Allpass Filter for Group Delay Correction of a Vented Loudspeaker Enclosure

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Introduction

Loudspeaker drivers are electro-acoustic transducers that convert electrical energy to acoustical energy. An electrical audio signal is sent to the voice coil which is suspended in a magnet. Due to changes in electrical input, there is change in the magnetic field which causes the coil to vibrate and the diaphragm to move back and forth. This back and forth motion produces sound waves due to the compression of air surrounding the diaphragm. A loudspeaker enclosure is the container that houses the loudspeaker driver(s). Its main function is to isolate the sound pressure waves generated from the rear of the driver so that their phases do not cancel those of the waves generated from the front of the driver. There are different types of loudspeaker enclosures, however, this project is concerned with vented enclosures. A vented loudspeaker enclosure is one that has a vent or a port, usually in the form of a hole that lies on a surface of the enclosure followed by a pipe inside the enclosure.

Phase Delay and Group delay both describe how signals are delayed in time. However, while phase delay describes the time-shift of an individual sinusoid, group delay describes the time-shift of the envelope of a group of sinusoids that move together.

Phase delay is calculated as the negative of the phase divided by frequency, and can be expressed as

$$T_p(\omega) = -\theta(\omega)/\omega$$

Group delay is calculated as the negative first derivative of the filter's phase response, and can be expressed as

$$T_g(\omega) = -d\theta(\omega)/d\omega$$

In both cases, $\theta(\omega)$ represents phase and ω represents frequency

This project is an attempt at recreating the study presented by Herzog et. al. (2014), wherein an allpass filter based correction mechanism is designed in order to equalize the group delay that occurs in vented loudspeakers at low frequencies. The problem and implementation of the solution proposed in the study are discussed in the following sections of this report.

Problem

Vented loudspeaker enclosures are essentially Helmholtz resonators. These are resonators that have a cavity through which air enters and exits the resonator. Vented loudspeaker enclosures are also called Bass Reflex enclosures. They have been awarded this title due to their ability to boost low frequencies produced by subwoofers/low frequency drivers. This can be attributed to the fact that they are Helmholtz resonators. A sound wave emitted by the rear of the diaphragm of the subwoofer has to travel some distance before it emerges from the port. If the distance traveled shifts it 180 degrees out of phase with the front wave, the rear wave would then be in phase with the front wave. This action (called the phase inverter principle) prevents destructive doublet cancellation and makes the sound from the rear of the speaker perform a cumulative effect with the front sound, thereby providing a second source of energy. However, this also causes group delay at low frequencies because the oscillations from the port are reaching the driver late. In addition, at the box resonance frequency, sound is almost solely being emitted from the port and not from the driver, and inherently has the box's group delay.

Method

In order to correct this group delay at and around the resonance frequency, an equalization filter can be applied. This filter can either have negative group delay or inverse group delay. That is, it can introduce negative group delay in the frequency range where group delay must be equalized and "speed up" the signal. Alternatively, in the case of inverse delay, it can introduce group delay in all the frequencies other than the ones in the frequency range where group delay must be equalized and “slow down” the other frequencies. While the first method is not feasible because the filter would have poles outside the unit circle, the second is feasible but inconvenient in real-time settings. In Herzog et. al. (2014), a solution is proposed that solves both these problems. An allpass filter that has the same group delay as the vented loudspeaker is implemented. This is a second order allpass filter. The reason behind it having an order of two is that although the whole loudspeaker acts as a fourth order highpass filter, the enclosure by itself acts as a second order system. The equalization filter is implemented in the following steps:

- Time-reverse x[n]
- Apply second order allpass filter
- Time-reverse x[n] again

Where x[n] is the response of the vented loudspeaker enclosure (containing group delay at the box resonance frequency).

By implementing a time-reversed, low order IIR allpass filter, the authors found a computationally efficient solution to the problem at hand.

