Speaker Crossover Network

By

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E-232 Section I Group 7

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I pledge my Honor that I have abided by the Stevens Honor System.

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Introduction:

The main goal of the project was to design and test a filter/amplifier circuit that would optimize the performance of two speakers—one woofer and one mid-range. Given a choice between four different filter designs, the group had to weigh the benefits and disadvantages of each to achieve the best possible filter circuit. Since gain, roll-off, and response curve are all important factors that affect the performance of a speaker filter, each aspect would impact the group's decision. After an initial assessment of each filter's common strengths and weaknesses, the group built four circuits to simulate in Simscape. In each circuit, there were two filters—a high-pass (HP) and a low-pass (LP) filter, which would feed into the woofer and mid-range speakers respectively. A 90 Hz frequency was fed into each filter and the resulting gain was measured. After closely analyzing the information gained from both research and the simulations, the group decided on one filter design being the best—Linkwitz-Riley.

Materials and Methods:

Using Simscape in MATLAB, the group created an amplifier/filter circuit to suppress certain frequencies by forming simulated circuits with transistors, resistors, inductors, and capacitors. After creating an amplifier earlier in the semester, the group began to combine the amplifier with a simulated circuit for a Bessel filter, Butterworth filter, Chebyshev filter, and Linkwitz-Riley filter to see which filter has the best features for the purpose of amplifying an audio signal and separating the frequencies to two separate output speakers. Each filter has its own distinct characteristics, which may make one far more effective in different situations. The Bessel filter has a maximally flat group delay resulting in a maximally linear phase response and no overshoot. These advantages come at a cost of its slow cut-off transition, which is much slower than other filters. The Butterworth filter has a maximally linear phase response like the Bessel, but cuts off far quicker at a cost of overshooting at higher filter orders. Meanwhile, the Chebyshev filter has the quickest cut-off transition with a cost of rippling in-band.

Filter and Amplifier Parts								
Filter Types	Capacitor 1 (μF)	Capacitor 2 (μF)	Inductor 1 (mH)	Inductor 2 (mH)	Woofer (Ω)	Mid-Range (Ω)	Source Resistor	Bias Resistor
Bessel	198.26	236.73	9.59	8.03	3.35	4.00	890 Ω	110 Ω
Butterworth	244.57	292.02	7.83	6.56	3.35	4.00	890 Ω	110 Ω
Chebyshev	346.09	413.24	5.54	4.64	3.35	4.00	890 Ω	110 Ω
L-R	173.04	206.62	11.07	9.27	3.35	4.00	890 Ω	110 Ω

**Inductor and capacitor values from DIY Audio and Video 2-Way Crossover Calculator Designer*

QFD for Filters

	Importance	Bessel	Butterworth	Chebyshev	Linkwitz-Riley
Response Curve	5	3	3	1	5
Q (roll-off)	5	3	3	5	3
Gain	5	5	5	1	3
Total	-	55	55	35	55
Rank	-	2	2	3	1

(5 - Good, 3 - Fine, 1- Poor)

Although the total scores were the same for the Bessel, Butterworth, and Linkwitz-Riley filters, the group determined that the Linkwitz-Riley filter would best fit for the project due to the overall flatness of its response curve.

Experimental Results:

Crossover Frequency (fc)	115 hz

Measured Filter Values (Current and Voltage)						
Filter Type	**Input Current** ($1*10^{-5}$ Amps)	**Output Current** ($1*10^{-5}$ Amps)	**Current Gain** (I_{out}/I_{in})	**Input Voltage** (Volts)	**Output Voltage** (Volts)	**Voltage Gain** (V_{out}/V_{in})
Bessel High Pass	1.373	6.311	4.597	0.875	$2.114*10^{-4}$	$2.416*10^{-4}$
Bessel Low Pass	1.373	64.51	47.053	0.875	$2.581*10^{-3}$	$2.950*10^{-3}$
Butterworth High Pass	1.373	6.246	4.556	0.875	$2.092*10^{-4}$	$2.391*10^{-4}$
Butterworth Low Pass	1.373	64.51	47.053	0.875	$2.581*10^{-3}$	$2.950*10^{-3}$
Chebyshev High Pass	1.373	5.724	4.175	0.875	$1.918*10^{-4}$	$2.192*10^{-4}$

Chebyshev Low Pass	1.373	64.24	46.856	0.875	$2.570*10^{-3}$	$2.937*10^{-3}$
Linkwitz-Riley High Pass	1.373	6.213	4.532	0.875	$2.081*10^{-4}$	$2.378*10^{-4}$
Linkwitz-Riley Low Pass	1.373	64.48	47.031	0.875	$2.579*10^{-3}$	$2.947*10^{-3}$

**Bessel Filter graphs shown below (Figures 2.1-2.6). See Appendix for all filter graphs and corresponding peak measurements*

