A Study of Off Axis Amplitude Response Due to Physical Transducer Separation

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I. Abstract

As an acoustic transducer reproduces a sound, the pressure wave it creates propagates into free space. If there are two transducers located near each other playing a similar frequency, the wave fronts will experience a constructive and destructive interference pattern. More often than not this is a detrimental phenomenon when designing a loudspeaker. The following paper explored this and different configurations of transducers and filters that can optimize a speaker looking for a "smooth" off axis response. It was determined that by controlling the driver separation or their crossover frequency, as well as their orientation to each other, off axis response variation could be greatly reduced and optimized.

II. Introduction

When designing a loudspeaker, off axis response, or polar response, it is important when preserving objective aspects of the reproduced signals "soundstage" (1). Siegried Linkwitz speaks much on this topic in his paper, "The Magic in 2-Channel Sound Reproduction – Why is it so Rarely Heard?" If the amplitude response changes as the observation point is moved, then the observer will have a different experience everywhere they go. It is well accepted that for a loudspeaker to reproduce a full bandwidth signal, multiple transducers covering different bands of the signal are required. This poses a problem: with multiple sources in the same space, there will be constructive and destructive interference in the wave front as they combine.

III. Theory

Ideally, two different transducers radiating into the same space will combine their wave fronts to reproduce the input signal coherently. This case is never achieved because there is a finite distance between the acoustic centers of each of the two transducers. The frequency that the two transducers are playing must also be considered. Since they both specialize in different frequencies, the only frequencies of concern are the frequencies of overlap in their pass bands. As the frequency that each of the transducers produce is moved away from the other the effect becomes less predictable and arguably more arbitrary.

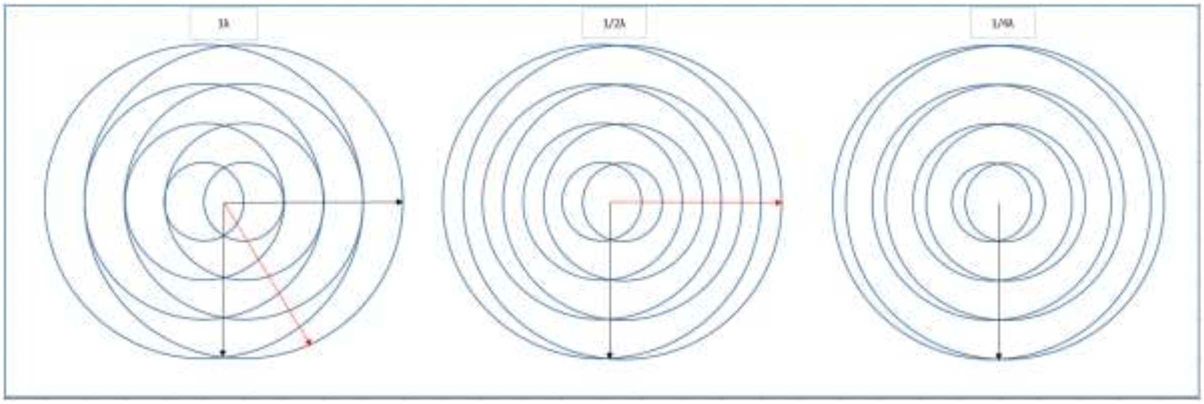

Figure 1 Interference of Two Transducers at 1, ½, and ¼ λ

With this established, the reference frequency can should then be determined. This is determined by the separation between the two transducers. Shown below in figure 1 is an illustration of two wave fronts interfering at different distances relative to their wavelength.

Changing the distance between two sources and leaving the frequency unchanged causes different variations in the interference pattern. The black arrows are constructive and the red arrows are destructive. This is an oversimplification, but it serves to explain the basics of what is occurring. As the distance decreases below λ, the interference effects become less severe where λ is the wavelength of the reference frequency in air.