Implementation

In order to implement the steps described in this study, I first simulated a vented loudspeaker in Python using the transfer function given in Eq. 1 of in Herzog et. al. (2014). The transfer function is that of a fourth order highpass filter, and is given as follows:

$$Gv(s) = (s/\omega 0)^{4} \;\mathbf{/}\; (s/\omega 0)^{4} + a3(s/\omega 0)^{3} + a2(s/\omega 0)^{2} + a1(s/\omega 0) + 1$$

Where ω0 is the box resonance frequency and a1, a2 and a3 are given by the following:

$$a1 = a1 = 1/(Ql*\sqrt{h}) + \sqrt{h}/Qts$$

$$a2 = (\alpha + 1)/h + h + 1/(Ql*Qts)$$

$$a3 = 1/(Qts*\sqrt{h}) + \sqrt{h}/Ql$$

Where,

Compliance Ratio, α = Vas/Vb

Tuning Ratio, h = fb/fs

Where,

Vas = Compliance of the low-frequency driver

Vb = Compliance of the air inside the box

fb = Resonance frequency of the box

fs = Free-air resonance of the driver

Once this transfer function was implemented as a filter, I applied it to some audio. Due to a minor error in pre-warping $\omega0$, I initially got much more low-frequency attenuation than required. On correcting this error, the low-frequency attenuation looks more in alignment with that of a vented loudspeaker. This can be inferred by comparing the spectrograms of a logarithmic sinusoidal chirp before and after applying the vented loudspeaker filter. Figure 1 shows the spectrogram of the unfiltered chirp on top and that of the filtered chirp at the bottom.

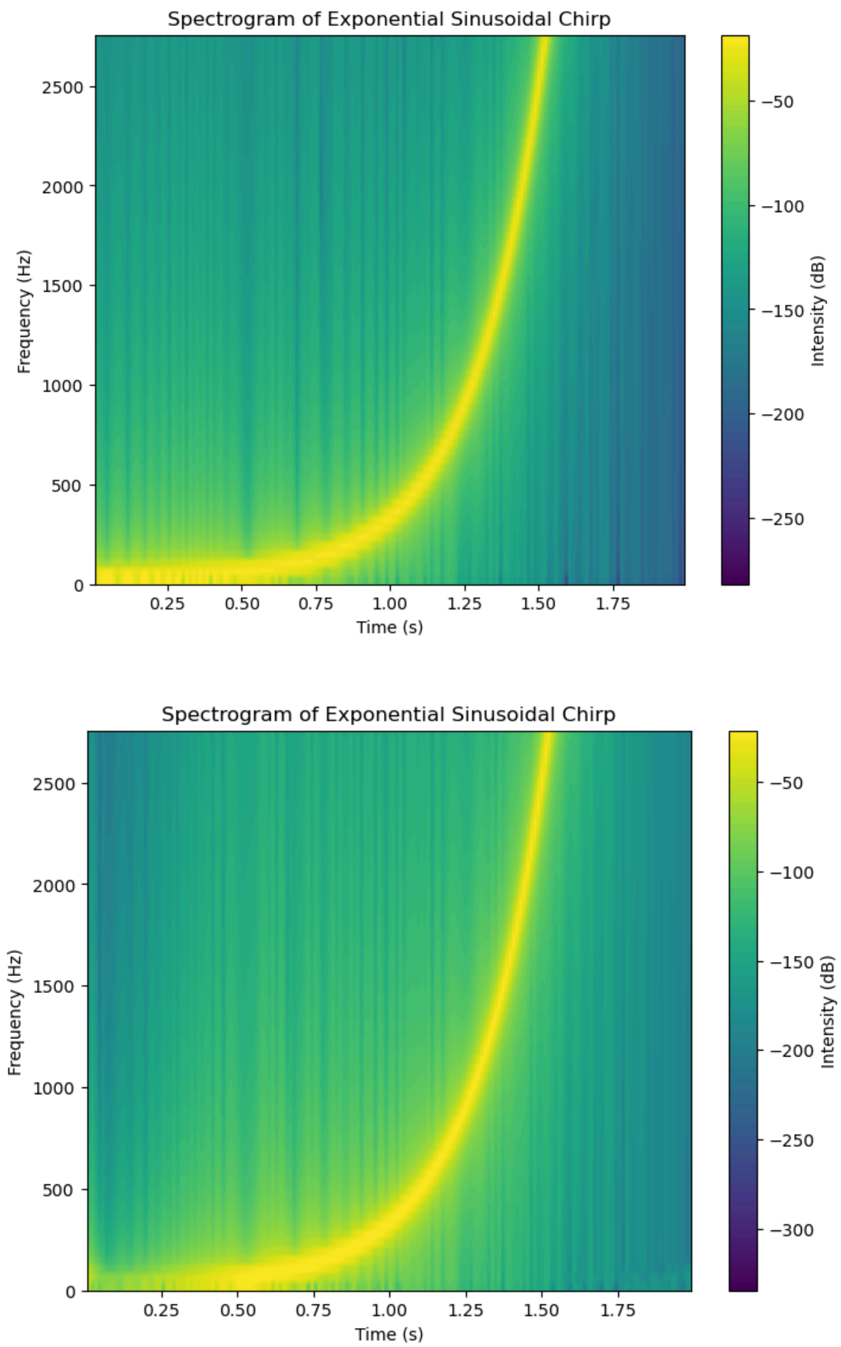
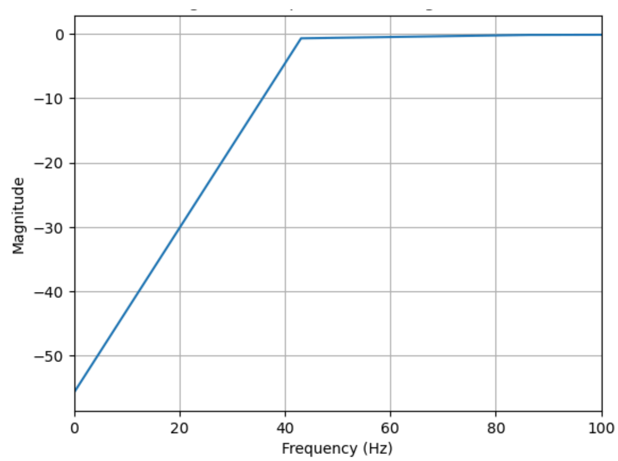


