Audibility of Group Delay for Sound System Design
Part 1 of ? on Group Delay

Or

"I do not think it means what you think it means."

By

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Introduction

When I do these speaker/sound system design write-ups some of the most difficult choices I have are where to start and stop. Loudspeaker and sound system design is complex, requiring juggling many competing factors. Many times a design choice will have to be made that result in improvements in one area and a degradation of objective performance in another section. The really skilled designers juggle these choices well enough that the degradation of objective performance is minimized subjectively.

This time I'm going to talk about group delay. This is probably one of the least understood topics in audio design. It's also a hotly debated topic…if you search the Audio Engineering Society Journal articles you get 1000 results, for perspective, the term "bass reflex" gets 274 results.

For this article I'm going to attempt a simplified discussion of Group Delay and audibility.

Now, for those of you with a background in signal processing that understand the relationship between frequency response magnitude, phase and group delay at a very detailed mathematical level, you might go into some convulsions with some of what I write. To be completely fair, these mathematical relationships make sense to engineers and physicists who deal with them on a regular basis, but I can't exactly throw the equation…

$$\tau_g(\omega) = -\frac{d\emptyset(\omega)}{d\omega}$$

…and expect that many folks to follow along. Even when as I was doing the research for this one I found myself going down some rabbit holes of surrounding topics, eventually ending up at the Heyser AES papers which, I believe, I'll fully understand one of these days[1]. The math is hard; the implications can be complicated…but the measurement itself can be very useful.

What is it?

Simply put, group delay is a measurement of time distortion in a system. More specifically, group delay is the delay of the envelope of the sinusoid at that frequency; phase delay is the delay of the sine wave itself. I could go into detailed drawings and diagrams explaining the difference. For this writeup, who the @#$! cares, we just want to know what a good number is vs. bad for our systems.

Warning, nerd alert time.

[1] Liar liar, my pants are on fire.

As if the equation above wasn't nerdy enough.

The good news is, that the literature from the AES and others I reviewed is plentiful. The bad news is…the answer is complicated. Like really complicated. Like really really complicated.

It's also probably not as well researched at low frequencies as I would like…and I don't think I'm alone in that opinion. The answers the researchers have gotten have varied and testing is complicated because a large number of things that impact the results…were the test subjects trained or untrained listeners, were special test signals employed or was it music, were the tests done with headphones, a dead acoustic space or reverberant room? All of these will wildly impact the results. A subtler issue is the exact question the test subjects were asked…things like "can you tell a difference between A and B?" or "Which sounds better, A or B?" may not seem like that big of a deal…but in subjective testing the exact question asked is huge.

I concentrated my literature review on testing concentrated around detection of group delay. Most of the papers used special test signals (clicks and pops or other impulse type sounds) although some of them included white noise.

These numbers represent the findings of the limits of detection, not a level of subjective objection. The authors of most of the papers are super clear on this. After reading these papers I'll go so far as to say…in use with actual music in a typical room even highly trained listeners have no hope of detecting issues let alone finding them objectionable at the group delay limits found in the literature. They represent an excellent real world goal for our complete systems.

This may be the most critical take-away, so I'll say it again:

- The papers concentrated on DETECTION, not if it was good or bad. I've listened to some of the sample waveforms and created my own in the past. Some of these differences with the special impulse type test signals are SUPER SUBTLE. Can a difference be heard reliably? Yes. If anything else is audibly happening in the background can a difference be heard reliably at the same group delay error…nope.

So what do those limits from all the papers I read look like? Well…if I plot them all on the same graph it looks like this:

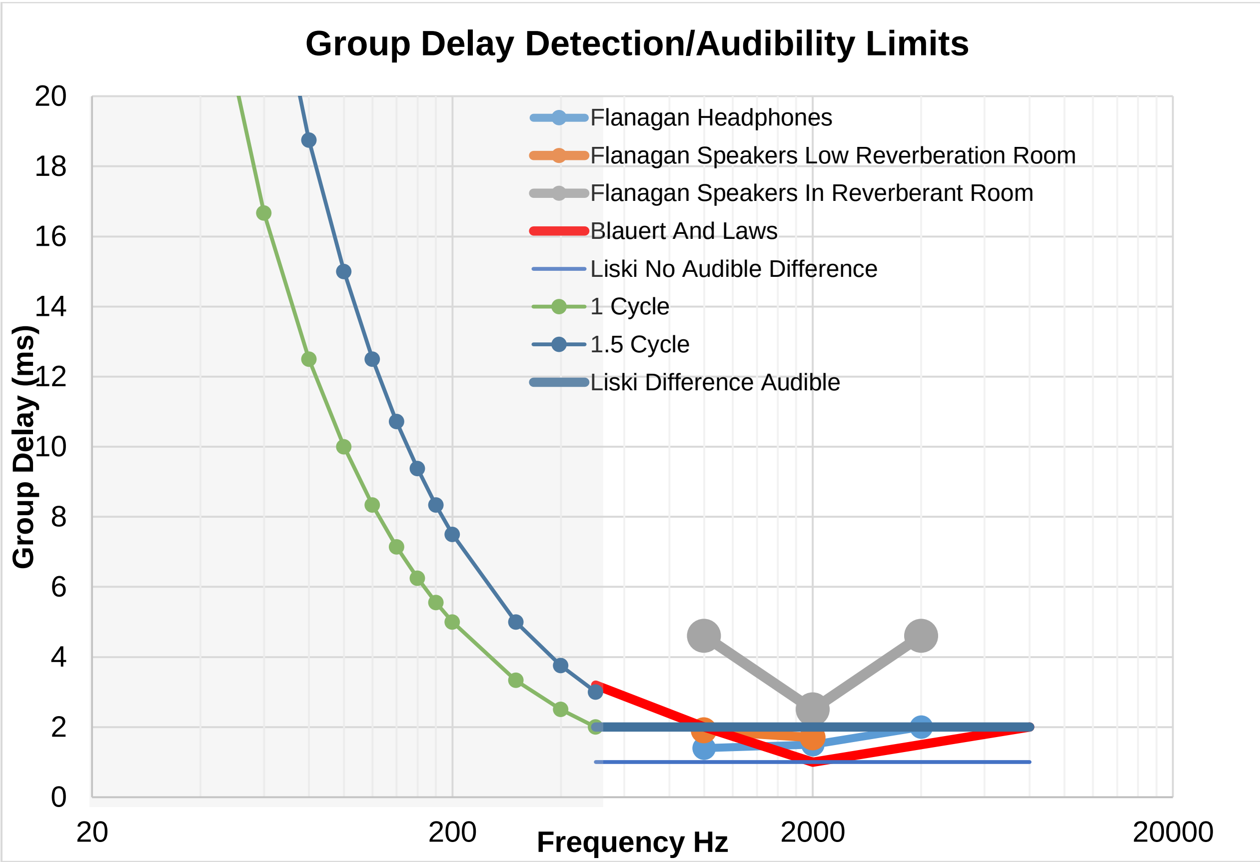

Figure 1 Group Delay Audibility Limits

Now…this is a lot of data. The three main studies I plotted were Blauert and Laws, Flannigan and Liski. These range from the mid 70's to not that long ago. Additionally, I plotted some "rules of thumb" curves for frequencies below 500Hz. In many places you read where group delay under 1 cycle or 1.5 cycles at bass frequencies is not objectionable. Notice that the 500Hz data for the 1/1.5 cycle seems to tie nicely into the study limits. I shaded that section since these are rules of thumb vs. well defined results in peer reviewed journals.

The real question is, how does this compare against real world systems?

First I plotted the group delay for an idealized 3 way bass reflex speaker using 4'th order Linkwitz-Riley acoustical slopes and a 4'th order bass rolloff at 40Hz.

