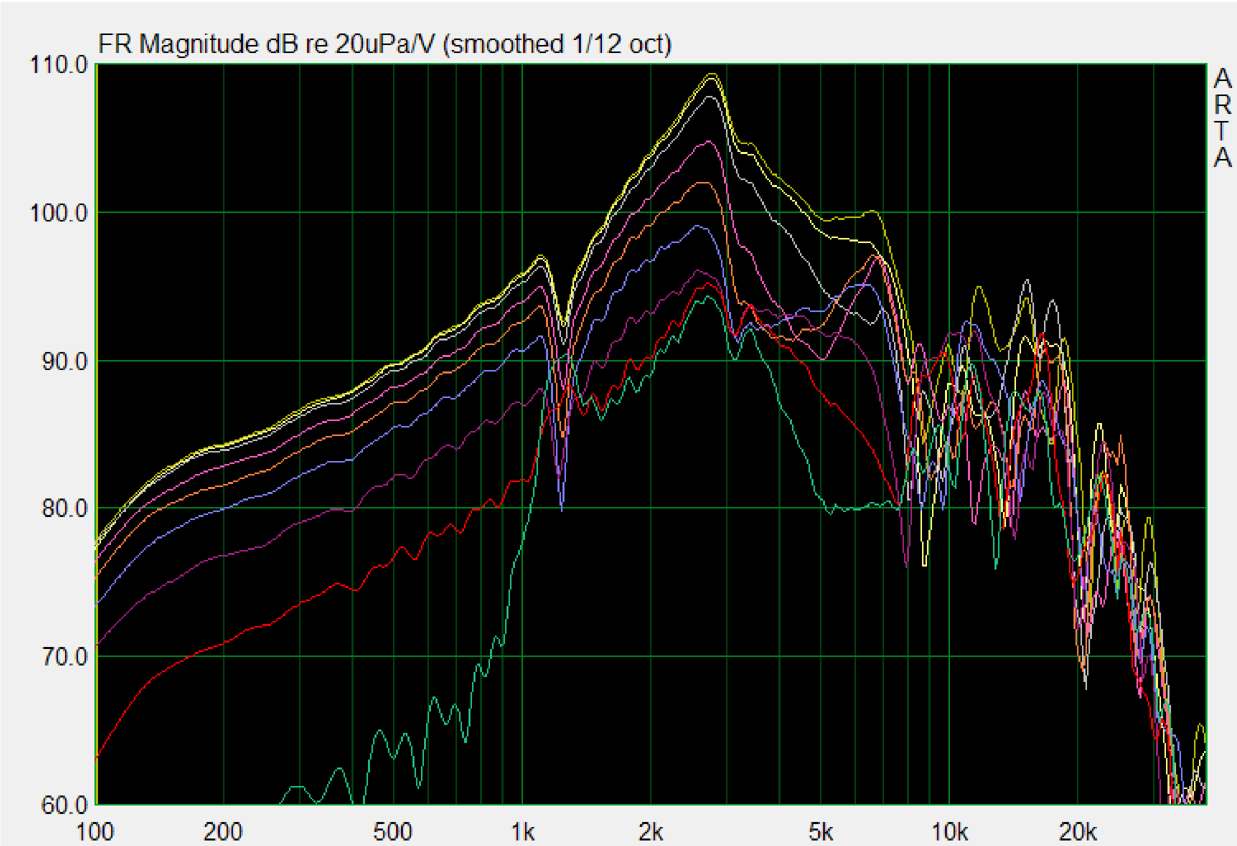
The following are measurements I have made myself with about 50 Hz resolution. In all cases the drivers are suspended by wires away from boundaries. The measurement angles used are 0, 11, 22, 33, 44, 55, 67, 78 and 90 degrees from the on axis (front or rear) position.

A SMALL DIAMETER DRIVER:

Below is an example of the front radiation from a small diameter (3.5") driver. The dipole peak is at about 2.9kHz and is relatively narrow and "peaky". In the front plane the main lobe is narrowing (lines are getting farther apart) above 2kHz but stays relatively intact until almost 10kHz.