Figure 1

On plotting the magnitude response of the filter, it can be seen that it behaves like a high pass filter in the appropriate frequency range. This can be validated by the magnitude response obtained in the study (Figure 2 shows a comparison of the two).



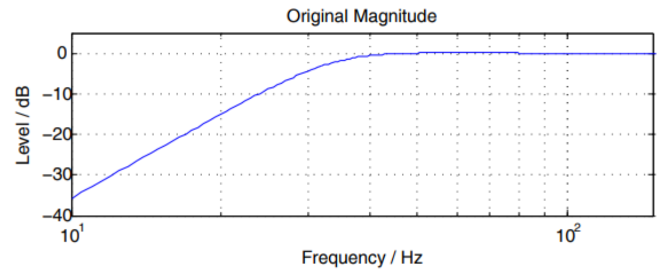
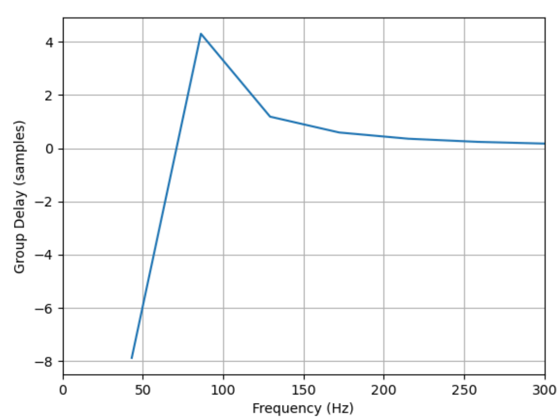


Figure 2: Loudspeaker enclosure magnitude response. Left- my implementation, Right- Herzog et. al. (2014).

A function for computing group delay was written, and the group delay of the loudspeaker enclosure was plotted. It was observed that there is indeed a peak in group delay in the low frequency range, but not exactly at the box resonance frequency. While the authors of the study observed a maximum group delay close to the box resonance frequency (30 Hz), I obtained a maximum group delay at about 85 Hz.