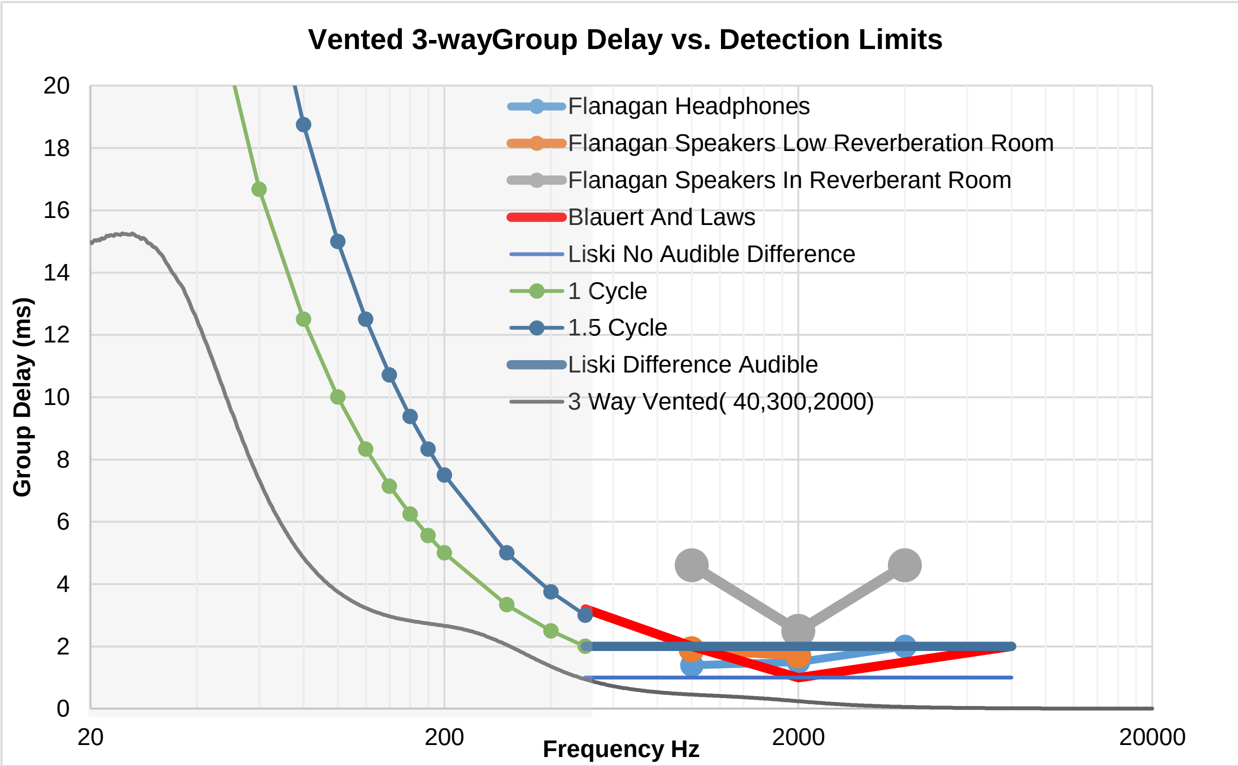

Figure 2 Group Delay 3 Way Vented, 40Hz F3, 300Hz and 2kHz Crossover Frequencies

Notice in Figure 2 that the group delay around 300Hz, the midrange crossover frequency, starts to approach the limits for audibility/inaudibility found by the Liski research. At low frequencies even the rolloff caused by the vented woofer alignment doesn't come close to the 1 cycle group delay figure.

Next I looked at the same speaker except chose a bass alignment of sealed, with the same F3.

