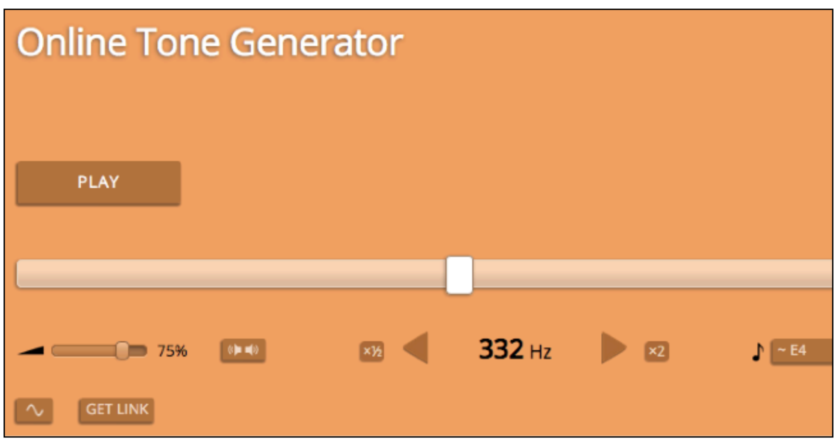
Headphone Essentials 4:

The Skinny on Headphone Frequency Response Graphs

Note: this document is part of a instructional series. If you would like to start with more foundational material on the nature of sound, see *Basics of Musical Sound* and *Basics of Headphone Sound* at Headphone Essentials.

If you are reading this document, you are likely interested in finding a headphone that matches your listening preferences. The single most important factor is the headphone's frequency response (FR). This is often called its tuning or tonality. Other factors, such as its dynamic responsiveness, sound staging, imaging and detail reproduction are also important considerations. But if the tuning is not agreeable those other factors are not likely to rescue it.

Getting started



To get started go to the Online Tone Generator in your browser. Make sure the volume on your computer is initially set to a fairly low level, then press the space bar once to turn sound on, then move the slider fairly slowly and evenly left and right. If the sound does not change in loudness you're hearing what's called a flat response. If it grows louder and softer as you move the slider, that's a non-flat response. If possible, you may want to try this with more than one headphone or speaker to see how they vary (remembering to start at a low loudness level with each one). (By the way, as is typical of tiny speakers, the one built into my laptop doesn't produce any sound at all to the left of about 100 Hertz.)

Now let's say we want to make note of what we're hearing when sound is being produced by a particular pair of headphones. Let's say we start at the far left and hear nothing until maybe 22 Hertz. Then we hear it gradually getting louder until 67 Hertz, then quickly getting quieter until 83 Hz, then starting to climbing again. We might draw a line like so to represent this:

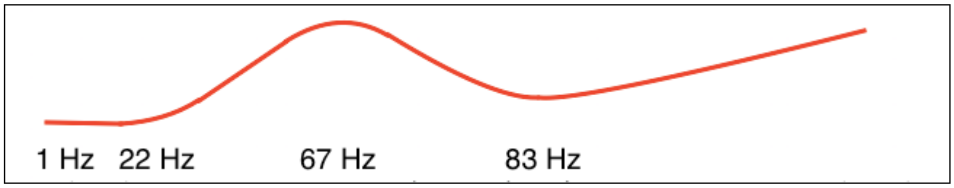


Fig. 1: freehand loudness line

What we're intuitively doing is recording the Hertz numbers from left to right, just as they appear when we move the slider from left to right. Plus, we're showing the change in loudness as an up and down movement. And that's all there is to a frequency response graph:

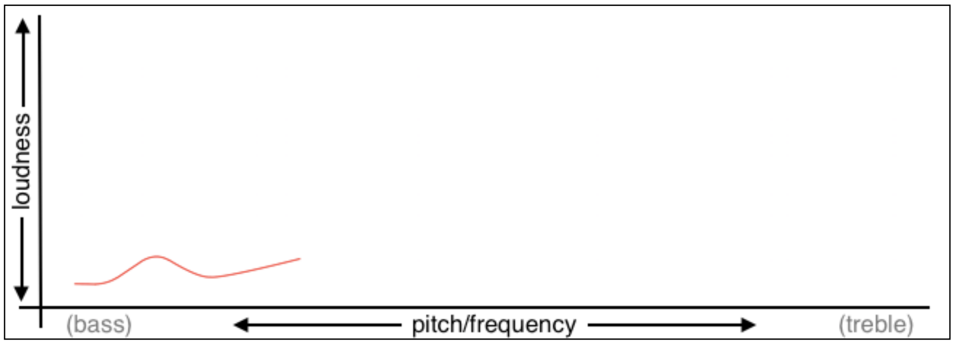


Fig. 2: frequency response graph axes

We can see that if we want to record the actual Hertz numbers we would need a very long graph from left to right, since the Hertz numbers go from 1 to 20,154. The math trick to deal with that is to use a logarithmic scale. This simply means the distance keeps getting shorter as the numbers keep getting larger:

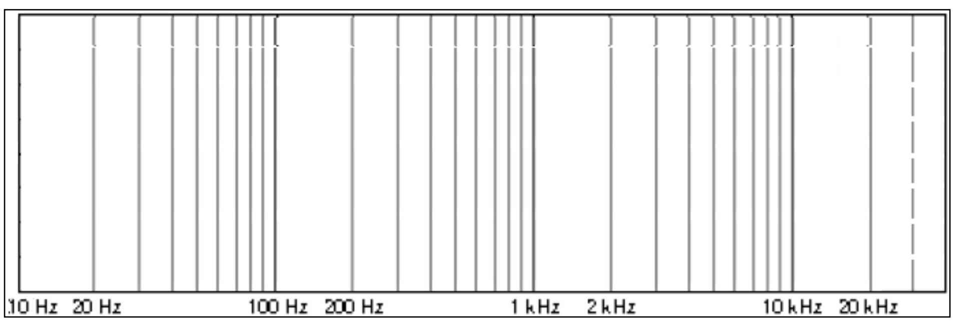


Fig. 3: frequency response graph with logarithmic Hertz scale

Fig. 3 has a logarithmic scale from left to right. From 10 to 100 there are guide lines on the tens. From 100 to 1000 they're on the hundreds. From 1000 to 20,000 they're on the thousands. Notice that for convenience we use the kHz notation to get rid of the increasingly large number of zeros, so 1 kHz = 1000 Hz. The scale concentrates on the range of 20 to 20,000 Hz since this is the range of human hearing. (Keep in mind that the highest frequency you can hear decreases gradually with age. So 20,000 Hz is highly optimistic.) Also notice that the distance between 10 Hz and 100 Hz is exactly the same as the distance between 100 Hz and 1000 Hz. And both are exactly the same as the distance between 1000 Hz and 10,000 Hz.