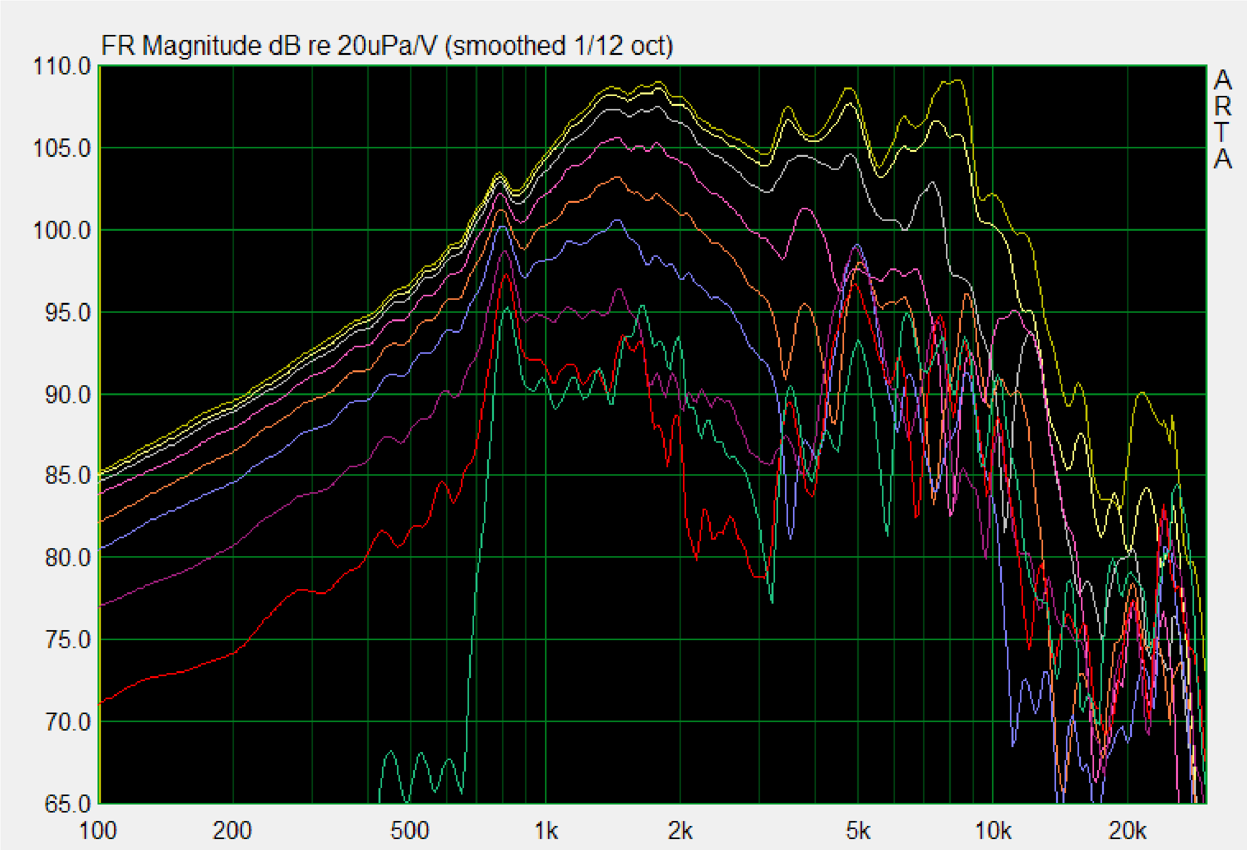
In comparison, the rear radiation (below) has some marked differences. The dipole peak remains at 2.9kHz but the response drops sharply above 3kHz, and there is some crossing of the lines that worsens around 4-6kHz. If the front SPL was corrected to be flat, the rear would start look quite different above 3kHz.