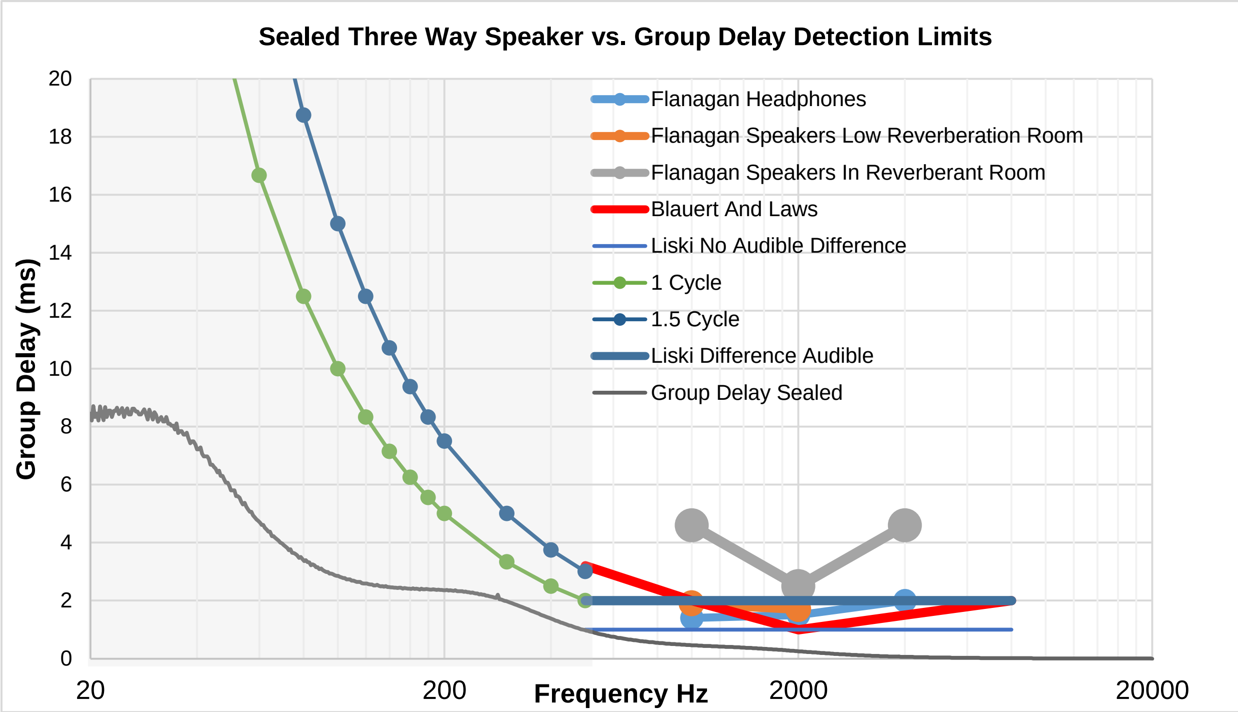

Figure 3 Sealed 3 Way System Group Delay

Figure 3 shows that the group delay in the crossover region really hasn't changed, but the sealed rolloff buys even more area under the potential audibility curve. Either way the system has enough margin, I highly suspect any audible difference between the two would have to do with frequency domain differences activating the room resonance modes vs. any group delay associated time distortion in the system.

Next up I plotted a big double 18" subwoofer, with and without the high-pass/low pass filters associated with typical use. In this case you can see that the subwoofer with the low pass filter starts to approach the limits. I've actually worked with some systems that depending on the slope and type of filters chosen do exceed the 1/1.5 cycle limits. However, it's often possible to make slight adjustments to those crossover points to avoid the issue without introducing issues elsewhere such as higher distortion and lower overall power handling.

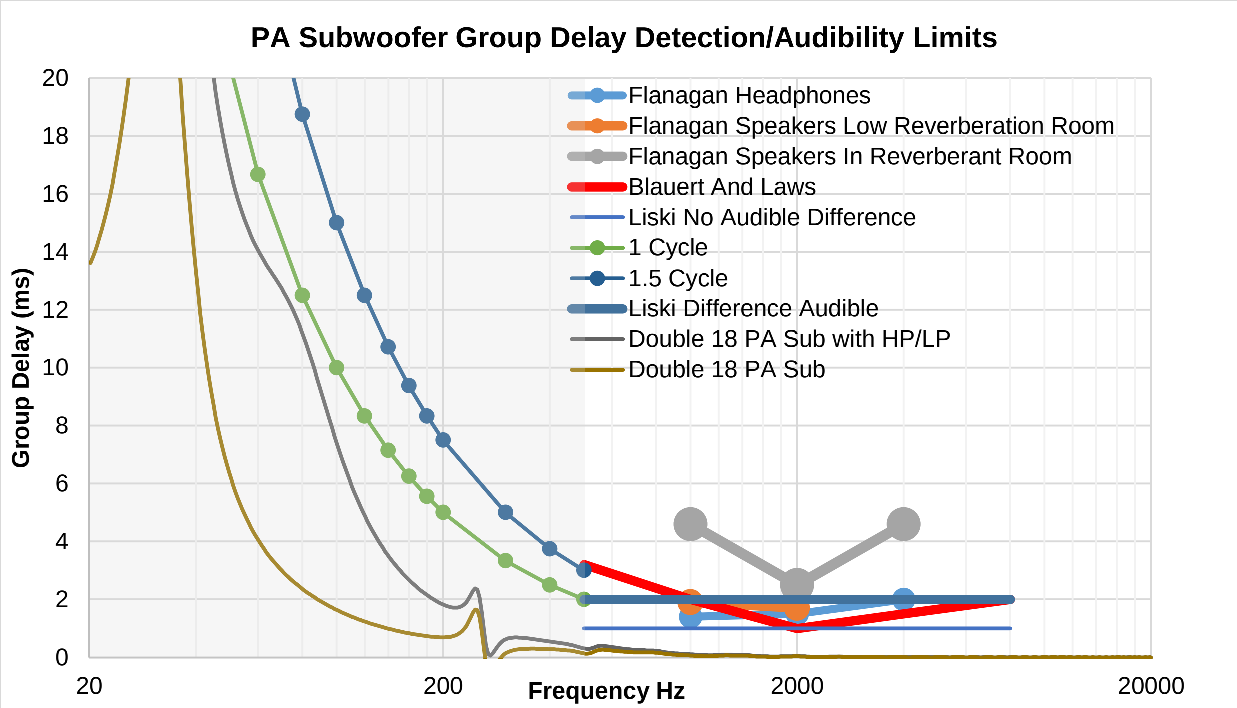

Figure 4 PA Sub Group Delay with, w/o filters.

Lastly I simulated a 3 way speaker with a tweeter offset backwards by 10cm. Again this change pushed the group delay up towards the audible limits….but really didn't cross them anywhere. It did however require adjustments in the crossover…but that will have to wait until part 2.