That takes care of the left/right scale. For up/down we can use logarithms again. But the units we need for loudness are notated as dB, which stands for decibels:

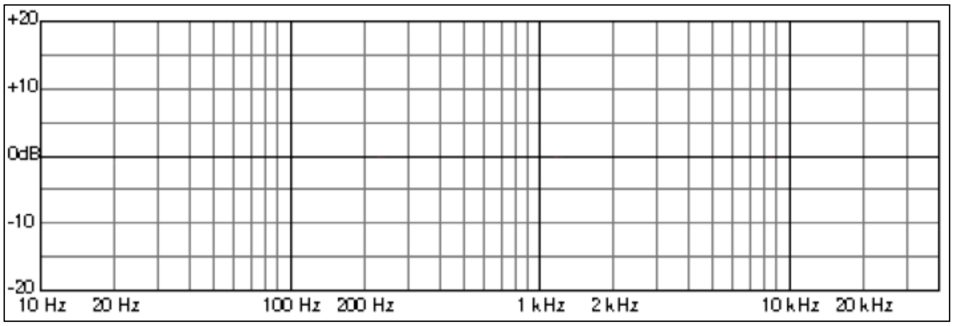


Fig. 4: FR graph with decibel loudness scale

In this case, any 10 decibel change indicates a doubling of loudness. And 1 decibel is about as fine a discrimination as we humans can reliably make. This might seem like an improvement until we actually try to use it. We can get frequency numbers from the Online Tone Generator. But how do we judge how high or low to place each loudness measurement?

Measurements done right

For this we need some fancy, technical, and expensive measuring equipment ($20,000+ is not uncommon) to achieve reliable results. Fortunately, there are several good samaritans doing such measurements and posting them on the web. One example is crinacle.com. Here's the Crinacle measurement for the still-popular Audio-Technica ATH-M50x headphone:

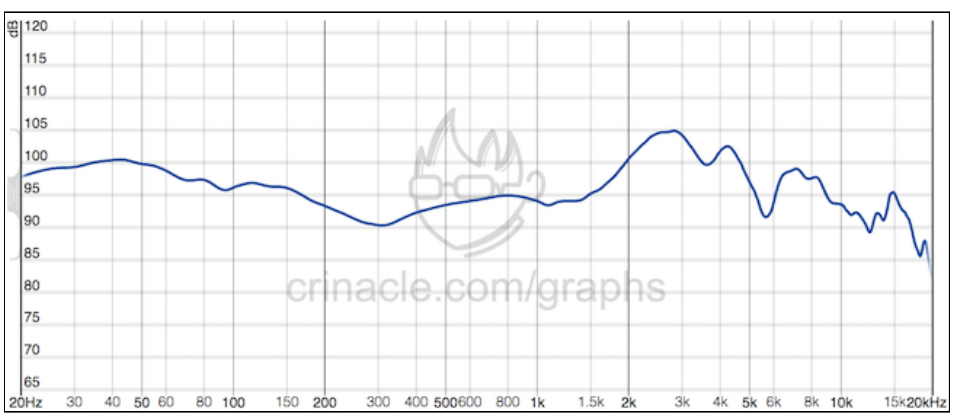


Fig. 5: Crinacle FR graph for Audio-Technica ATH-M50x (done with an earlier measurement rig)

Unfortunately, there's a slight gotcha. The blue line shows changes in loudness going across the human hearing range of frequencies. But, since it shows actual measurements, the line is much more of a jagged rollercoaster ride than your ears would lead you to believe. Also, our ears and brains are designed to hear the faintest possible sounds that are critical for survival.

The peculiar shape of our ears are in fact natural amplifiers for high frequency sounds. Here are the results of a fairly recent study:

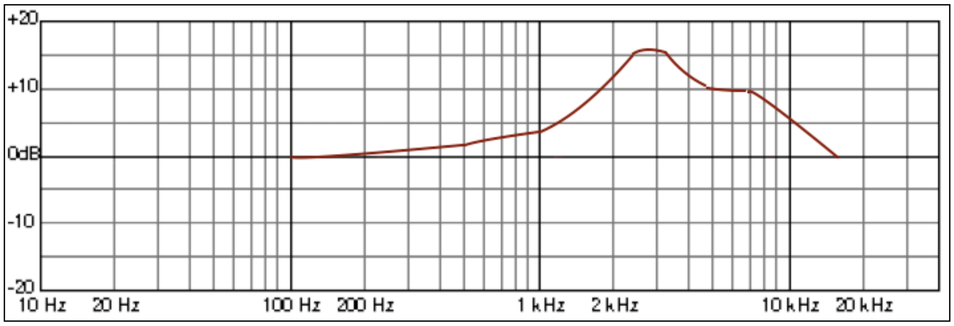


Fig. 6: Hammershøi and Møller, ear amplification in a diffuse sound field, 2008

In theory a headphone that exactly re-produced this measurement curve would produce a perfectly even, or flat-line, sound if we used it to listen to the Online Tone Generator. In other words, our brains translate the curve shown in Fig. 6 into the subjective "curve" shown in Fig. 7:

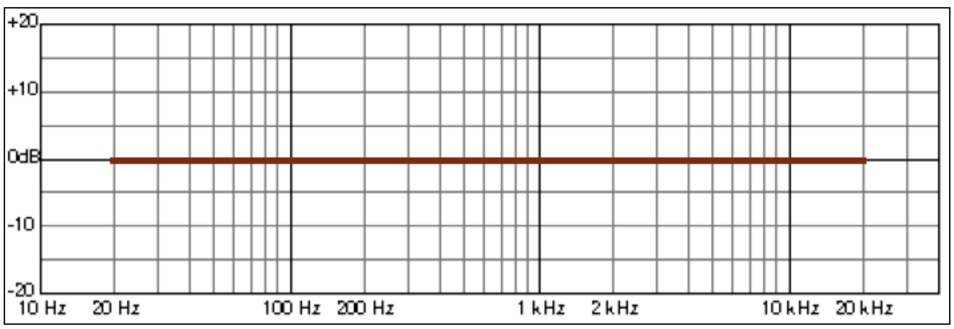


Fig. 7: subjective experience of a perfectly even loudness across the frequency range

If we overlay the H & M ear amplification curve from Fig. 6 onto the M50x measurements of Fig. 5 we get:

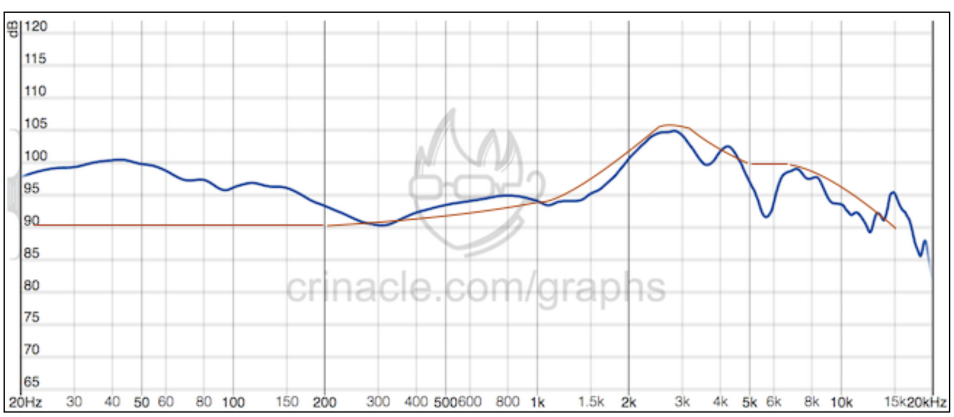


Fig. 8: ear amplification (red) vs M50x frequency response (blue)

The sheer number of ups and downs in Fig. 8 may look like a problem. But it's actually about average for today's headphones (especially if they're a closed-back design like this one is). Our ears can't easily distinguish small up/down changes, and manufacturers simply don't have the technology to do better.

What we should hear if we use a pair of M50x to listen to the Online Tone Generator is an increase in loudness where the blue line climbs above the red line. Plus, we should hear a decrease in loudness wherever the blue line drops below the red line. And that's pretty much what I do hear when I do that. (Except I don't hear the rise above the red line on the left side of the graph from 20 to 250 Hz being nearly as prominent as shown.) From there on I do hear the rises and dips shown.

Another source, especially for measurements of lower-priced headphones, is Rtings.com. Here's their measurement presentation for the M50x:

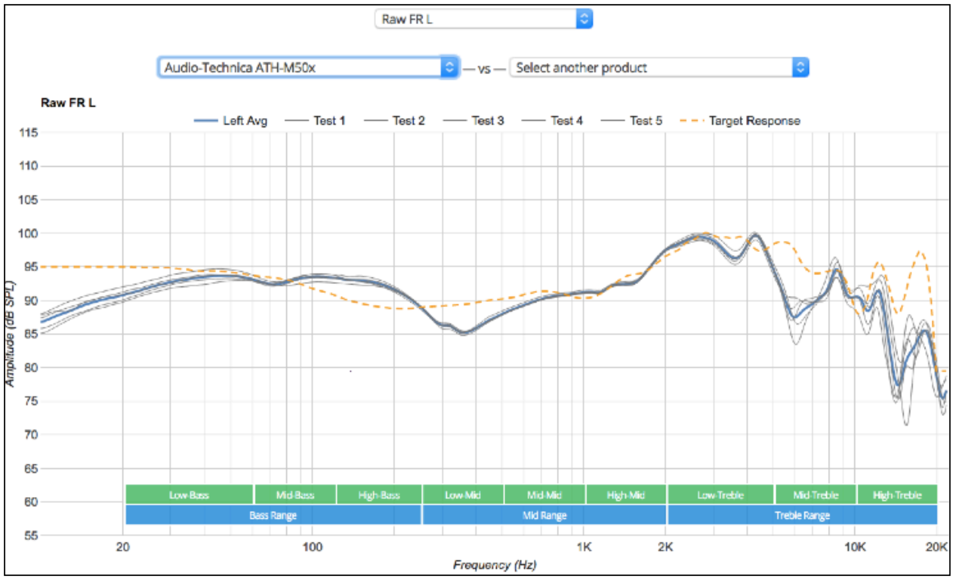


Fig. 9: Rtings.com measurements for M50x
(source: https://www.rtings.com/headphones/1-4/graph#295/4011)

One difference is that Rtings show measurements between 10 and 20 Hz on the far left. Mostly, we would perceive these as vibrations rather than sound. Another difference is the dotted orange line. This is their version of a common reference for an ideal headphone sound response as adapted for their measuring equipment.

A third site with a large collection of excellent measurements is Oracle1990's reddit page. This site focuses on headphone equalization, which is beyond the scope of this tutorial. But the measurements we want are on the top left of each headphone page, see Fig. 10 below. In Fig. 10 the frequency response is the orange line. The broad green line is a well-known headphone reference curve called the Harman Target.

Two other sites have significant collections of quality raw FR measurements: SoundStage!Solo, Headphonetestlab. Also Resolve Reviews has recently (as I write this) started doing measurements which can be found scattered about the forum of headphones.com.

Finally, there is an older site, sadly now defunct but happily available on Archive.org, InnerFidelity.com. This site has an extensive collection of headphone measurements that look as shown in Fig. 11, plus many other invaluable resources. Again, the FR graph is upper left. But confusingly it contains two sets of lines. The lower, grey lines are multiple trials of measurements for the M50x with the headphone moved slightly for each one. (Rtings, Crinacle and Oratory1990 use the same multiple-trial procedure, only showing the average of the trials.) But the red line above the grey lines is a modification of the grey lines. It adjusts for the properties of the measurement equipment by comparing them to a now-obsolete reference. Simply ignore the red line.