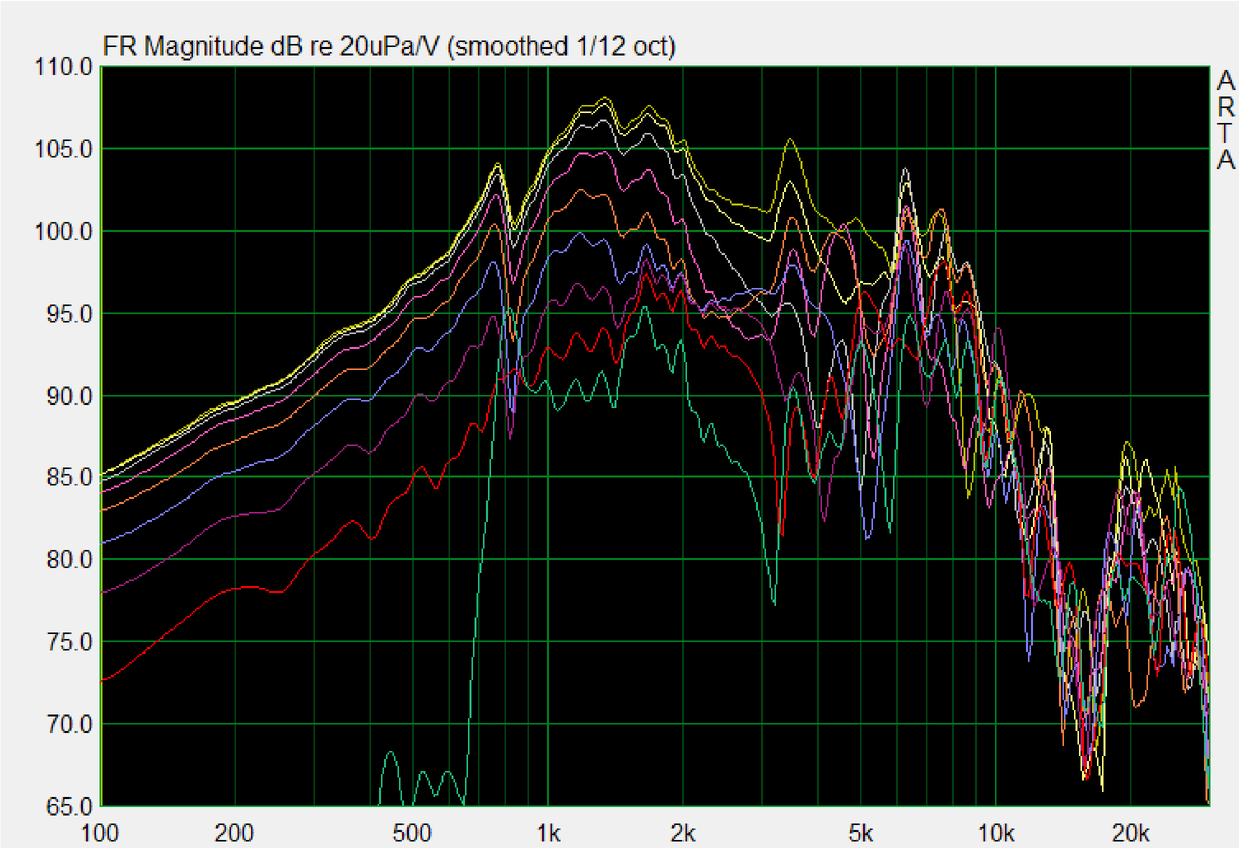
There are some downsides to using a small fullrange driver as the highest-band driver in a dipole system. When the dipole peak is pushed up this high, there are large SPL losses at lower frequencies. In addition, the 3.5" driver's voltage sensitivity and power handling are both low. This would make the driver useful only above about 1kHz, however there is a resonance of some kind occurring around that frequency. Putting the driver in a baffle to lower the dipole peak will result in the b>>a behavior predicted by Beranek and Mellow. All in all this is not be a great choice for either a dipole tweeter or midrange.