IV. Methods

To explore a two ways of reducing the effects of interference, a test box and anechoic chamber were used. The anechoic chamber was provided by the University of Toledo with permission from the chairman of the College of Electrical Engineering and Computer Science. The test box was constructed using a woofer, midrange driver, and tweeter. The woofer and midrange drivers are isolated by themselves in separate sealed chambers. The size of the midrange driver chamber was designed arbitrarily and overdamped, while the woofer's chamber size was calculated off of an excel sheet using sealed box equations from the Loudspeaker Design Cookbook authored by Vance Dickenson (2). It's Q factor is roughly 0.8. The microphone used to analyze this setup was a Dayton Audio Omni Mic placed 1 meter from the tweeter. To filter the drivers, a Dayton Audio DSP box was used. A Marantz SR8200 receiver amplified the test signals. The test setup is shown at left in Figure 2.

Figure 2 The Test Setup Inside the Anechoic Chamber

The first experiment was to confirm the information in figure 1. The distance between the tweeter and the midrange driver is of interest, and the two are separated by 3.5”. Using the equation f = C/ λ, where C is the speed of sound in inches and f is the reference frequency, it was found that the reference frequency at λ is 3850 Hz.

First, the test box was set up so that the drivers were next to each other, or horizontal, in orientation. The DSP was configured so that the crossover frequency was 3850 Hz for both drivers; a 3850 Hz 4th order low pass was put on the woofer and a 3850 Hz 4th order high pass was put on the tweeter. Both filters used were Linkwitz-Riley filter with Q factors of 0.5. The amplitude response of the two drivers were measured from 20 Hz to 20 kHz, and the test was repeated 3 times while pivoting the microphone off axis at 15 and 45 degrees. The following figure 3 shows the data collected.

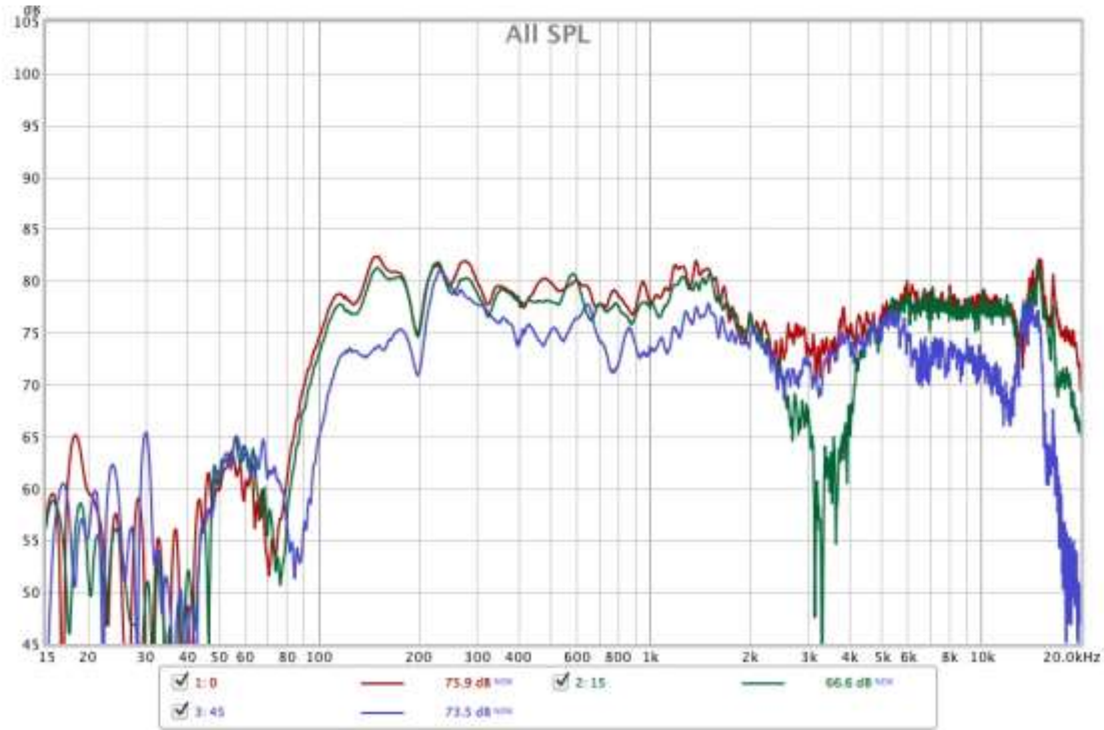

Figure 3 3850 Hz Crossover Measured at 0, 15, and 45 Degrees.