Figure 1: Simscape Filter model

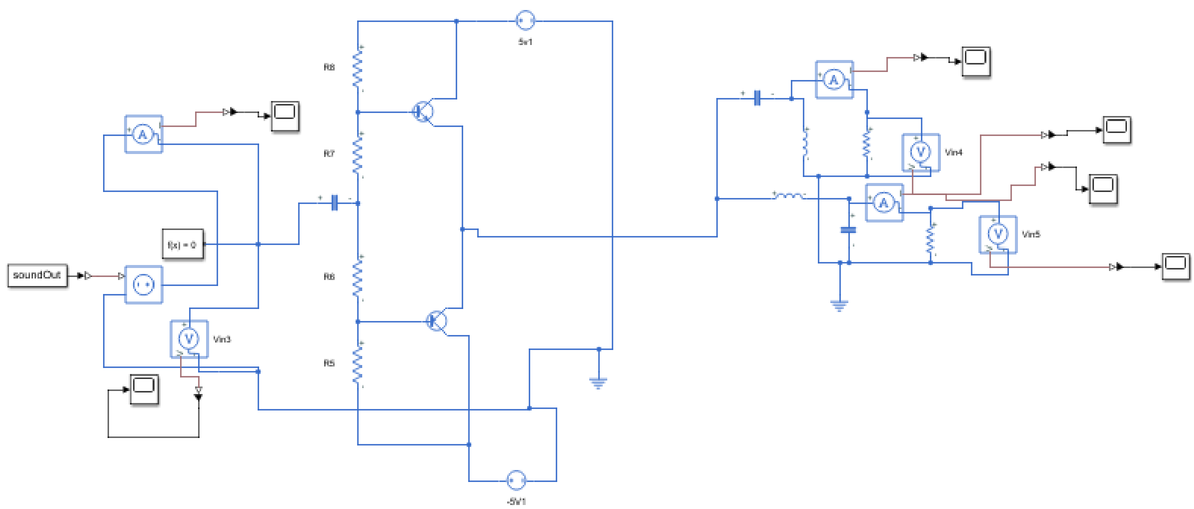


Figure 2.1: V_{in}

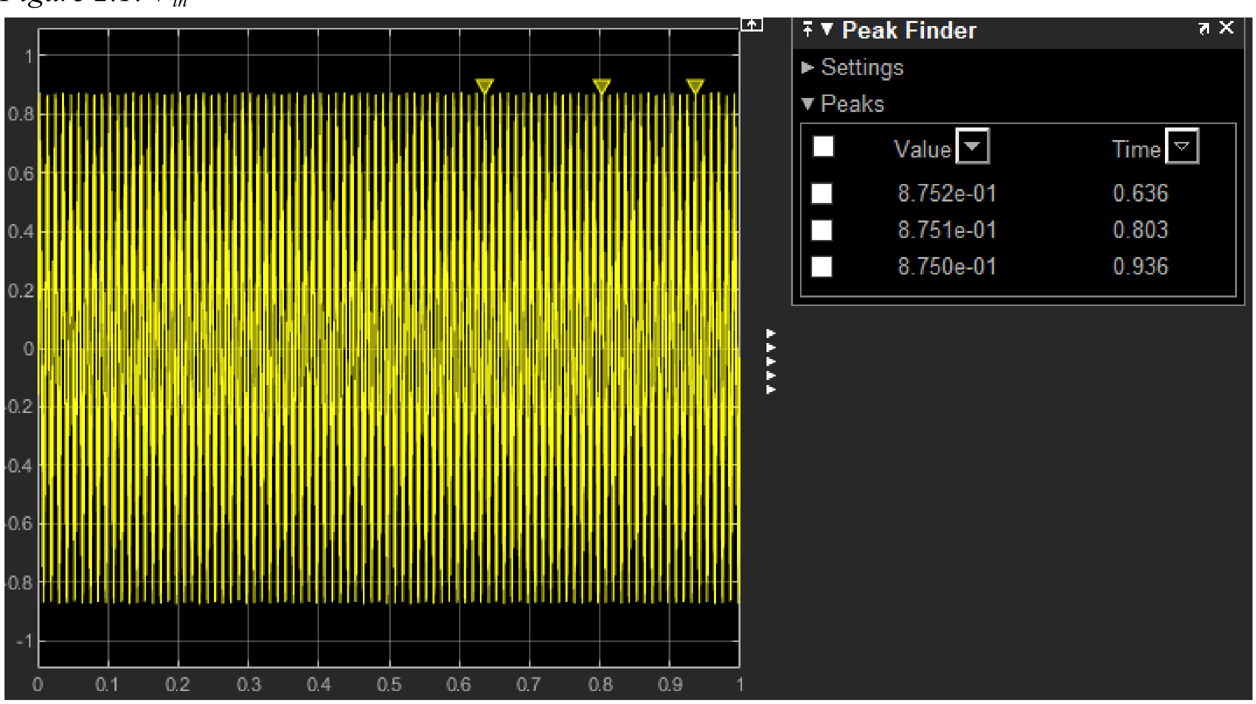


Figure 2.2: I_{in}

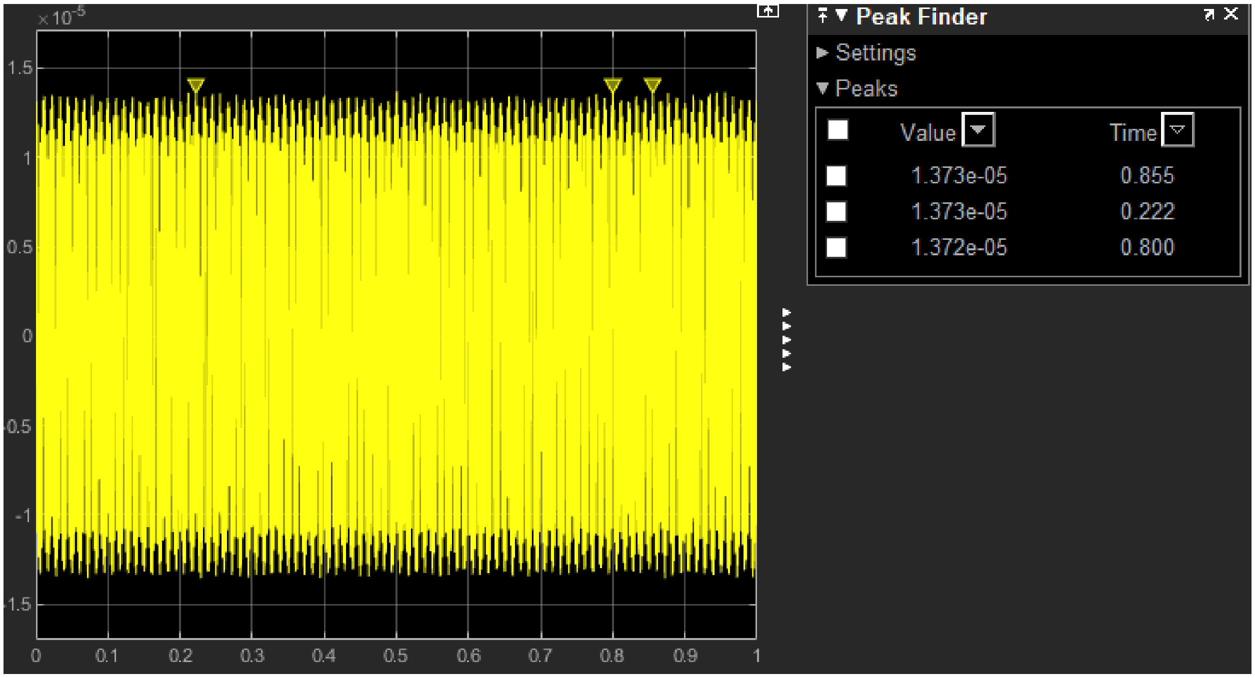


Figure 2.3: Bessel HP V_{out}

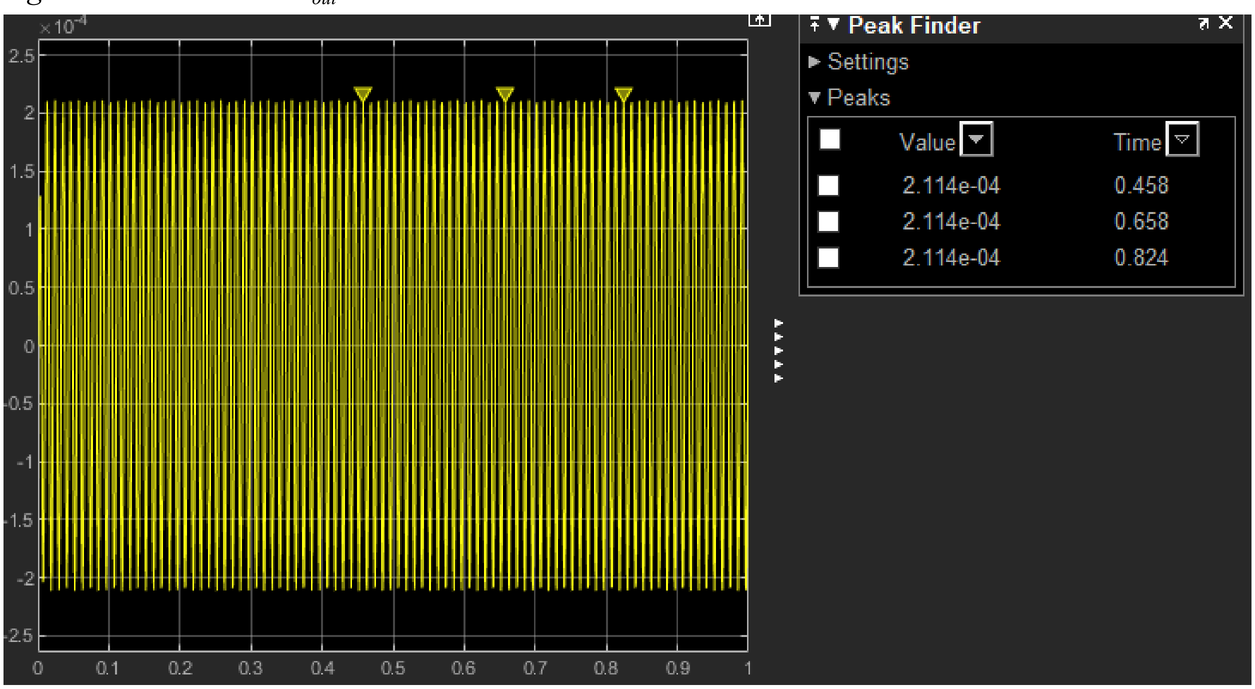


Figure 2.4: Bessel HP I_{out}

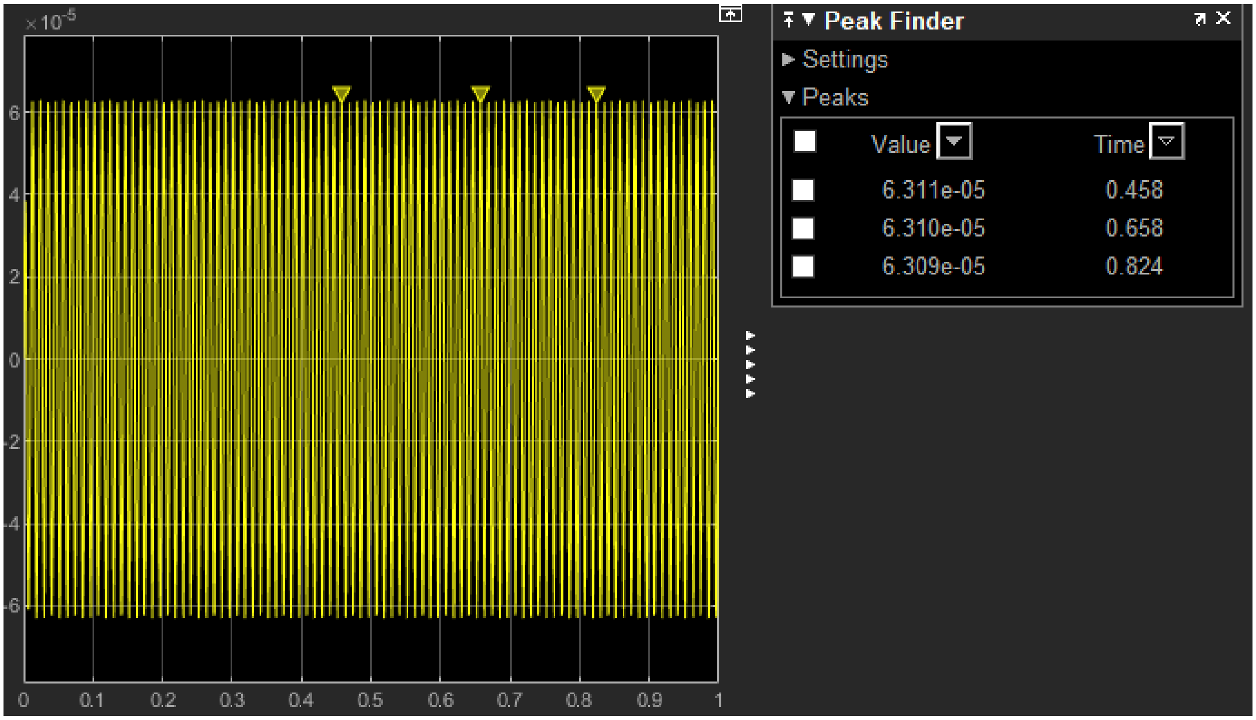


Figure 2.5: Bessel LP V_{out}

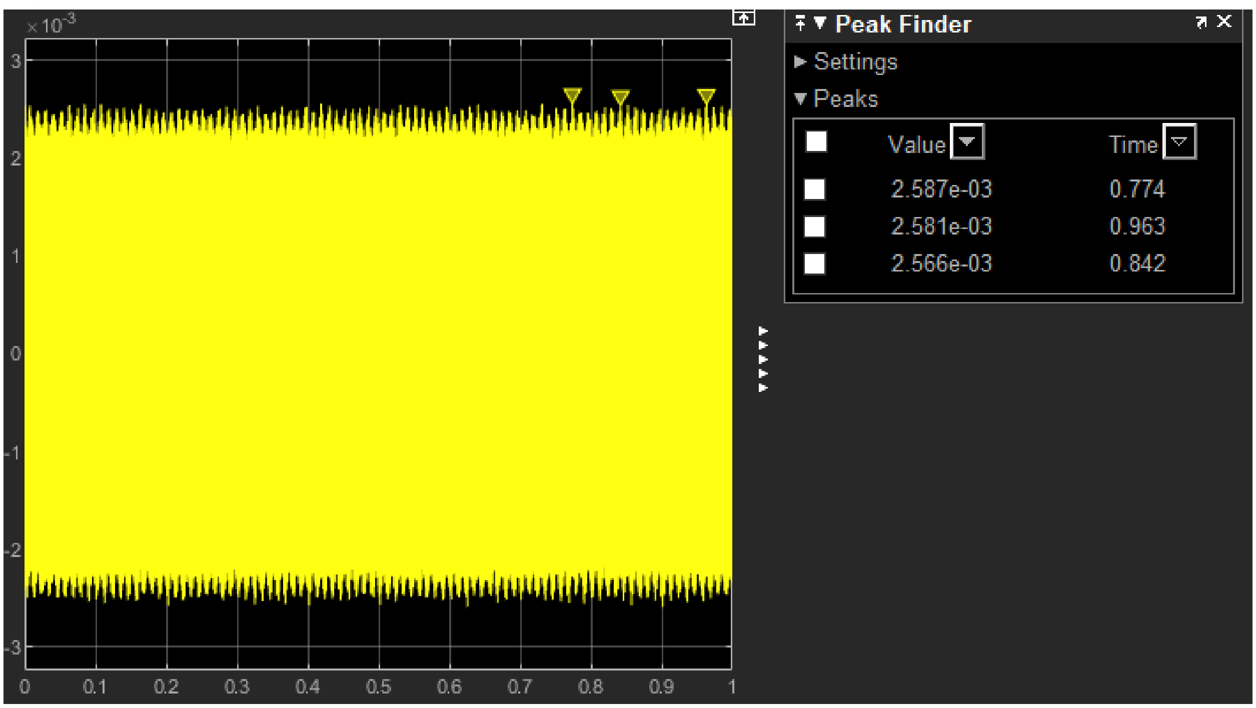
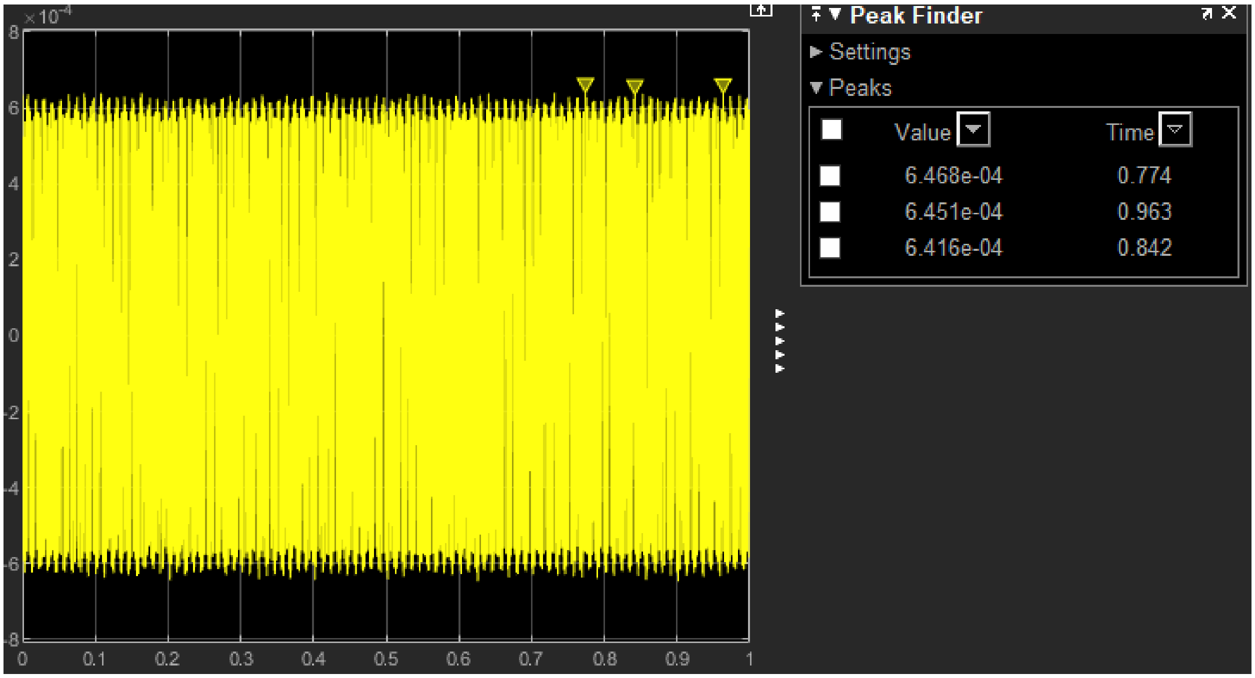


Figure 2.6: Bessel LP I_{out}



Discussion:

Testing the four simulated circuits left the group with four very similar results. The screenshot of Simscape shows the filter/amplifier circuit being used for the tests. The left half of the circuit was the zero-gain op-amp, and the right half was the crossover filter. The tables and charts above demonstrate how with each circuit there came six raw values: an input current and voltage, a HP current and voltage, and a LP current and voltage. Dividing the output values by the input values would give the overall gain of the filter-amplifier combination. This filter was designed to have a crossover frequency of 115Hz, meaning that the HP filter would silence any frequencies above 115, while the LP filter would silence anything below that cutoff. Because a 90Hz signal was being fed into the circuit, it makes sense that the HP filter was able to relay that 90Hz frequency. For the LP filter, however, any frequency below 115 would have a large negative gain applied, effectively removing the signal. So it came as no surprise when the 90Hz signal was lost in the LP outputs.

Since the data coming from the circuit made sense, the group felt confident in using the gain measurements to aid the design process. Yet, when the values were calculated, the gains of the four filters all fell within a very small range. This meant that the gain would become a negligible factor in determining the best filter design to use. The process of simulation, however, was useful as a proof of concept. The group was able to confirm the validity of the four designs in consideration.