A MIDWOOFER:

Below is an example of a 6" midwoofer. Compared to the small driver already mentioned above, this has a broader dipole peak region and a lower dipole peak frequency (around 1.5kHz). The front response pattern looks like this:



The rear radiation pattern still shows some of the same traits as the 3.5" driver to the rear (see below) but these are less severe

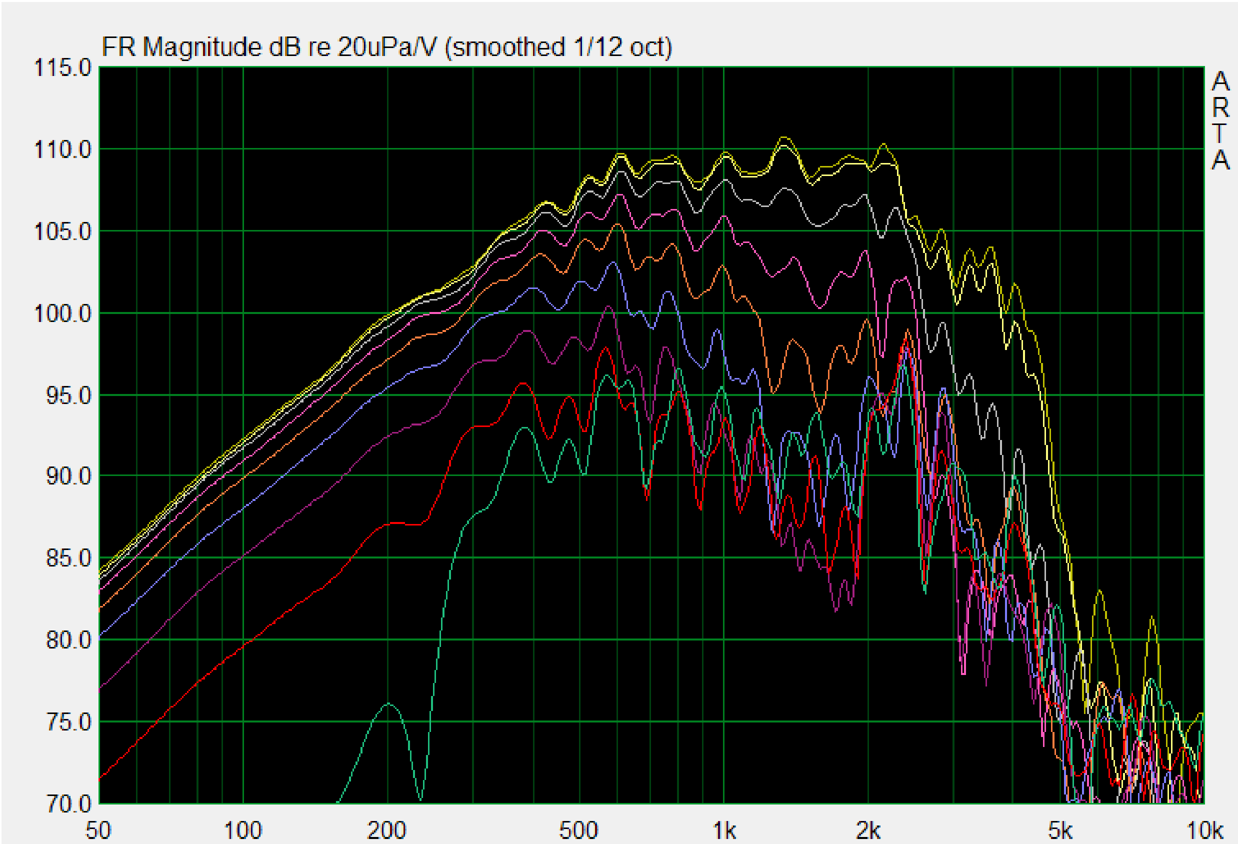


Even though compared to the front the rear response is drooping above the dipole peak, both the front and rear patterns are usable through the dipole region and up to about 3kHz, where some breakup peaks start to appear. There is still some kind of 3dB tall resonance in the response at about 850Hz, and drivers without that feature would be preferable.