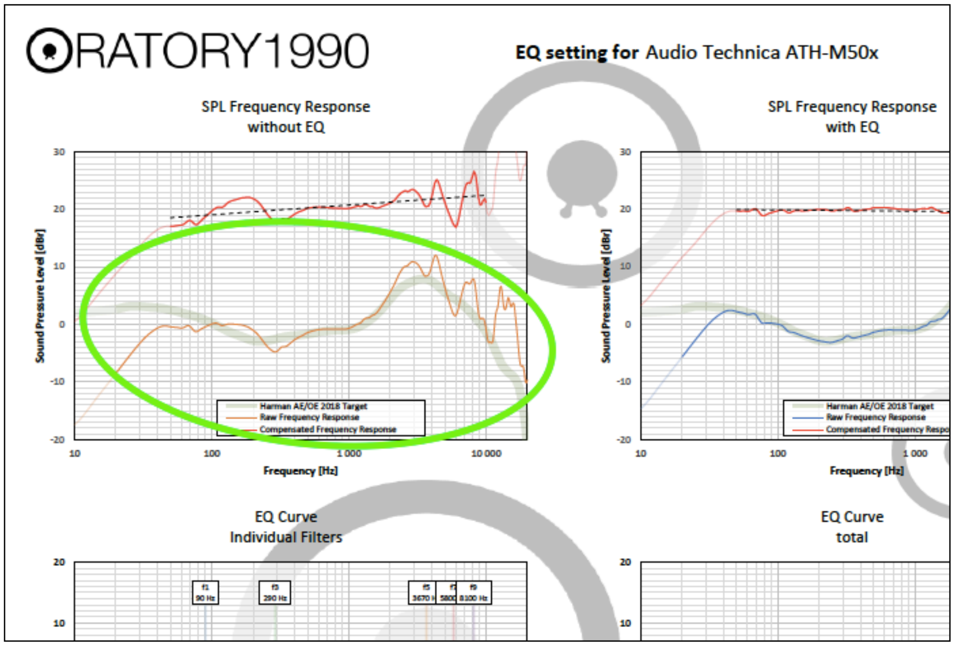


Fig. 10: Oratory1990 page for M50x with FR graph circled in green

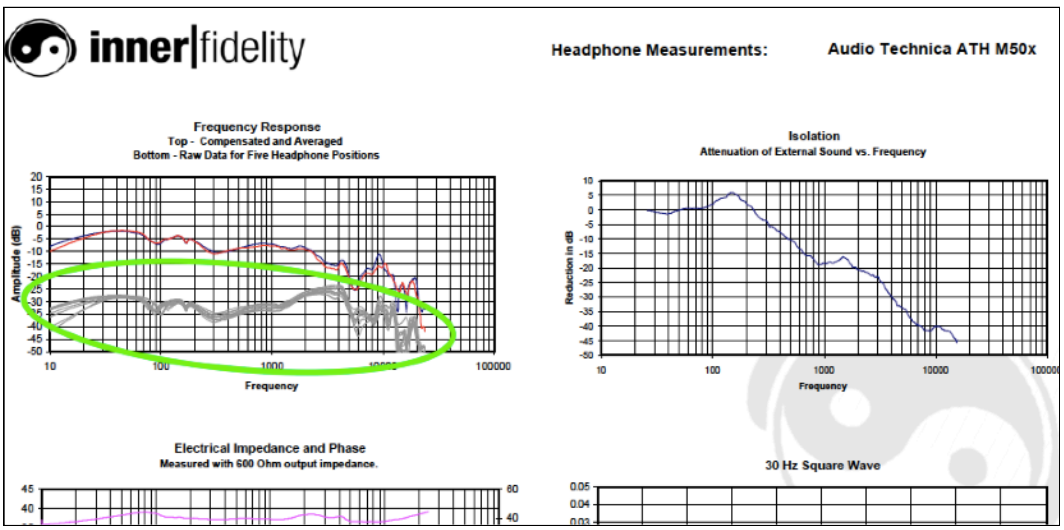


Fig. 11: innerfidelity.com measurement page for M50x, FR graph circled in green

Oratory1990, Crinacle, Brent Butterworth of SoundStage!Solo, Keith Howard of HeadphoneTestLab and Resolve Reviews are using some permutation of the well-regarded and expensive GRAS43 measurement rig. This uses a carefully molded simulacrum of a human ear, including the ear canal. While Rtings and InnerFidelity use an older HeadAcoustics set-up with a molded outer ear but a straight cylinder ear canal.

The GRAS ears are notable for more accurately representing what a hypothetically *average* human ear would hear, based on an international standard. Yet look at a half dozen different people's outer ears to see just how far we all depart from the norm, and ear canals vary as well. So the best measurements are the ones that most closely match the total acoustic signature of your own ear anatomy. A straight cylinder may not look like a human ear canal, but it may result in measurements that come closer to matching your ear than the GRAS ear does. The only way you can make that determination involves some considerations that will be discussed in later documents in this series.

Until then, measurements from the other sites are still plenty useful. Often measurements of a particular headphone won't be available on any site, let alone on the site you prefer. The trick is to only compare the measurements on a given site to the other measurements on that site.

Measurements done less right

The above are competent and useful sources of information. Far more often, however, you'll encounter measurement graphs done by amateurs using inexpensive equipment.