In the preliminary research of each filter, the group found that Bessel and Butterworth filters are very similar. Both had a flat response curve as well as a relatively shallow rolloff. The Chebyshev filter had a wavy response curve, which would not be ideal, but it also came with a better roll-off slope. Finally, the Linkwitz-Riley filter had a flat response curve, and a perfectly flat crossover gain. Since a HP and a LP filter would be paired together to fit with the woofer and mid-range speakers, when the strength of the crossover signal on one speaker would decrease, the strength would increase on the other (Audio Judgement). With the Bessel and Butterworth filters, there would be a slight increase in relative gain around the crossover frequency. But in a Linkwitz-Riley filter, the gain would stay constant throughout the crossover, meaning there would be no unnatural rise in volume for that cluster of frequencies (Wikipedia), making the Linkwitz-Riley filter the group's final decision for best filter design.

In reality, mid-to-high order Linkwitz-Riley filters are the most commonly used for high quality audio equipment. One of its only downsides is the relatively high cost (Rane). But since this project did not consider cost as one of the constraints, the Linkwitz-Riley filter was the optimal choice. For the sake of simplicity yet effectiveness, the group decided on a second-order filter, which would provide the speakers with a cleaner transition between frequencies.

Overall, the group found this project to be helpful. The exposure to filter designs used in real world applications was neat. Also, it was enlightening to see that the different types of filters all use the same hardware, just with different values for the inductors and capacitors. The group felt, however, that an in-person experience would likely have been more practical. Since simulation removes many of the unknowns and challenges of real engineering, the process was definitely easier than it would have been building the filter on campus. It is also more satisfying to build a working speaker filter. But given the circumstances and the impossibility of meeting on campus, the Design IV course was conducted well in the group's opinion.

Appendices:

Figure 2.1: V_{in}

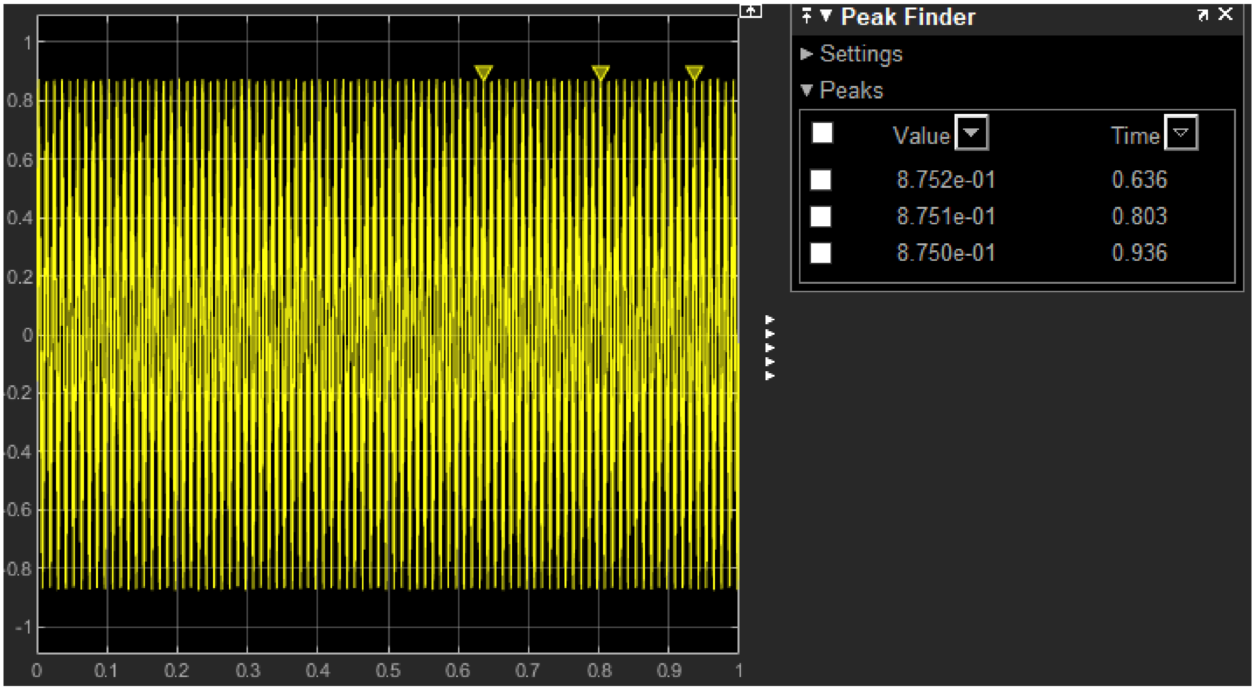


Figure 2.2: I_{in}

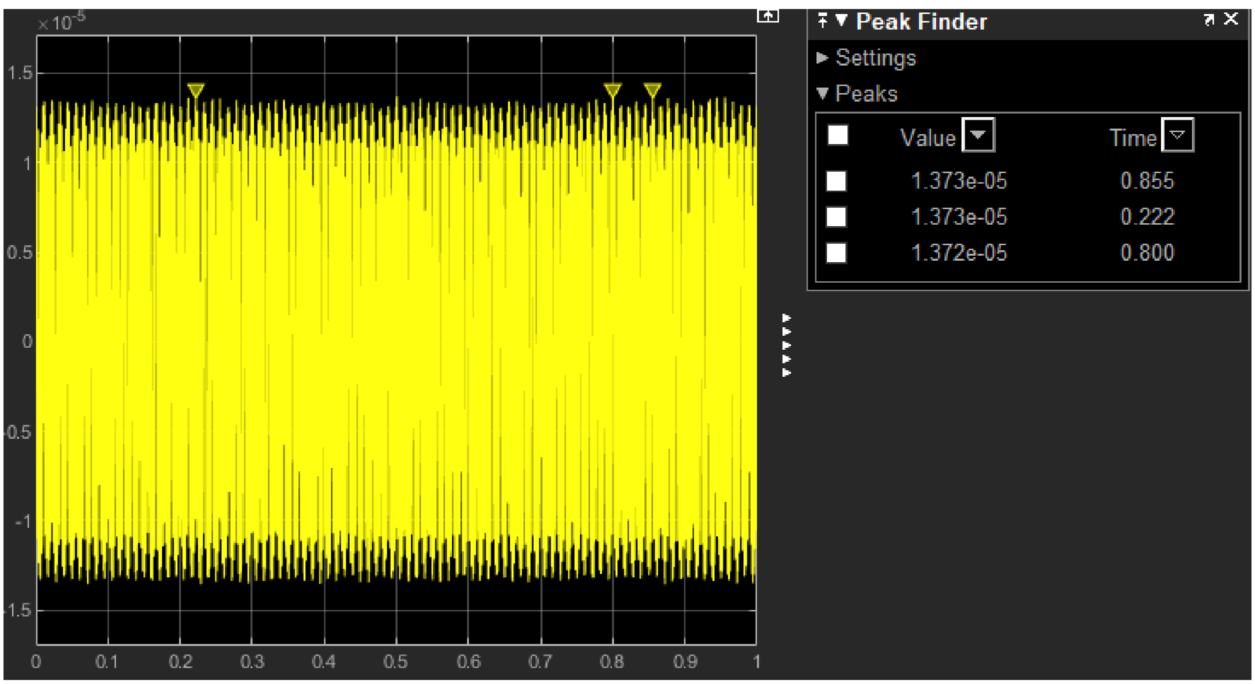


Figure 2.3: Bessel HP V_{out}

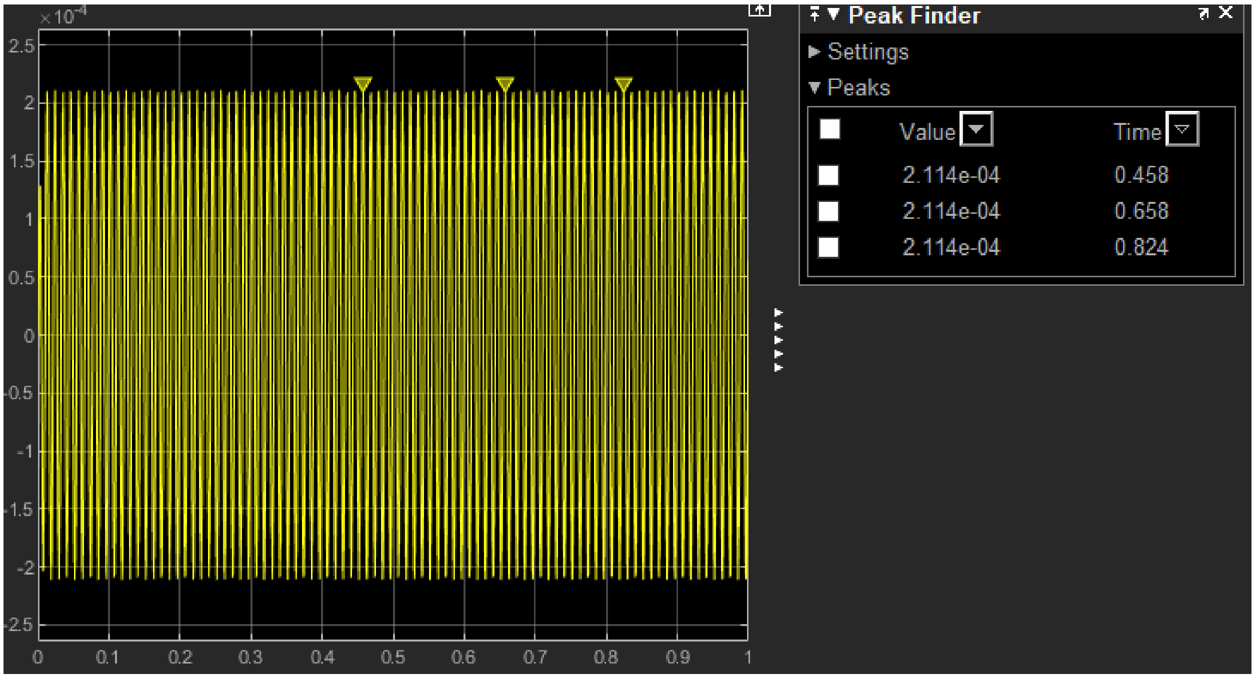


Figure 2.4: Bessel HP I_{out}

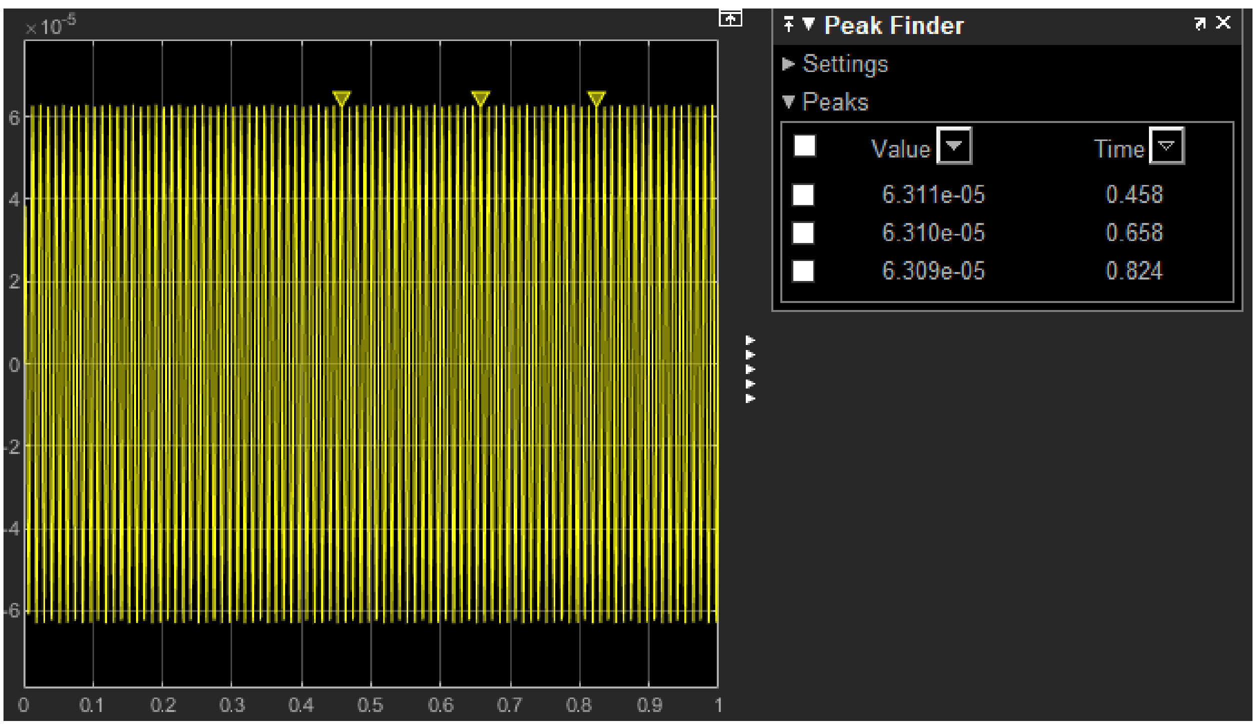


Figure 2.5: Bessel LP V_{out}

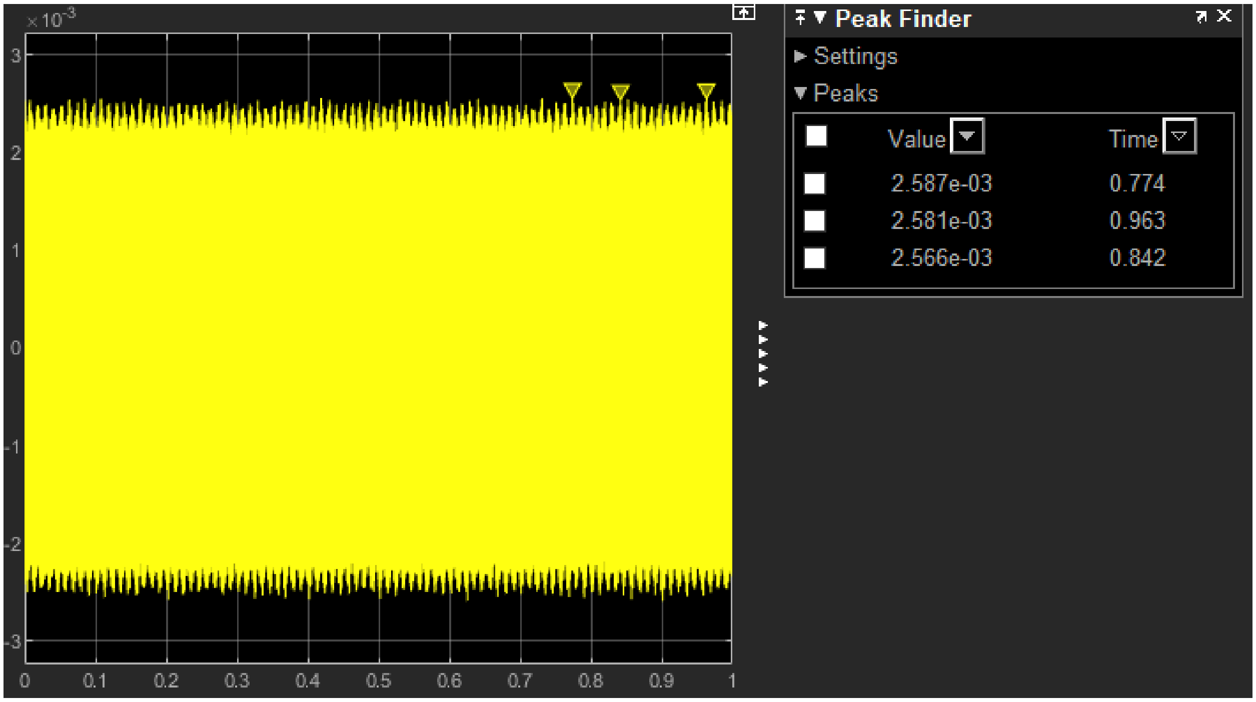


Figure 2.6: Bessel LP I_{out}

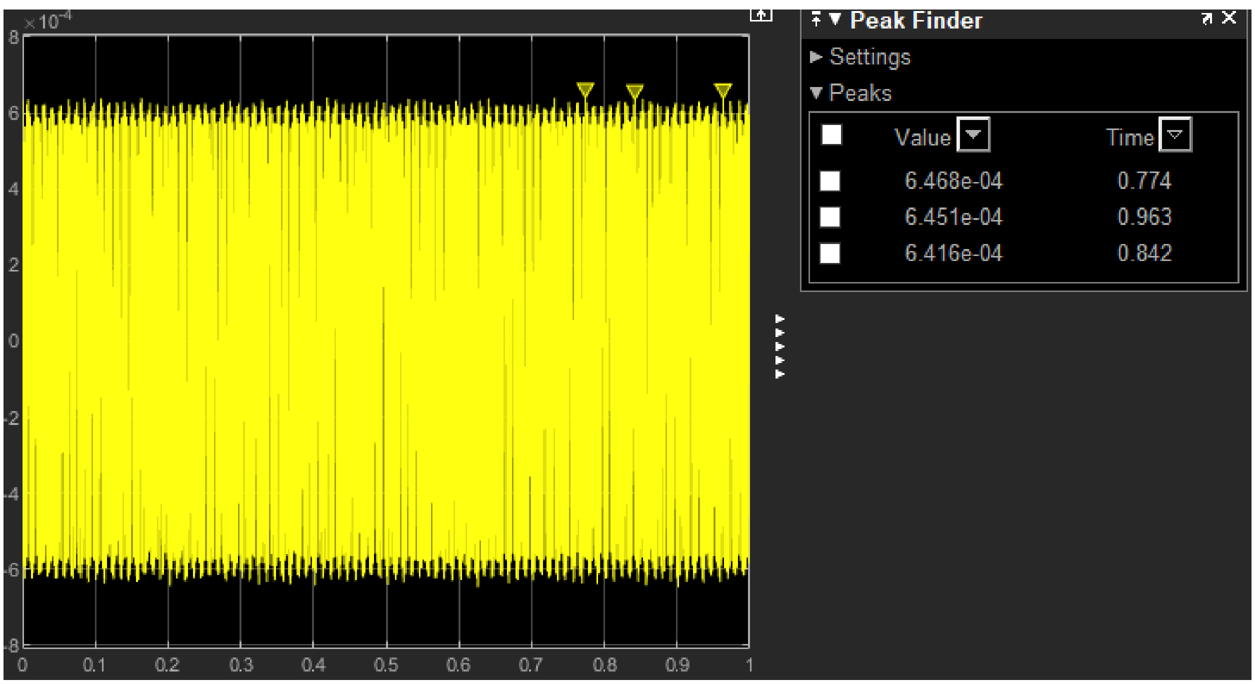