Compared to the smaller 3.5" driver this driver has higher voltage sensitivity and higher power handling. This means that the driver can be used relatively lower in frequency relative to the dipole peak, which increases the potential bandwidth as a dipole source. The broad dipole peak can easily be accommodated in the crossover network. This driver would be suitable for a dipole midrange between approximately 600HZ and 2.5kHz.

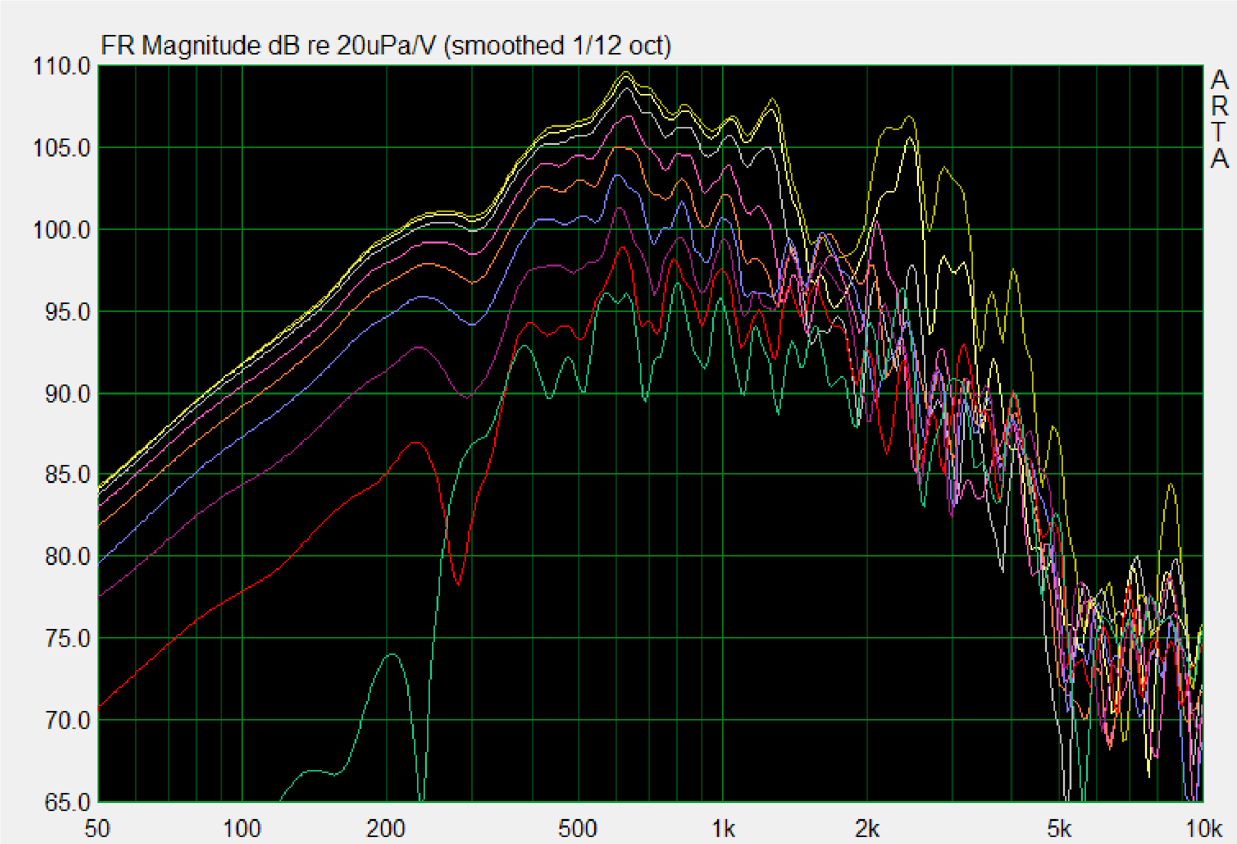
A LARGER DIAMETER DRIVER

A large (15" to 18") driver can make a great dipole woofer even when used nude. Here is an example of such a driver, measured from the front:



Compared to the smaller drivers the dipole peak is clearly MUCH broader and it is even difficult to determine where the dipole peak is located exactly. On and off axis responses track well and do not cross. At the same time the radiation pattern is narrowing well below 1kHz because of the large diameter of the cone. Still, the pattern stays intact to over 2kHz, which could almost make this usable in a 2-way system.