Here's Oratory1990's measurements for the recent AKG K371:

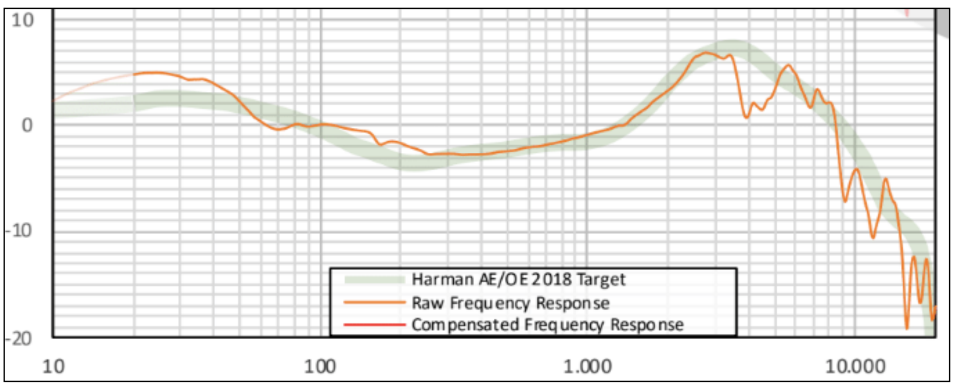


Fig. 12: Oratory1990 FR graph for AKG K371

This headphone was designed to reproduce the Harman Target frequency response as closely as possible. As we can see it does so admirably. Now here is an amateur measurement of the K371 I found by using Google:

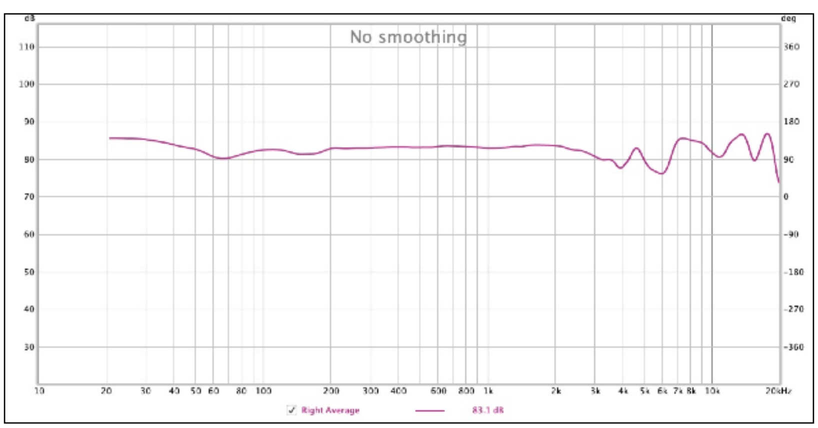


Fig. 13: MiniDSP EARs frequency response graph for AKG-K371

This was done using an inexpensive and popular tool called the MiniDSP EARs. We may scratch our heads as to how to relate the purple line in Fig. 13 to the orange line in Fig. 12.

They both claim to show the frequency response of the same model headphone. The first thing we need to know is that we're not seeing the actual data in Fig. 13. What we're seeing is a plot of the *difference* between the actual measurements and some unspecified reference curve. And reference curves vary all over the proverbial map. The graphs we've been looking at previously were what's called raw or uncompensated. Fig. 13 is called a *compensated* FR graph. Yet it makes no mention of that fact, nor of what reference its compensated to.

Understanding compensated frequency response graphs

Let's start with a frequency response graph including measurements and a target curve like this one by Oratory1990 of the Audeze LCD-1:

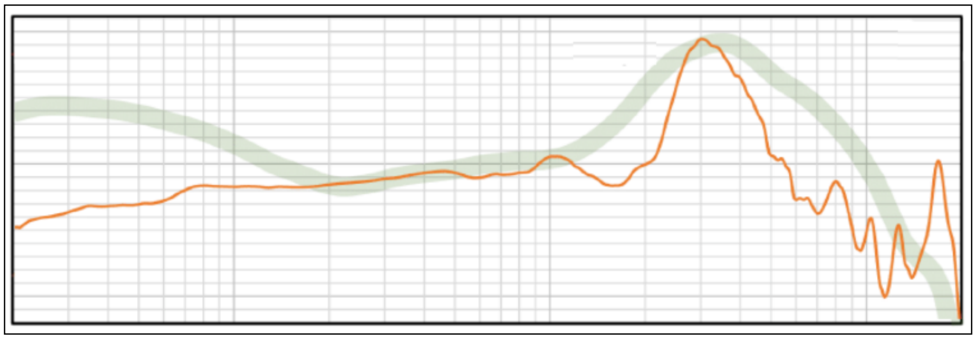


Fig. 14a: Audeze LCD-1

Now that you've dived down the frequency response rabbit hole the odd and squiggly lines make perfect sense. But for anyone else the graph is meaningless, not to mention put-off-ish as well.

First, we'd have to explain that left to right means low-pitched to high-pitched sounds and top to bottom means loud to quiet sounds. Then we'd have to say that the orange line shows how this particular headphone changes the loudness of the sounds being listened to, making sounds at some frequencies louder than they actually were and making other frequencies quieter than they actually were. Then we'd have to explain that the human brain actually expects some frequencies to be louder than others, which is represented by the green line. So we're supposed to pay attention to the differences between the green and orange lines.

The green line is supposed to show how much physical loudness (sound pressure) it takes for our brains to perceive subjectively equal loudness. We can make this a little easier to digest if we flatten out the green line and have the orange line tag along for the ride. In other words imagine the green line is a string and we pull the string taut so the green line goes from wavy to straight. In Fig. 14b I used my limited Photoshop abilities to warp Fig. 14a until the green Harman curve is more or less straight. Now the orange line is compensated:

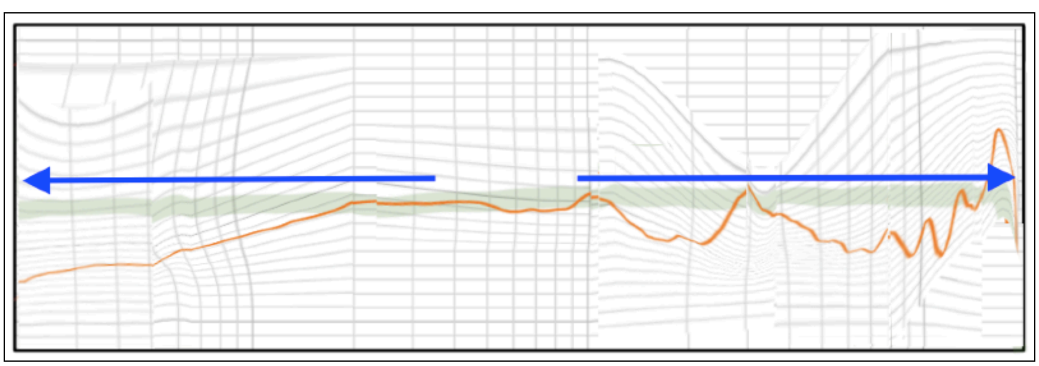


Fig. 14b: Audeze LCD-1 graph morphed to straighten the Harman curve

Now let’s return to my scathing critique how compensated graphs are typically used.