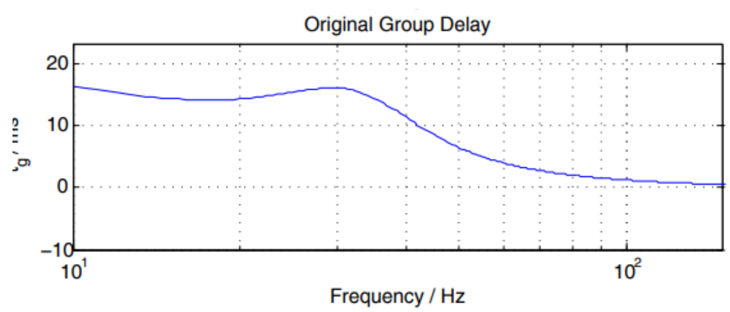


Figure 3: Loudspeaker enclosure group delay. Left- my implementation, Right- Herzog et. al. (2014).

I then wrote a function for an IIR all pass filter that has the same group delay as the loudspeaker enclosure as described in the study. The transfer function of this filter is as follows:

$$H_2(z) = (1 - 1/r\, e^{j\omega 0}\, z^{-1})(1 + 1/r\, e^{-j\omega 0}\, z^{-1}) \,/\, (1 - 1/r\, e^{-j\omega 0}\, z^{-1})(1 + 1/r\, e^{j\omega 0}\, z^{-1})$$

I also plotted the magnitude response and group delay response of the all pass filter as shown below:

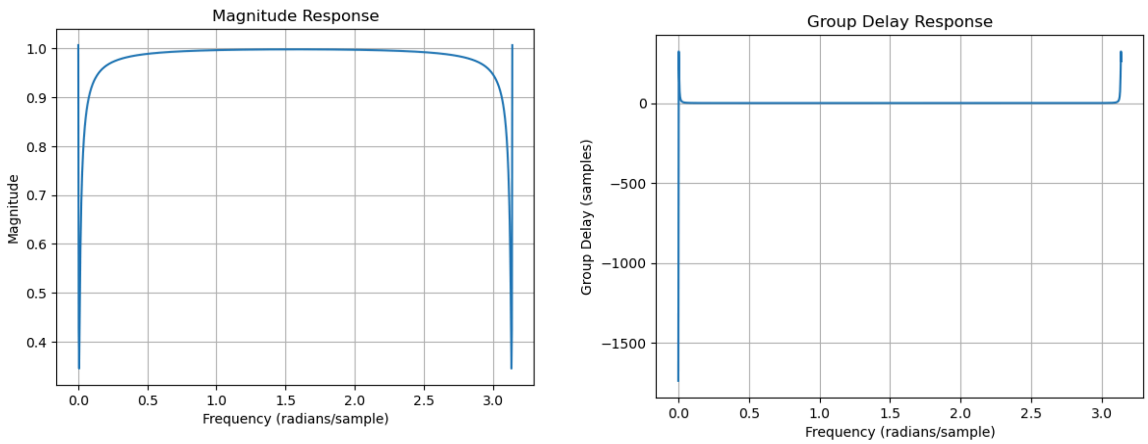
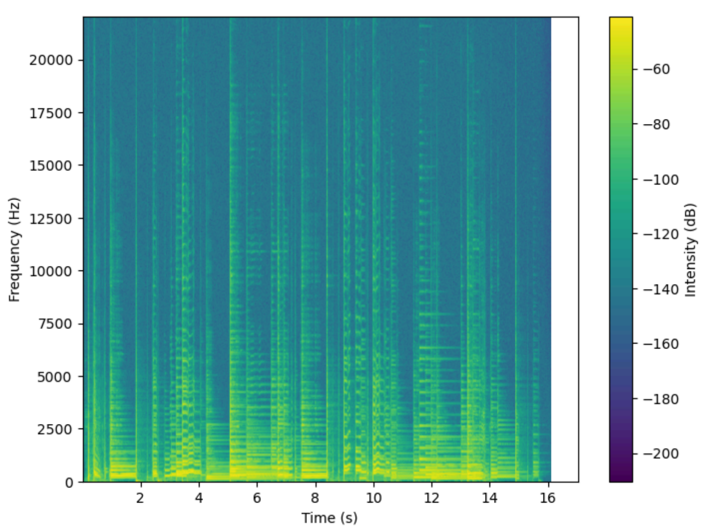
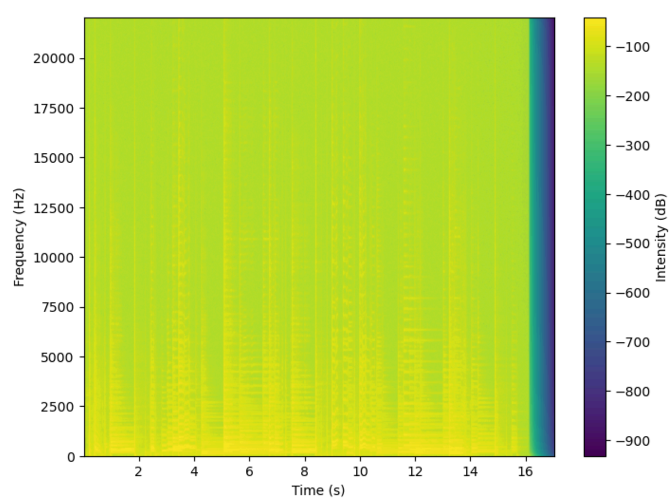
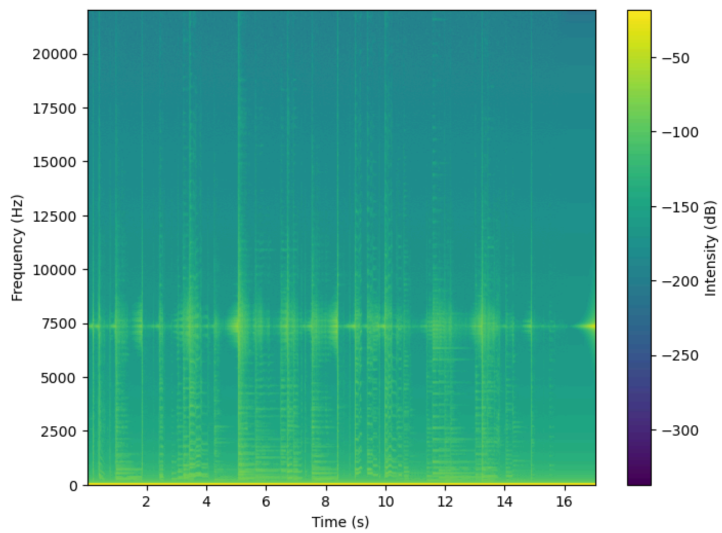