Looking at the rear radiation pattern (below) we can discern that the dipole peak is probably around 600Hz based on the drop (relative to the front pattern) in the response at that frequency. The rear pattern stays intact only to about 1.2kHz.



This driver happens to be a pro audio driver and has a high voltage sensitivity (>95dB SPL @ 1W, 1m). At the same time, the lower dipole peak frequency means that the low frequency dipole losses are not too bad until you reach about 100Hz. In combination with the high native sensitivity, little low frequency lift and response shaping are necessary. This driver would work well from 100Hz to 600Hz or even 800Hz. Remember, all of these measurements are without a baffle - the driver frame is hung by wires in free space.

DIPOLE TWEETER OPTIONS

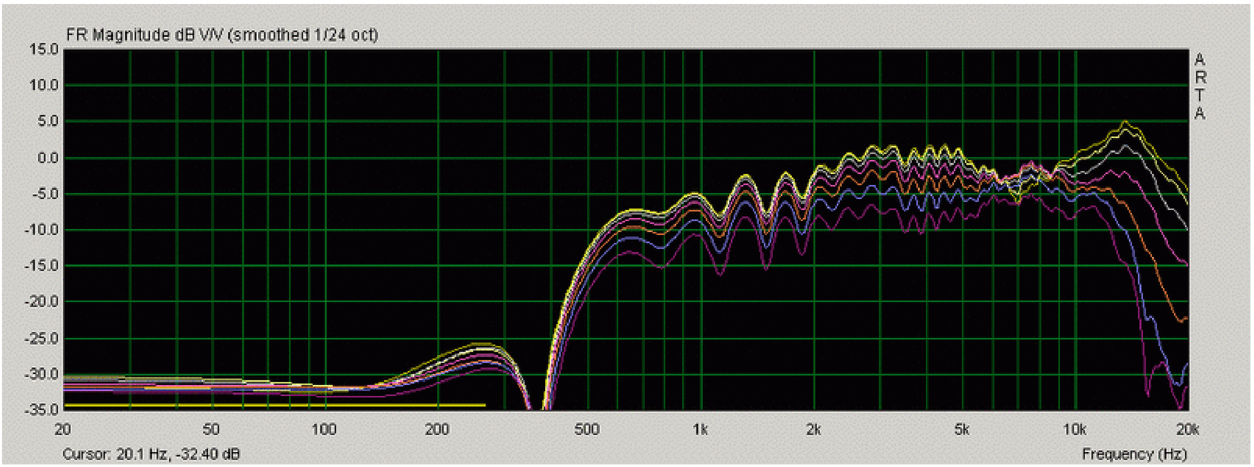
It looks like we can use the large pro driver as a woofer from 100-600Hz, and the 6" midwoofer from 600Hz – 2.5kHz. What remains to be found is a dipiole tweeter that can operate down to 2.5kHz.

RIBBONS:

Open-back ribbon tweeters are natural dipoles. They should be small in size to limit the pattern narrowing that occurs with larger surface diaphragms. They must be able to cross over around 2kHz-3kHz. Fitting these requirements are a couple of contenders:

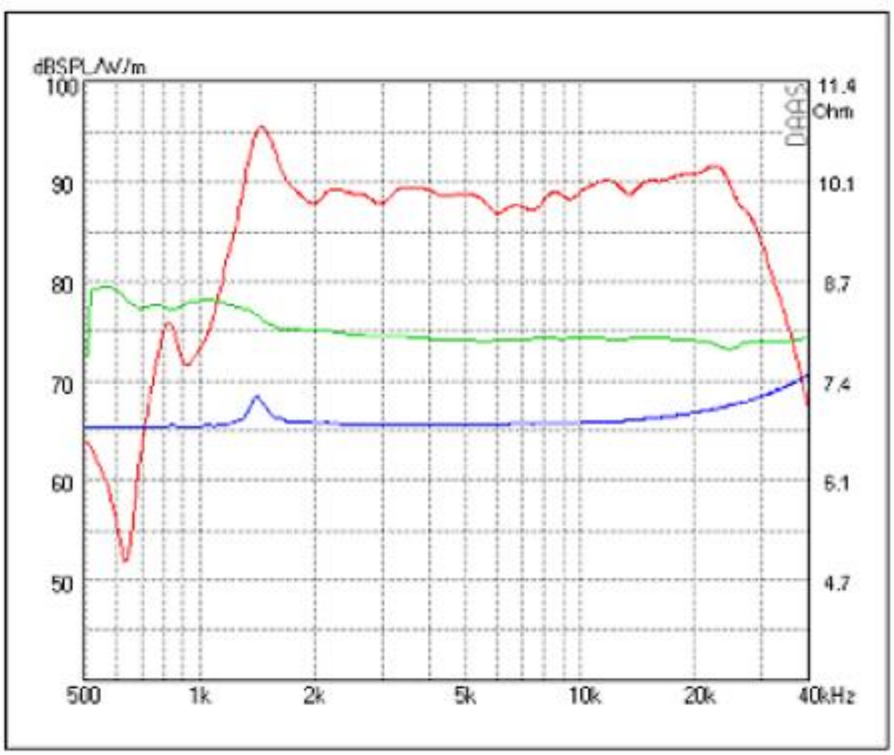
B&G Neo3-PDR:

I have not conducted measurements on this driver myself, however, I have seen front side measurements [https://www.diyaudio.com/forums/multi-way/142015-baffle-dipole-beyma-tpl-150-a-post1990640.html] that indicate this driver can be used down to 2kHz (or lower). The MFG suggests using 2kHz as the minimum crossover frequency for the driver. The Neo3PDR has been proven in other dipole loudspeaker systems as a good tweeter option.



Mundorf AMT23D1.1:

This AMT transducer has a passband that begins around 1.5kHz but the MFG claims that the crossover can be as low as 2.3kHz. The AMT23D1.1 has good power handling and reasonable sensitivity and might work well. The downside is that it is rather expensive.



BACK-TO-BACK DOME TWEETERS AS DIPOLE

I have seen several DIY efforts to use two compact dome tweeters, arranged back to back with the rear until operated out of phase with the front, to create a dipole. Most of these have not produced the desired response pattern. Primarily the problem is that the distance that two monopoles should be separated in order to act as a dipole to high frequencies (above 10kHz at least) is typically smaller than the physical dimensions of the tweeters themselves. When you place the two sources farther apart, the dipole peak occurs lower in frequency and then the pattern falls apart above that.

There might be some tricks that can be used. I suggested one recently: use two small (0.5”-0.75”) dome tweeters but instead of putting them back to back just put them next to each other, e.g. both facing up, with the “rear” tweeter running out of phase with the front one. The center of the domes must be placed as close together as possible so you need small, compact units without a faceplate. Another trick would be to roll off the rear tweeter at around the dipole peak frequency, however, you would need to take into account the fact that a low-pass filter has phase rotation, and it will likely wreck the dipole pattern. It might be possible to use an FIR filter to do it, since they allow phase and amplitude to be varied independently. That might be an avenue for some investigation.

I have personally done some experimenting with back-to-back tweeters and the results look promising, however, I am not quite ready to show my cards on that one until I redo my measurements. This might make for a good winter project, so I might try that in the near future.

DO WE REALLY NEED A DIPOLE TWEETER, OR DIPOLE RADIATION AT ALL?

My opinion is yes, as long as you do not need to sacrifice too much to get it. Loudspeaker building is all about balancing tradeoffs. My favorable opinion of dipole systems is based in part on extensive listening to a fully nude 3-way system I built in 2017. The listening space was relatively undecorated with mostly hard surfaces (wood floor, gypsum wall and ceiling) and a soft, large sofa. This system provided the largest soundstage I have ever experienced, and I did not need to sit in one spot to enjoy it. I could move about the room, even stand in between the loudspeakers, and the sound was still excellent. Both the loudspeakers and the room contributed to what I heard. I have listened to Linkwitz’s SL521 system a few times and was very pleased with the sound apart from some midbass bloom (which I think he intended).