Figure 3.1: Butterworth HP V_{out}

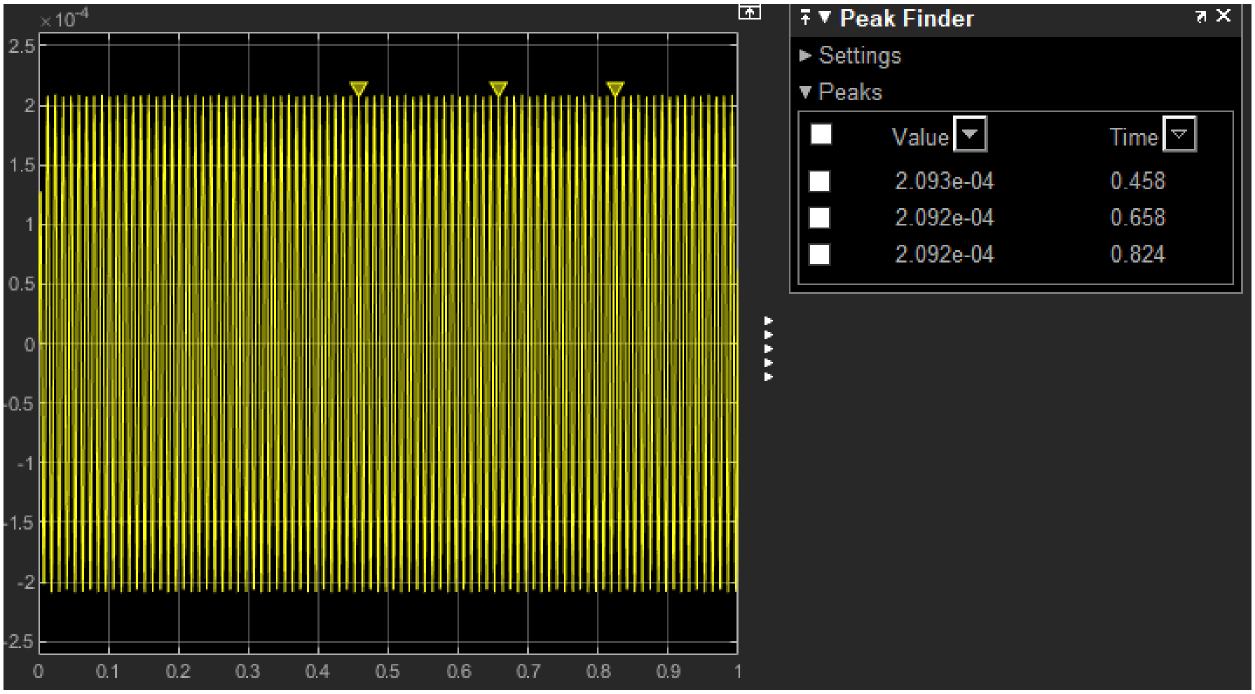


Figure 3.2: Butterworth HP I_{out}

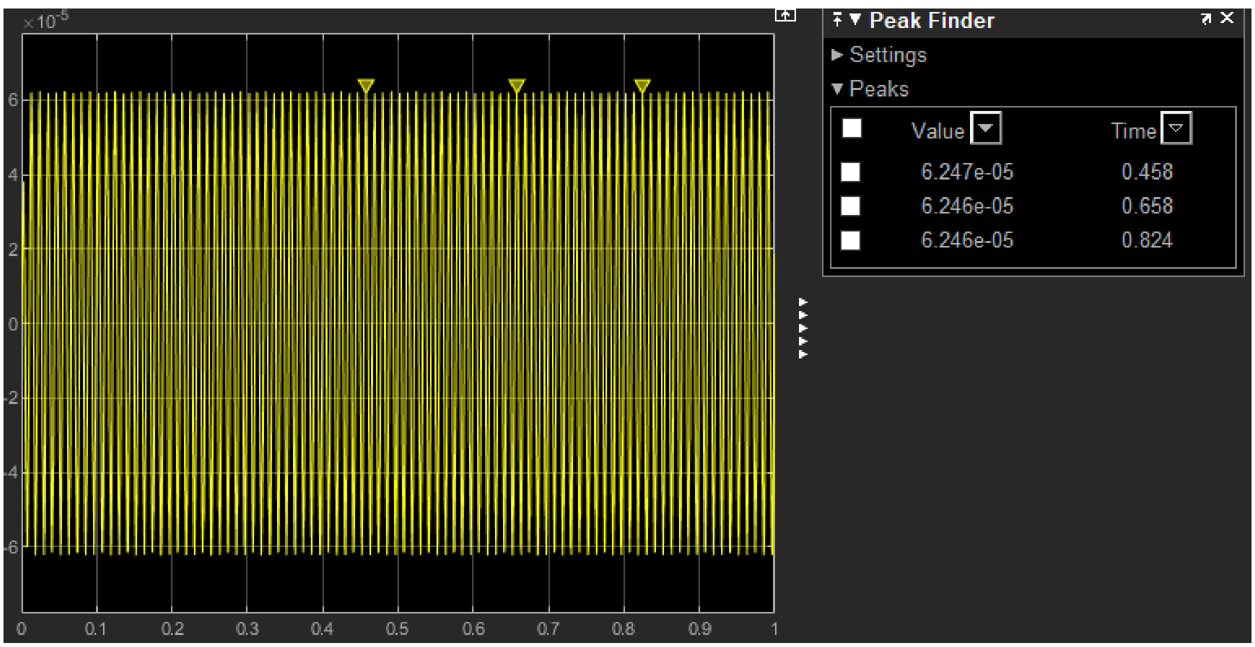


Figure 3.3: Butterworth LP V_{out}

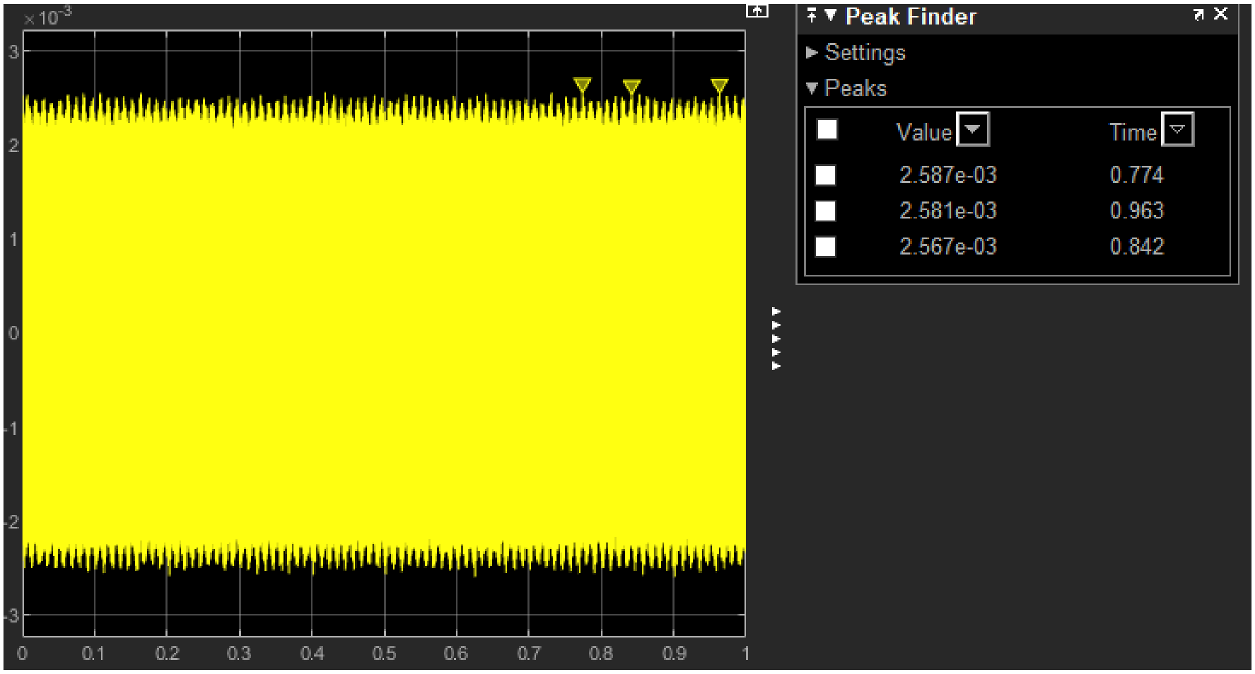


Figure 3.4: Butterworth LP I_{out}

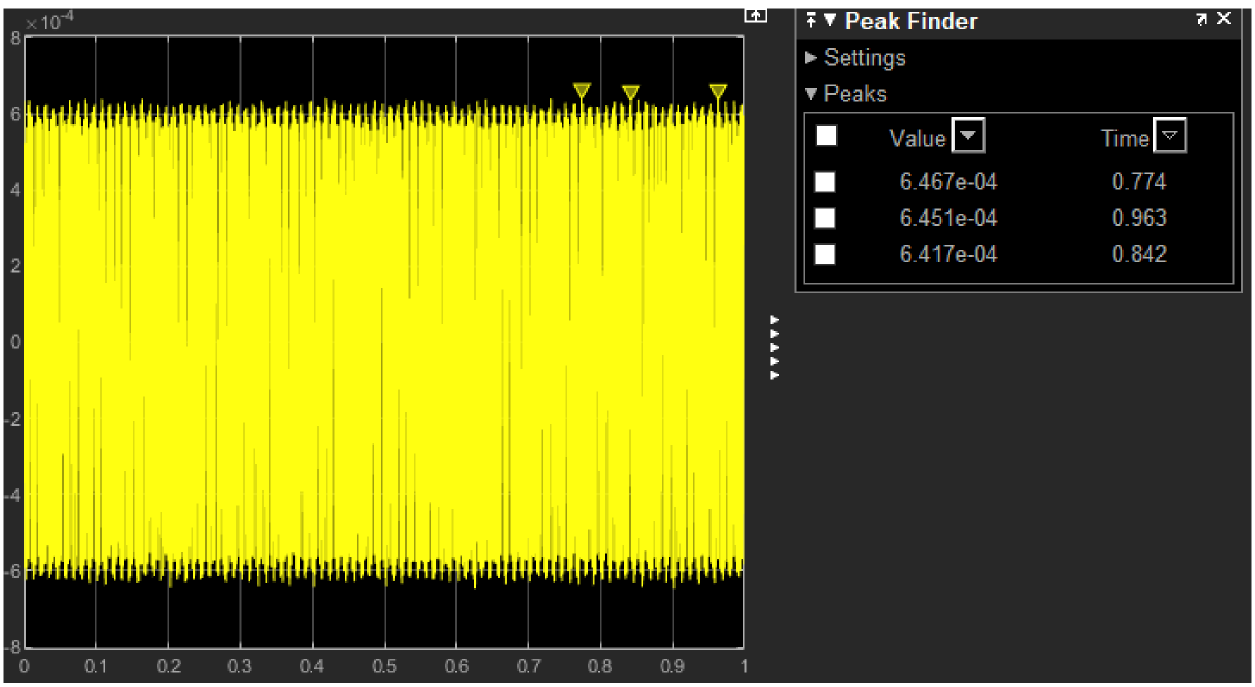


Figure 4.1: Chebyshev HP V_{out}

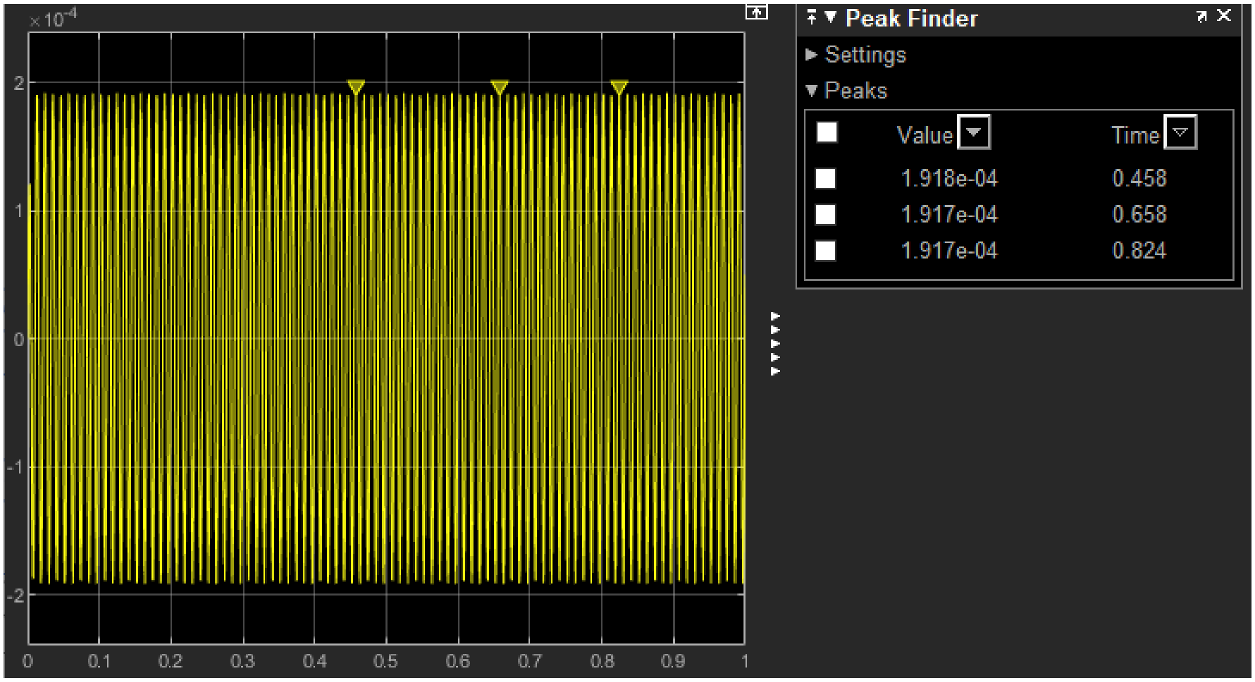