The MiniDSP EARs tool comes with two different reference curves. One, called HPN (headphone neutral), is somewhat similar to the diffuse field curve. The other, called HEQ (headphone equalization), is somewhat similar to the Harman Target. Given the relative flatness of Fig. 13 (back on page 7) we can make an educated guess that the HEQ curve was used. But that information is rarely provided. In Fig. 12, looking from left to right, we see three obvious discrepancies between the Harman Target and Oratory1990’s measurements of the K371. There is a rise from 20 to 50 Hz, a smaller rise from 100 to 250 Hz and the dramatic dip from 3.5 to 5.5 kHz. Looking at Fig. 13, only the first of these shows up. From 100 to 250 Hz we see nothing but a slight dip. From 3.5 to 5.5 kHz we see a gentler dip, rise, dip.

Here’s another MiniDSP EARs graph of the K371:

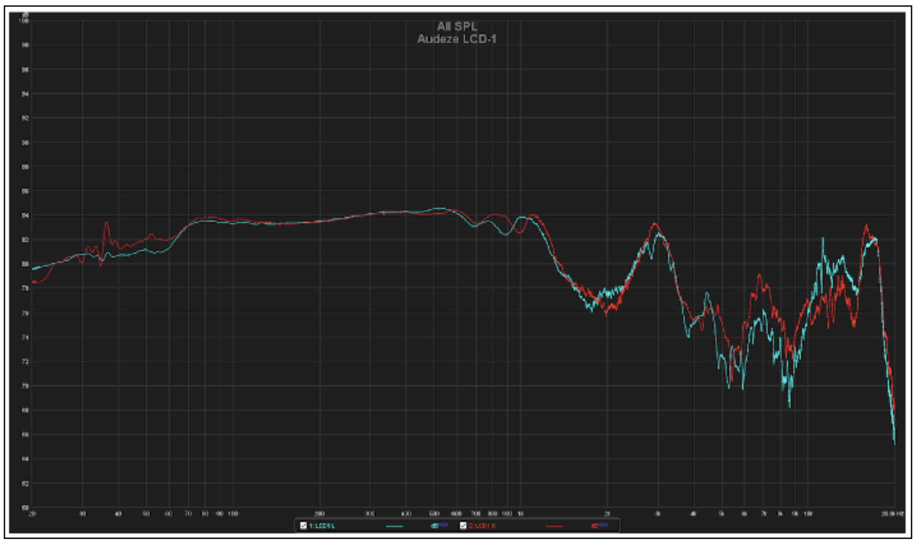


Fig. 15: Metal571 MiniDSP EARs FR graph for AKG-K371

This one was done by YouTube headphone reviewer Metal571. Metal is a careful and thoughtful guy. He makes sure to tell us that the MiniDSP EARs graphs are seriously limited (especially in the region around 4.5 kHz). He also makes sure to tell us that he’s using the HPN compensation. (Don’t be confused by the dramatic black background. That’s purely cosmetic.) The overall downward slope of the measurement curve is due to the increasing difference between the diffuse field curve and the Harman Target curve in the ear amplification area above 1 kHz.

But another major difference between Fig. 13 and Fig. 14 is the vertical scale. In Fig. 13 each horizontal reference line is 10 dB above or below the next. In Fig. 13 they’re only 2 dB apart. In consequence, Fig. 13 tends to downplay the rises and falls of the measurement curve. Fig. 14 highly exaggerates them.

This scaling effect can be used to great effect to put a headphone in a good light. The headphone forum head-fi.com occasionally produces FR graphs of headphones released by sponsoring companies. The head-fi measurement equipment is the same as Oratory1990’s can buy and they know how to use it. Accuracy is not at issue.