If your listening space is over damped by furniture, wall to wall carpeting, and other adsorptive materials you may not achieve the same effect. Unlike other types of loudspeakers, the dipole is helped by reflections from the room. Dipole loudspeakers should be placed at least 1m away from walls (rear, side) and slightly more than this distance is better. Thus the dipole is best in a room of a certain size with a certain rom response character to sound best. Not everyone may have such a listening space at their disposal.

Regarding the tweeter as a dipole source: conversations I have had with other DIYers have suggested that above 5k-7kHz it is not as important to have the rear firing radiation and the pattern can shift to predominantly front firing monopole. But this must be done carefully, for example using an FIR filter on one of two closely spaced monopole tweeter sources operated as a dipole (see prior explanation).

WHAT ABOUT FREQUENCIES BELOW 100 HZ?

Once you get to low frequencies it's just not effective to use a nude driver, even a large one, to provide the necessary SPL. This is not only because the dipole source cancellation will be increasingly severe, but also because the inherent response of most woofer/subwoofer drivers will be drooping at low frequencies. The nude driver's near-resonance-frequency response is much like what you get in free-air, which is to say it has a low-Q, high-pass character. This combines with the 6dB/oct falling dipole response to create a strongly drooping low end and losses can be too high to make up even with high input power. I assume this may explain why dipole bass is thought of as "thin sounding" but the real cause might be more due to the designer not knowing what they are up against in terms of losses.

An approach that retains the dipole character but helps to increase the bass output is to make the front-to-back pathlength of the dipole larger. Luckily, at low frequencies the wavelengths are large and even relatively large baffles do not alter the dipole pattern significantly. The front-to-back pathlength can be increased by introducing a barrier between the two such as a planar baffle, but since the required baffle size for good low bass can be quite large, folding the barrier into a U- or H-frame is more practical. I prefer the H-frame because the front and rear line (tunnel) resonances are the same and can be largely EQd out. Also, when you constrain the air load next to the diaphragm more of it becomes part of the moving mass of the driver, and doing this on both sides of the cone increases this effect. The additional moving mass causes the driver's Qts to increase and Fs to drop, and both of these are desired effects. There will be some loss in sensitivity, but it is not large so long as the cross-section of the frame's "tunnel" is at least the same as, or larger than, the Sd of the cone. Dimensioning an H-frame has been described by me previously on the DIYaudio forum (see "Load That Bass" at this link: https://www.diyaudio.com/forums/multi-way/320815-multi-ob-post5389471.html).

SOME PRACTICAL CONSIDERATIONS

With all these drivers, each of them requiring response shaping and EQing of peaks, pulling off a good multi-way dipole system is a significant, if not daunting, challenge for a passive crossover. In addition, to flatten the dipole response a passive crossover can only attenuate the input power. This may result in a significant decrease in the system sensitivity of the loudspeaker. As a result, active analog and DSP crossovers are almost always a better approach and will let the user make the most from what the drivers can do. Of course this requires several channels of amplification, however, the situation is not so dire. A 3-way nude system plus a central large H-frame dipole subwoofer can be run from a 7-channel home theater amplifier, and these are relatively common. DSP-DACs can be found with at least 8 channels of output, or two 4-channel DSP-DAC units can be used.

Recall that the dipole peak is +6dB in SPL (on axis) compared to a monopole. When a driver can be used primarily around its dipole peak level (e.g. by restricting its passband), the higher will be its average sensitivity. This is another motivation for using a 3 or 4 or more way dipole system with drivers of increasing diameter, to stagger the location of the dipole peaks across the audio band with the top several octaves handled by a dipole tweeter. For the lowest frequencies, a large folded dipole such as an H-frame can provide sufficient low frequency output and will still provide dipole pattern.