The data was collected and displayed with Room EQ Wizard.

The reference amplitude response is 0 degrees in red. Clearly, 15 degrees off axis takes a significant dip near the crossover frequency. At 45 degrees off axis the response begins to flatten out again, but is not perfect. This corresponds with the 1 λ illustration where around 20 degrees the destructive interference takes over the response, then constructive interference begins to raise the response at 90 degrees. The interference is in between those two extremes at 0 and 45 degrees.

Next, the experiment was repeated for the 1/2 λ illustration. It would be impossible to change the physical distance between the drivers on the test box, so the crossover frequency was changed to achieve the same effect. The formula f = C/ λ was again used to determine that 1929 Hz has a λ of 7”. Therefore, the physical λ is ½ the reference λ. The high and low pass filters on the tweeter and woofer were changed to 1929 Hz and the following data in figure 4 was collected from this experiment.

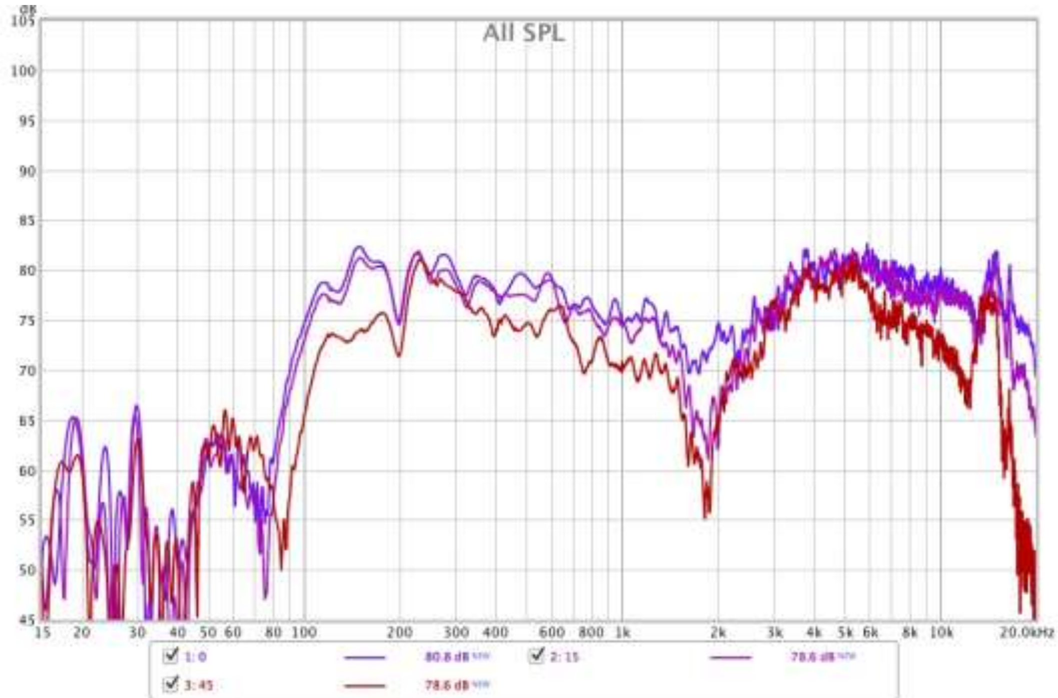

Figure 4 1929 Hz Crossover Measured at 0, 15, and 45 Degrees.

The data was collected and displayed with Room EQ Wizard.

The reference 0 degrees off axis amplitude response is shown in dark purple. At 15 degrees off axis, the amplitude response begins to take a severe dip in response around the crossover frequency. The response dip worsens still at 45 degrees off axis. These results confirm the 1/2 λ illustration, where the response progressively becomes more destructive as the reference position becomes further off axis.

By carrying out these two experiments, the theory in figure 1 was confirmed. The predicted off axis response variations matched those of the measured response variations. This information can now be applied to optimizing the driver configuration and filtering so that these off axis response variations can be minimized.