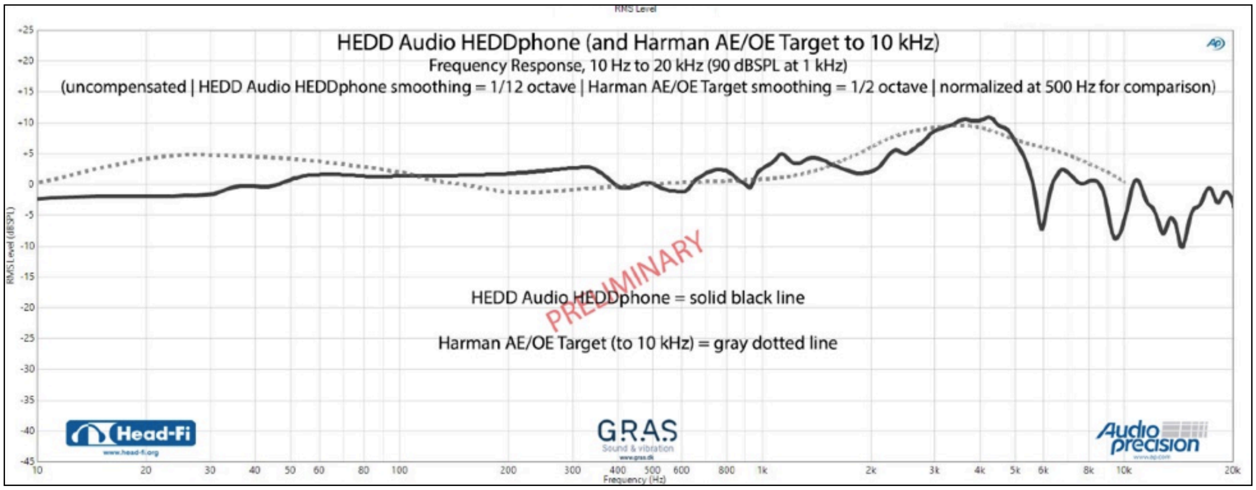


Fig. 16a: Head-fi measurements for the HEDDphone

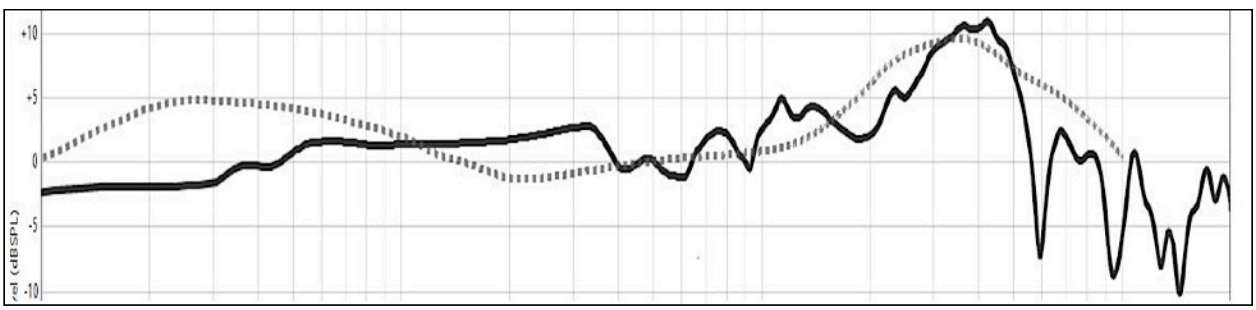


Fig. 16b: Fig. 16a re-scaled

The graph in Fig. 16a is directly from the head-fi website. This particular headphone currently sells for $1900US. The solid black line are the raw measurement data. The dotted black line is the Harman Target. Notice how shallow the Harman curve is compared to what we're used to from the green line version in Oratory1990 graphs. For the graph in Fig. 16b I've simply taken the original graph and stretched it vertically so the horizontal reference lines are now a more typical distance apart. The dotted Harman Target curve now looks familiar. Same data, dramatically different presentation. Another example of vertically compressed presentation is the MiniDSP EARs graph in Fig. 13, while Fig. 15 is just the opposite.

The small print in the Head-Fi graph legend says the data are presented with 1/12th octave smoothing. This was frequently done. It simply acknowledged the limitations of even the best measuring equipment and measuring techniques of the not too distant past. Applying it to GRAS results is less appropriate. However, from time to time you'll see FR graphs with much smoother measurement curves, even as extreme as 1/3rd octave. When the graph line looks smooth and simple, be suspicious that more aggressive smoothing has been done.

In short, it's the wild west out there in the land of headphone FR measurements. We have to be wary of:

- Amateur-grade test equipment
- Unspecified compensation curves applied to the data
- Loudness scale compression applied to the data
- Excessive smoothing applied to the data.

Do even good measurements agree?

Even if we choose to focus our attention on the three or four quality measurement sites for frequency response graphs that doesn't mean their results are completely interchangeable.

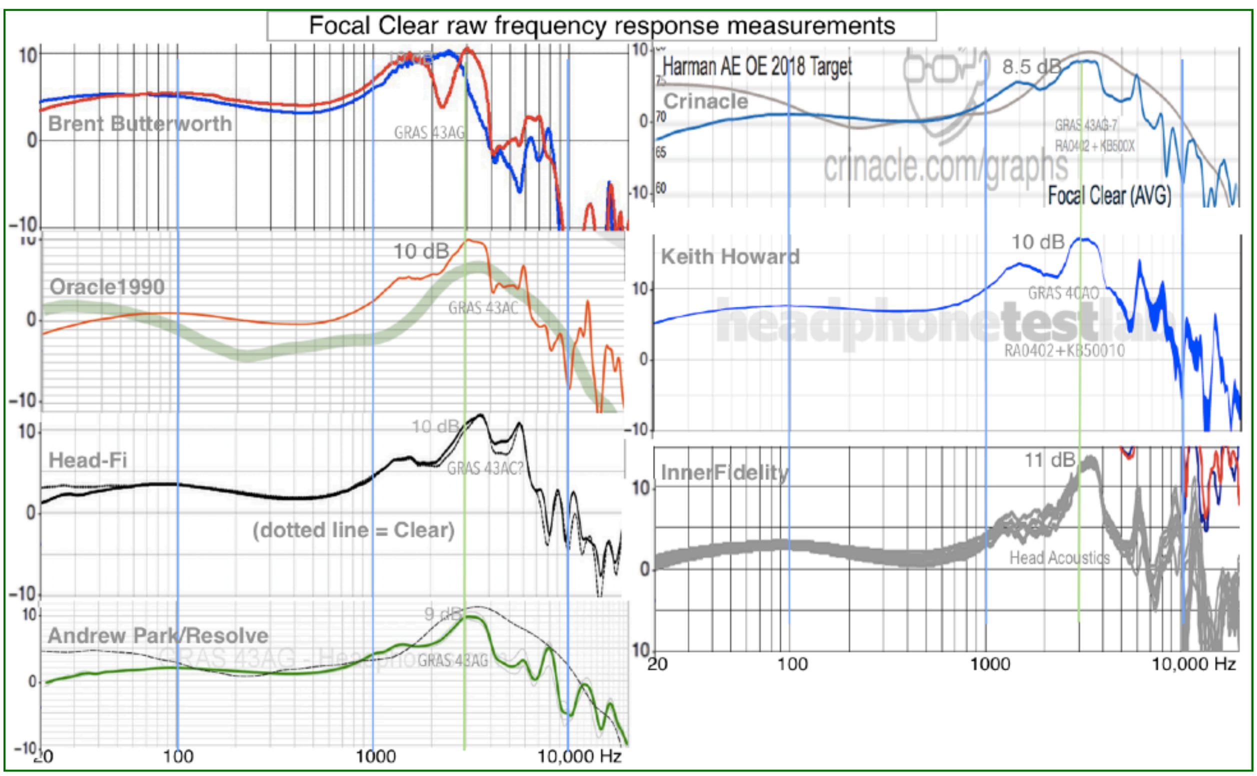


Fig. 17: seven-way comparison of raw measurements of the Focal Clear headphone, all scaled identically

In Fig. 17 we see a lot of agreement but also some disagreement. There will often be disagreement in the very lowest frequencies. This is due to the difficulties getting the ear pads to rest completely on the side of the measurement head surrounding the artificial ear with no air gaps. Equally, there are disagreements in the high frequencies above 2 kHz. This is at least in part due to differences in the artificial ear canal's properties between the six GRAS measurement ear and InnerFidelity's straight cylinder ear canal.