Figure 4.2: Chebyshev HP I_{out}

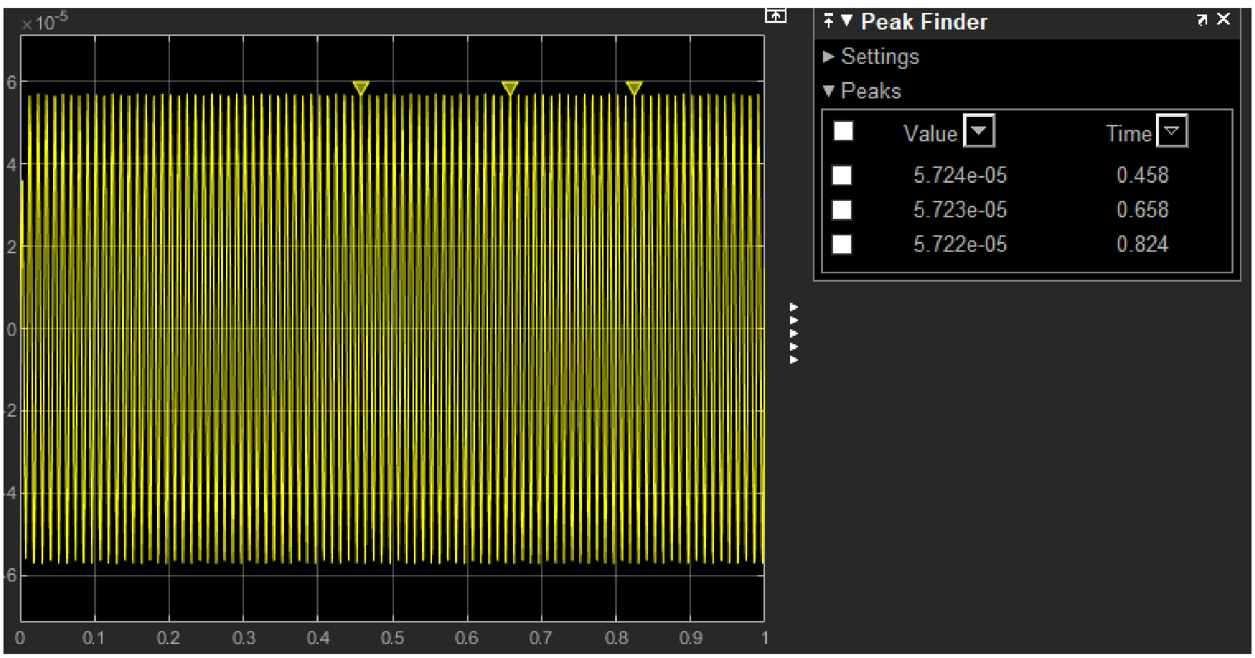


Figure 4.3: Chebyshev LP V_{out}

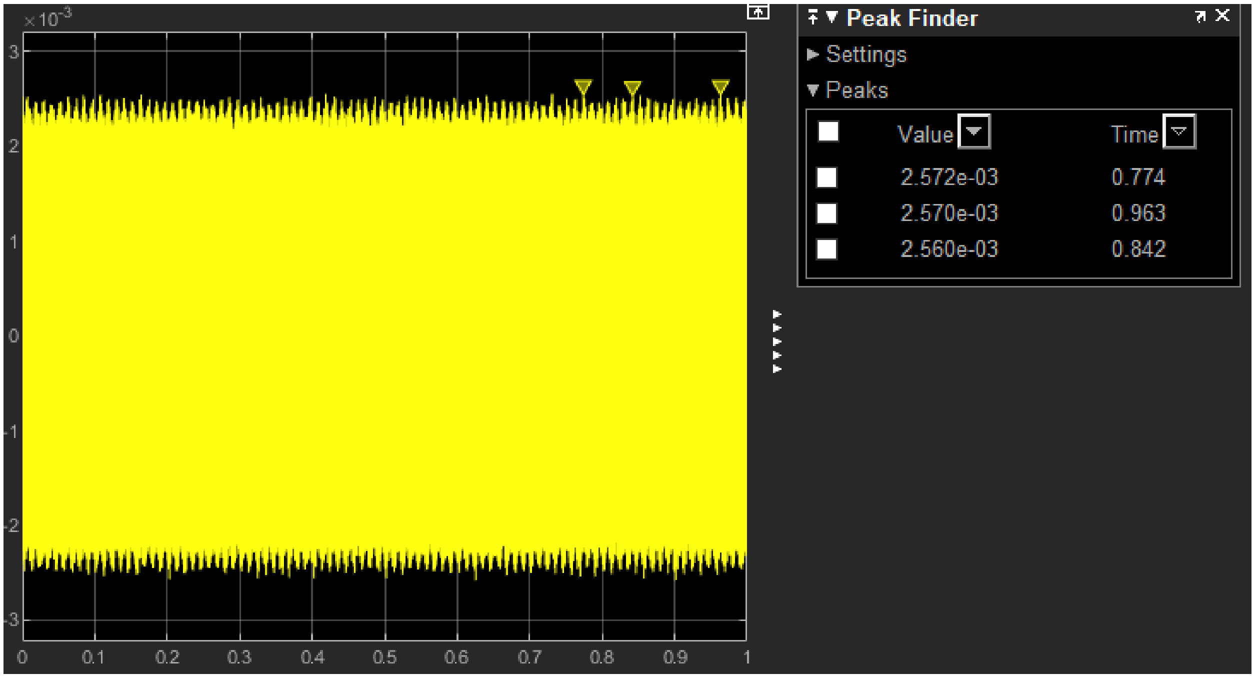


Figure 4.4: Chebyshev LP I_{out}

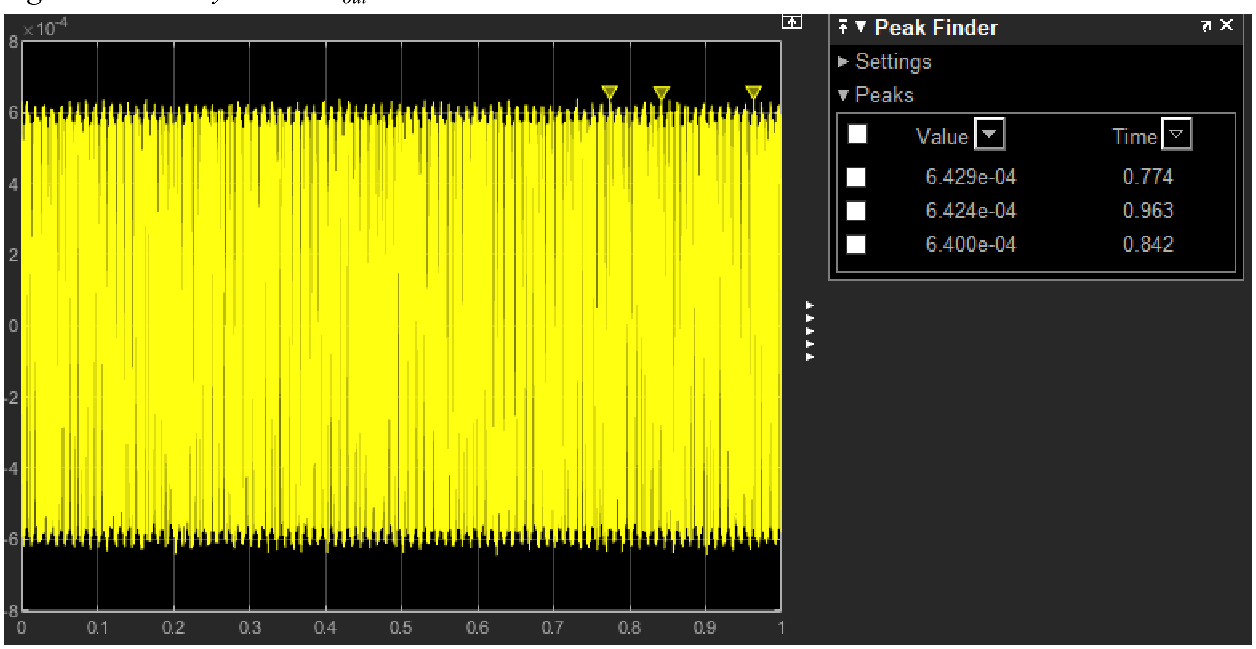


Figure 5.1: Linkwitz-Riley HP V_{out}

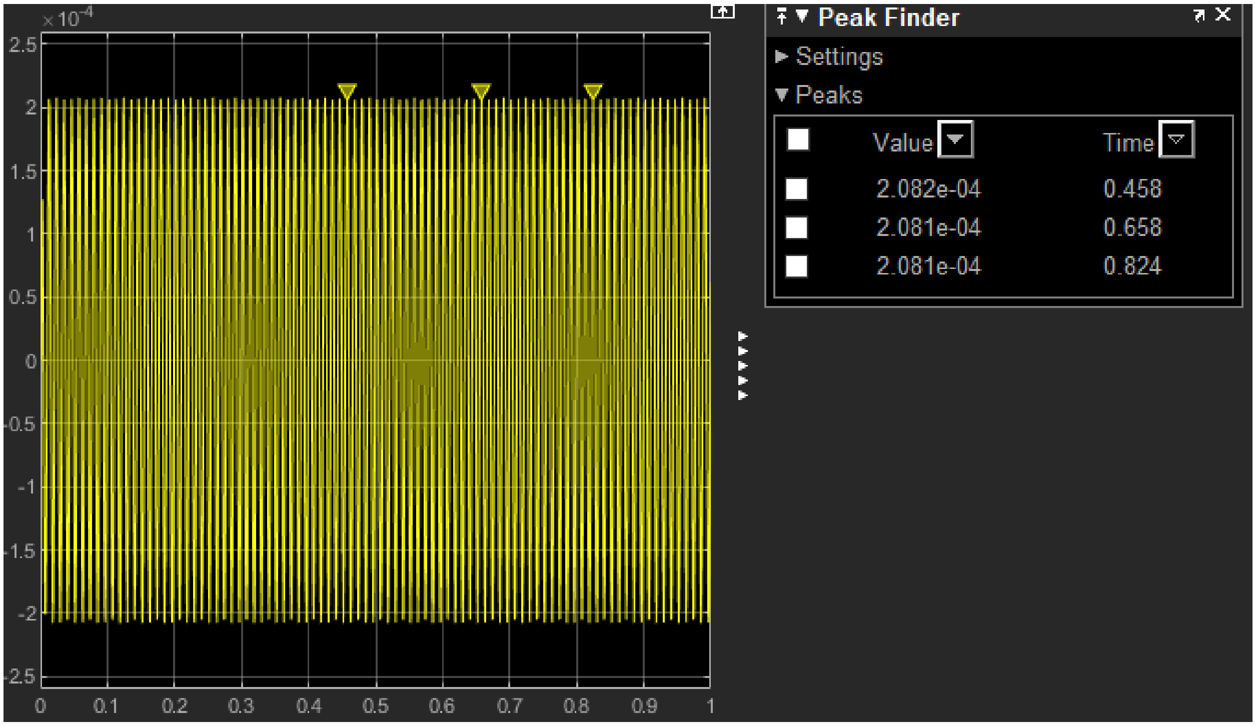


Figure 5.2: Linkwitz-Riley HP I_{out}

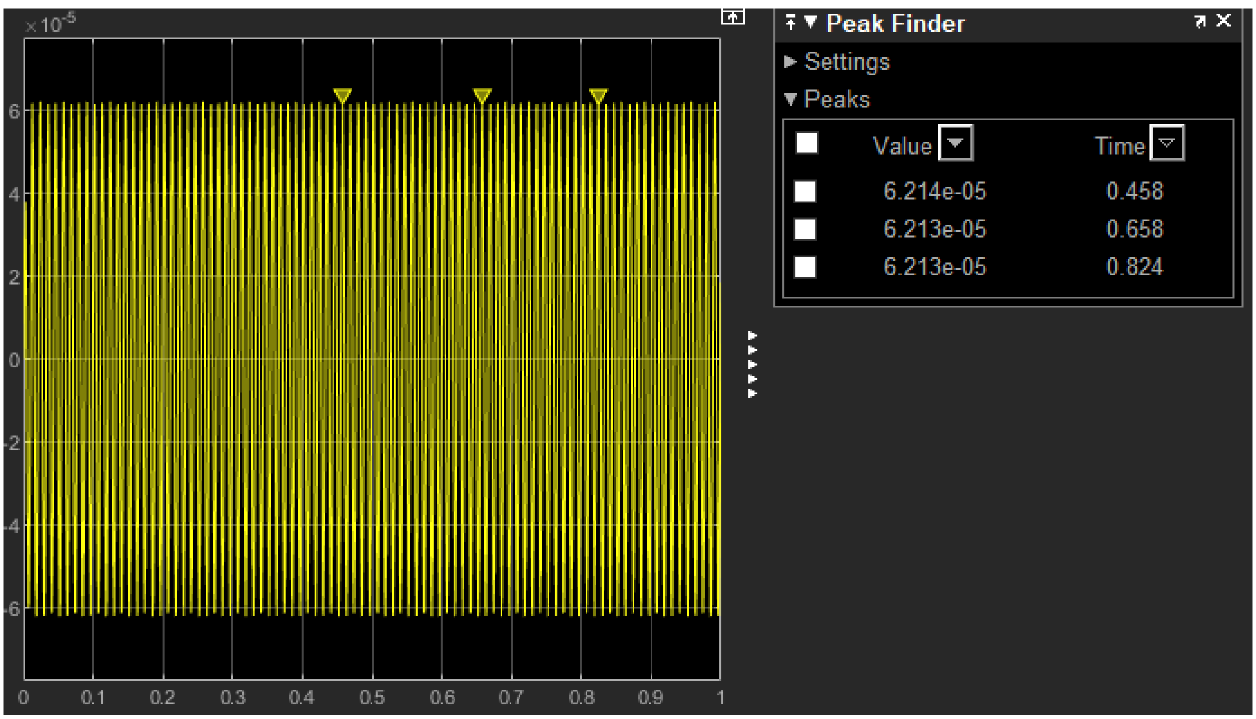