The first step towards optimizing the off axis response would be to limit the change in the reference location, or "listening position". It will be assumed that the listener is sitting in one position and that their height will not change. That leaves only side to side head movement, or if there are multiple listeners, seating position left and right. By orienting the driver so that they are always the same distance from the reference position, the designer of the loudspeaker can design around the known response variations and assume that the up and down movement of the listening position will be relatively consistent. This is achieved by orienting the two transducers in question vertically, or one atop the other. The following data was collected by repeating the previous two excitements and changing the orientation of the drivers in the test box. To do so, the box was simply turned 90 degrees on its side as shown in figure 2. The data is displayed in figures 5 and 6.

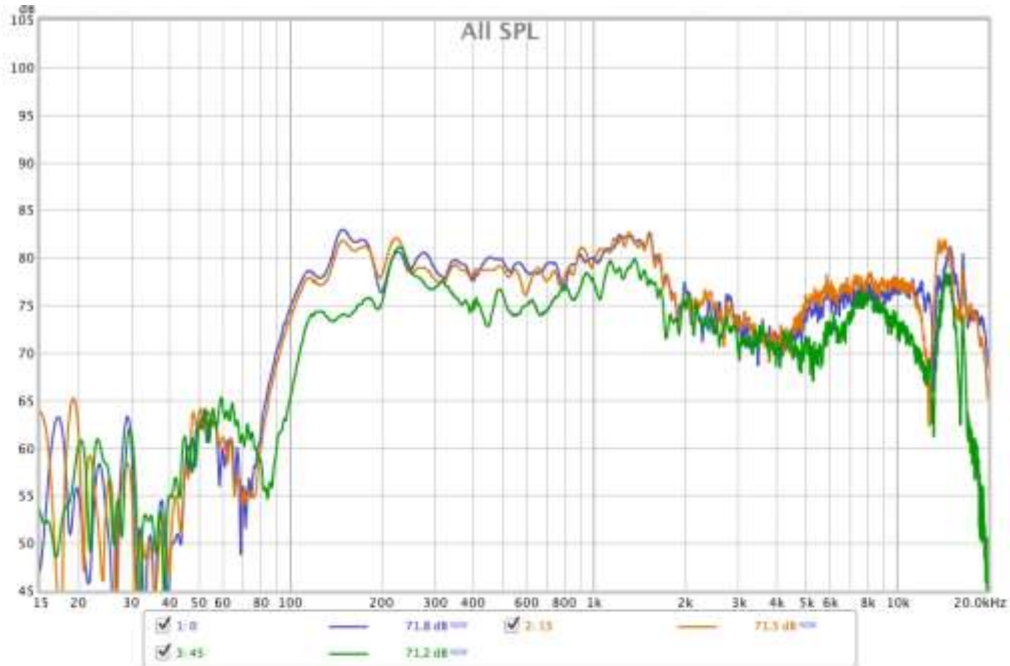

Figure 5 3850 Hz Crossover Frequency, Vertical Orientation.

The data was collected and displayed with Room EQ Wizard.