But another factor is unit-to-unit product variation. Suppose you buy three units of exactly the same headphone that you find right beside each other on a store's shelves. Suppose you then sent them to one of the review sites asking for measurements. Experience shows there would be measurable differences between the three units. The amount of difference tends to vary from manufacturer to manufacturer. Sennheiser has a reputation for minimal variation, for example. So when we look at Fig. 17 we have no idea how much of the discrepancies between the first six of the measurement curves is due to the test equipment being used and how much is due to unit-to-unit differences.

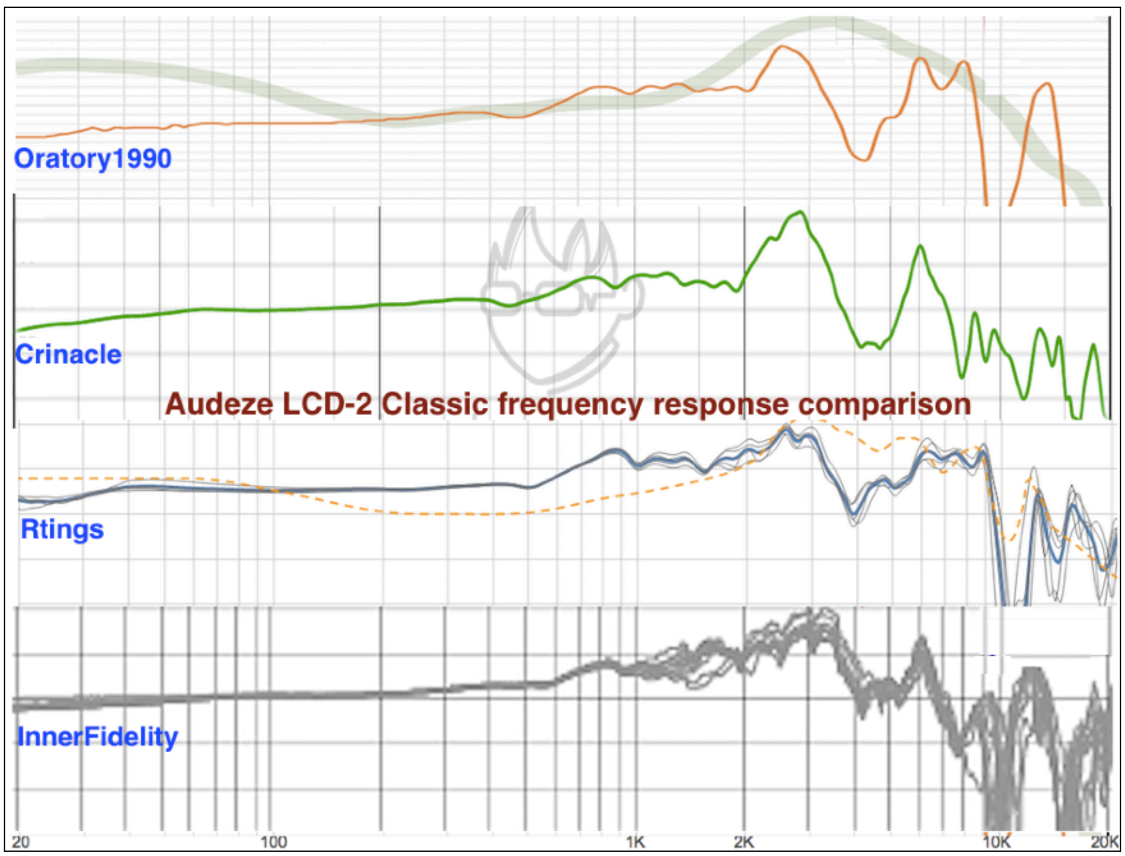


Fig. 18: four-way comparison of measurements of the Audeze LCD-2 Classic

Yet another factor is what we call silent revisions. Manufacturers occasionally change internal components or assembly procedures over time in the production of a particular headphone model. A common scenario is for a manufacturer to experience a significant number of returns after releasing a new model headphone. The manufacturer will investigate what the failure was then fix the problem, if possible, in the production of that model going forward. (It's always wise to hold off for several months on purchasing an exciting but brand new product.)

Silent revisions, however, can occur at any point in a product's life cycle. Just one cause is a component supplier going out of business. So any difference between an Oratory1990 vs Crinacle vs Rtings, etc. measurements may be due to actual differences in the sample of the headphone model being tested.

Note: It's easiest to see in the InnerFidelity graphs but also present in the Rtings graphs in Fig. 18. A responsible headphone measurer takes **multiple readings** of the same over-ear headphone, shifting its position around the measurement head's ears in each case. If you have a pair of over-ear headphones on your head and shift them up, down, right, left, etc. you're actually changing the frequency response by varying (small) amounts at each frequency.

There is no one right position. Indeed, you may prefer to pull a particular headphone forward on your head, for example, if you notice that gives you a wider sound stage experience. Someone else may do the opposite for the same reason. If a single line is shown on a graph, it's typically the average of the multiple measurement readings.

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And that's it. You're now far more knowledgeable about headphone frequency response graphs than 90% of the Internet's self-appointed expert forum commentators.

In this episode we looked at what the frequency response of headphones actually looks like when properly presented, why they sometimes don't and how much they can be trusted even when no trickiness is involved.

So now be sure to proceed on to the next exciting instalment in my must-read Headphone Essentials series: *HE-5 The whole flat/neutral/Harman headphone thing* (http://daystarvisions.com/Music/index.html). In that episode we'll delve into what headphones *ought* to sound like but don't.