Figure 5.3: Linkwitz-Riley LP V_{out}

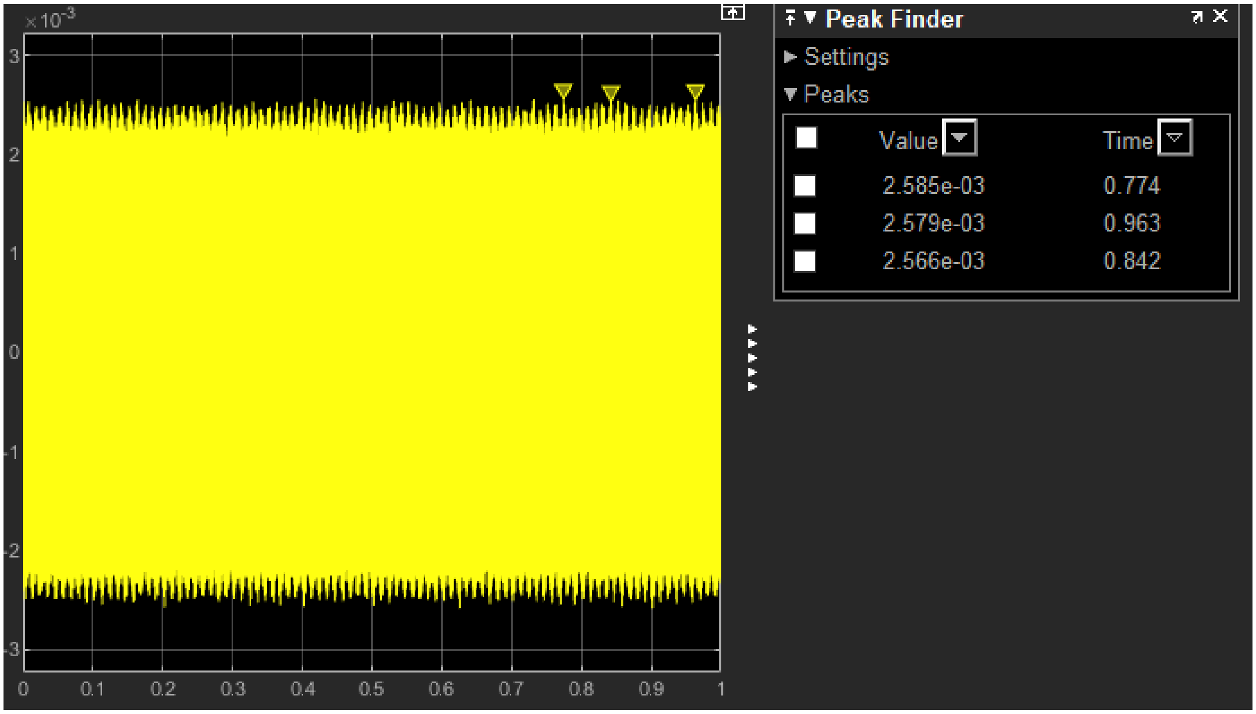
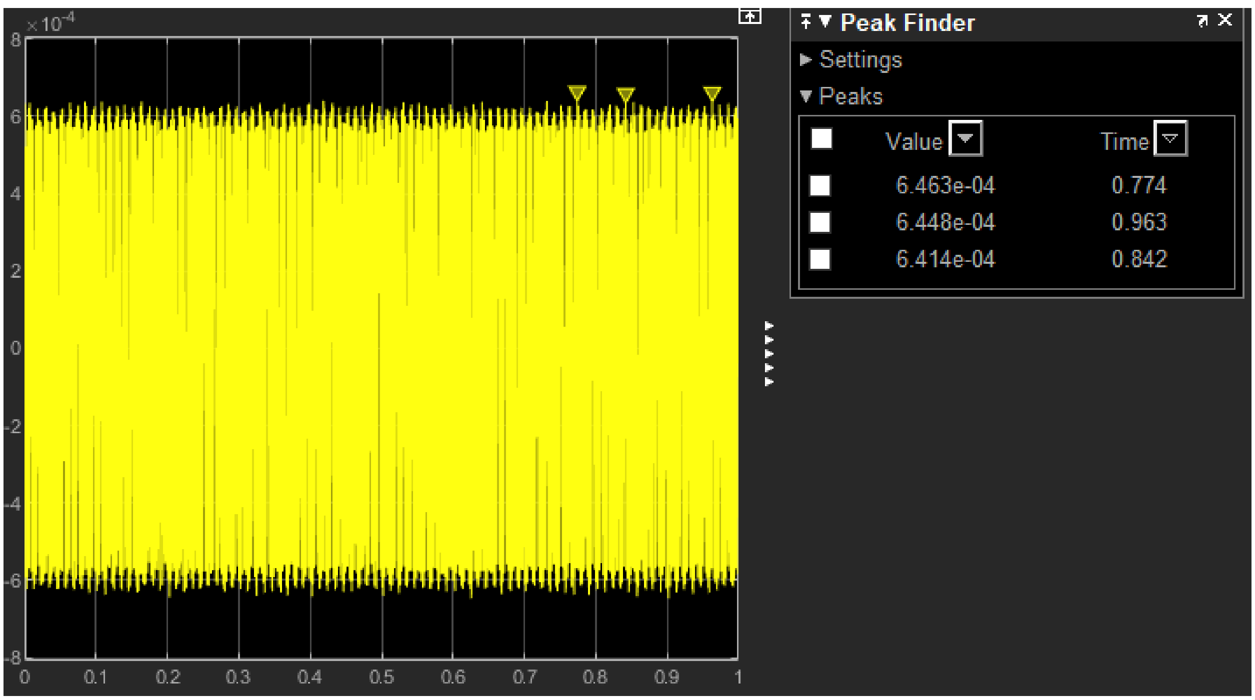


Figure 5.4: Linkwitz-Riley LP I_{out}



References:

Works Cited

LaLena, Michael. “2-Way Crossover Calculator Designer.” *DIY Audio And Video*, https://www.diyaudioandvideo.com/Calculator/SpeakerCrossover/. Accessed 28 April 2021.

“Linkwitz-Riley Crossovers: A Primer” *Rane Commercial Audio Products*, https://www.ranecommercial.com/legacy/note160.html. Accessed 28 April 2021.

“Linkwitz–Riley Filter” *Wikipedia*, Wikimedia Foundation, 28 April 2021, https://en.wikipedia.org/wiki/Linkwitz%E2%80%93Riley_filter

Tanasescu, Mark. “Passive Crossover Network Explanation.” *Audio Judgement*, https://audiojudgement.com/understand-the-passive-crossover-network/. Accessed 28 April 2021.