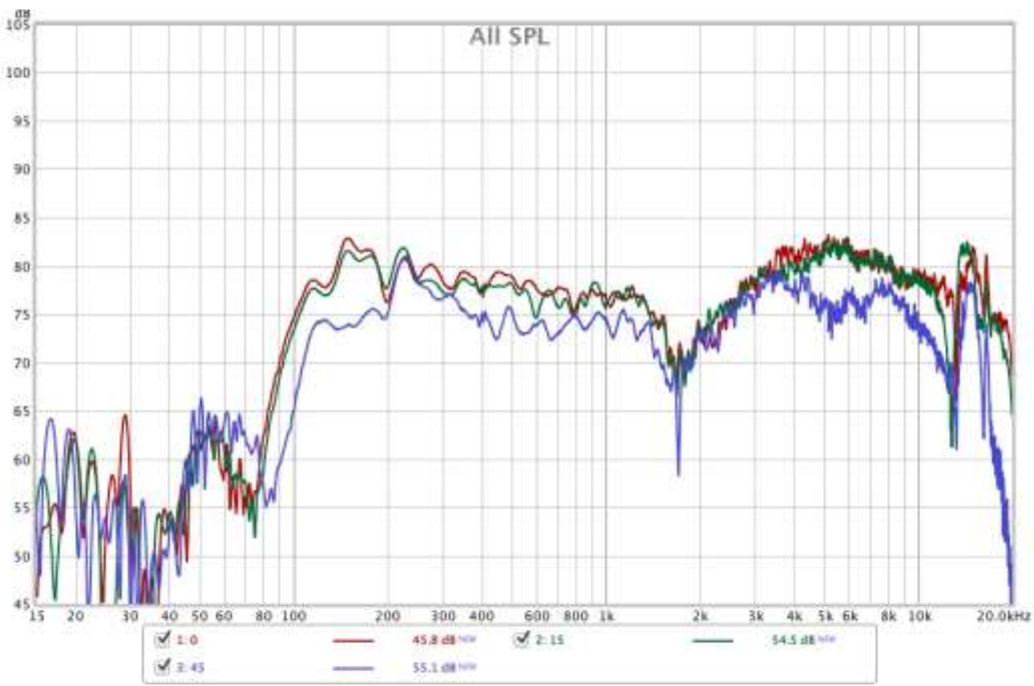

Figure 6 1929 Hz Crossover Frequency, Vertical Orientation.

The data was collected and displayed with Room EQ Wizard.

Analyzing the data presented in figures 5 and 6, the off axis response fluctuations are significantly reduced when orienting the drivers vertically with each other compared to when they were beside each other horizontally. There is an extreme and narrow dip in response in the 45 degree off axis plot in figure 6. The location of the dip is different than the location of the interference dip in the previous experiment by about 150 Hz. This implied that the dip is not because of the same interference affects, and more likely due to error in microphone position or off axis baffling affects.

V. Discussion

The first experiment proved that by changing the distance between two acoustic transducers, the interference pattern is changed. As the two transducers separate, the interference pattern becomes more complex and unpredictable. From these conclusions arise several ideas on how to optimize a system.

According to figure 1, 1/2 λ is as far apart as two transducers can be before the destructive interference 90 degrees off axis begins to merge towards constructive, and the destructive lobes move closer on axis. This is only applicable for the reference frequency. However, any frequency below that frequency will have only improved interference effects as λ increases with decreasing frequency. Considering that, the loudspeaker designer can choose that frequency based on the distance between the transducers and keep that distance equal to 1/2 λ. It becomes an “upper bound” when choosing a crossover frequency. Objective results could be improved. The upper bound should be some percentage above the crossover frequency based on the filter slope (decreasing as filter order increases due to less passband overlap). To determine this metric, more testing will be required.

The second experiment concluded that off axis response fluctuations due to transducer interference were significantly reduced when orienting the transducers vertically with eachother. This is highly beneficial to a loudspeaker designer because by simply orienting drivers vertically to each other, response fluctuations on the design axis can be nearly eliminated. This only leaves vertical change in the listening position to cause error. Depending on the application of the speaker, the vertical listening position can be used as a reasonable assumption.

VI. Conclusion

Together these two design guidelines could benefit the objective performance of a loudspeaker. Further testing is required to determine what the metric for setting an “upper bound” should be. Likewise, to determine that objective results truly due correlate to shrinking distance (or decreasing crossover frequency) between two transducers, a blind study must be conducted. Due to the limited supplies available during this experiment, only one test box could be constructed and so had to be oriented in different ways. More accurate data could have been collected with several test boxes of similar baffles and physically different distances between drivers. Changing the crossover frequency works well, but is ultimately a workaround for changing the distance between them.

Internet Documents

[1] S. Linkwitz, “The Magic in 2-Channel Sound Reproduction - Why is it so Rarely Heard?,” *International Journal of Architectural Engineering Technology*, vol. 2, no. 2, pp. 113–126, 2016.

[2] V. Dickason and D. R. Raichel, “The Loudspeaker Design Cookbook, 5th Edition,” *The Journal of the Acoustical Society of America*, vol. 106, no. 5, pp. 2329–2330, 1999.