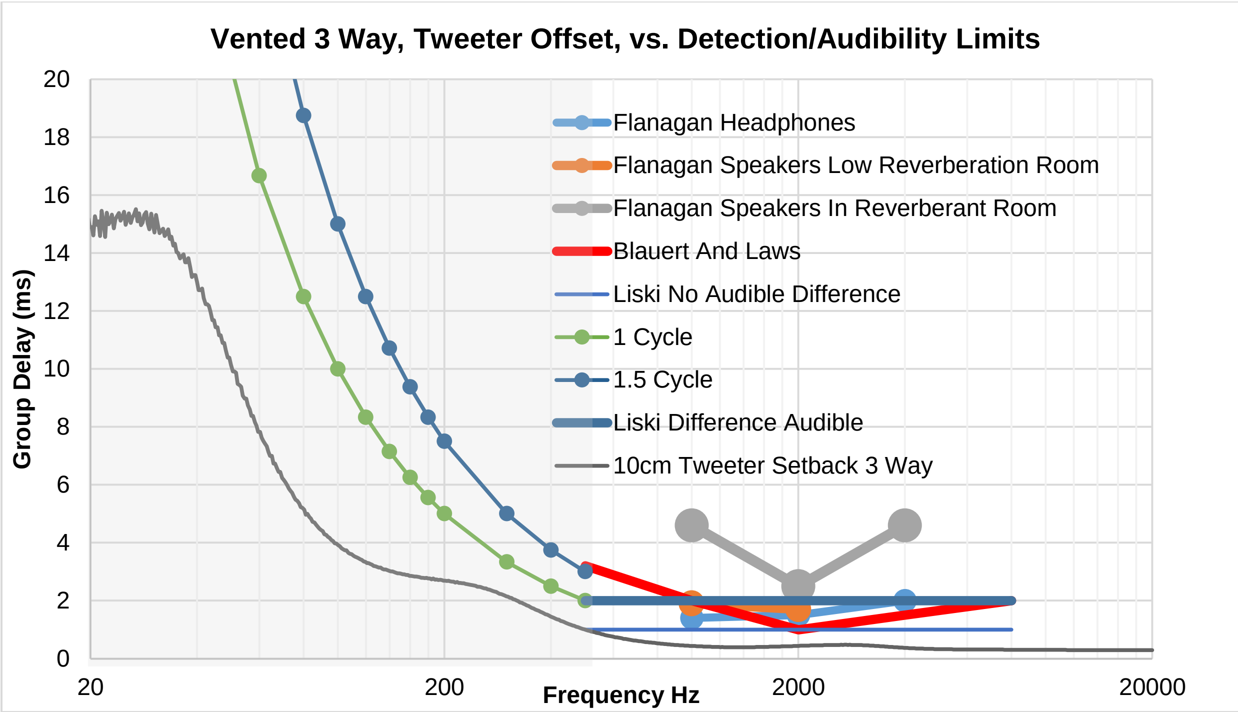

Figure 5 Offset Tweeter Group Delay

Conclusion

As I did more and more research and more and more simulations/measurements of speakers for this paper I was firmly convinced of the following conclusions:

1. Group delay, in and of itself is rarely a worry for direct radiator speaker systems unless high slope crossovers have been chosen…even then the group delay involved probably gets pushed from the "not audible even under controlled conditions" to "audible, but only under certain special circumstances". I can't conceive of a buildable, reasonable dynamic three way speaker system that would go so far past the audible stage as to be objectionable in a typical listening space.
2. Even when large offsets (10cm) for a dynamic system are involved the group delay of the resulting systems is still well controlled.
3. Changing a system with equal -3dB points from 2'nd order to 4'th order rolloff (sealed to vented), again at reasonable frequency limits for residential system, yields nothing in the group delay curves that present concern. Subjective concerns are not warranted based on group delay alone.
4. It is possible, for larger PA systems with much narrower bandwidths or long horn based acoustic center differences to approach the audible range.

So, why all the hubbub? Well…it turns out that if you don't understand the relationship of phase between the drivers, while the resultant system phase, or group delay issues may be inaudible, there is a corresponding frequency response error that is absolutely, unequivocally audible. The group delay curve might point you to those issues, but if you're used to looking for them in the frequency response curve, impedance curve or any of the spectral decay type measurements it might be easier to figure out what's really going on in those measurements instead.

References

Blauert, J. and Laws, P "Group Delay Distortions in Electroacoustical Systems"
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Liski, Juho; Mäkivirta, Aki; Välimäki, Vesa "Audibility of Loudspeaker Group-Delay Characteristics, AES Convention Preprint, May 2018 (It's like group delay is studied in May!)

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