Figure 4: Magnitude Response and Group Delay of all pass filter

In order to use this all pass filter to equalize the group delay of the loudspeaker enclosure, I stored the output audio signal of the loudspeaker enclosure filter and time reversed it. The time-reversed signal was then fed to the all pass filter. The output from the all pass filter was time-reversed once again. Spectrograms for the following signals are shown below: 1. Original audio signal without any filtering 2. Audio signal after being processed by the loudspeaker enclosure filter 3. Output signal from the previous step after being processed further by the group delay equalization mechanism.







While it can be observed that the equalization mechanism does remove the effect of the loudspeaker enclosure on the frequency spectrum of the audio signal, it does not fully restore the signal to its original form. On listening to the final output audio signal, it can be observed that the signal is much softer and has many artifacts.

Conclusions

I was able to successfully simulate a vented loudspeaker enclosure as a fourth order high pass filter in python and obtain the expected magnitude response, and a group delay response quite close to the expected value.

The IIR all pass filter based equalization mechanism described in the reference study was implemented, however its results could not be fully analyzed. In order to compare the group delay of the all pass filter applied to the loudspeaker enclosure, I would have to calculate the combined group delay response of both filters. This could not be successfully implemented on Python due to errors that I was unable to debug in time.

In the future, I would like to debug this error and obtain the combined group delay in order to analyze whether or not the equalization mechanism has an appropriate effect, and modify it such that the restored/corrected signal is identical to the input signal with the exception that it's group delay is reduced at low frequencies.

References

1. Hersog, S., Hilsamer, M. (2014). *Low Frequency Group Delay Equalization Of Vented Boxes Using Digital Correction Filters*. Proc. of the 17th Int. Conference on Digital Audio Effects (DAFx-14), Erlangen, Germany, September 1-5, 2014

2. Loudspeaker Enclosure Design Guidelines by Rod Elliott