Optimize signal gain in Class D amplifiers to achieve more than 110 dB SNR

About this document

Scope and purpose

This design guide discusses a method to optimize the signal gain stages in a Class D amplifier to improve system noise performance. By minimizing the signal gain applied to the Class D amplifier stage and applying the majority of signal gain to a preamplifier (preamp) stage, the noise attributed to the Class D amplifier is minimized and the signal-to-noise ratio (SNR) of the system is improved. Additionally, the impact of different preamp operational amplifiers (opamps) and speaker types on residual noise and SNR is described.

By providing both theoretical insights and practical guidance, this application note aims to equip audio amplifier design engineers with the necessary tools and knowledge to optimize gain settings effectively. This will result in high-fidelity audio systems with superior SNR and minimal residual noise, meeting the demands of modern audio applications.

Intended audience

The intended audiences for this document are audio amplifier design engineers who want to optimize gain settings.

Table of contents

About this document **1**
Table of contents **2**
1 Introduction **3**
1.1 Overview 3
1.2 Residual noise vs. signal gain 4
2 Optimizing system gain **7**
2.1 Overview 7
2.2 Design example 110 dB with MA5302MS 7
2.3 Impact of preamplifier opamps on the noise floor 8
2.4 The practical impact of speaker types on SNR 9
3 Conclusion **13**
Revision history **14**
Disclaimer **15**

1 Introduction

1.1 Overview

In an amplifier design, it is essential to distinguish between signal gain and noise gain as they play distinct roles in the noise performance of the circuit. Signal gain refers to the amplification factor applied to the input signal, directly affecting the amplitude of the output signal. On the other hand, noise gain refers to the amplification factor applied to the internal noise of the amplifier. Noise gain determines the overall noise performance of the amplifier. Higher noise gain increases the internal amplifier noise seen at the output, reducing the overall signal-to-noise ratio (SNR) and increasing residual noise. By focusing on optimizing the gain settings in the preamp and Class D amplifier stage, designers can significantly improve SNR and reduce residual noise.

The SNR and residual noise are critical metrics in amplifier design for several reasons:

- **Audio quality:**
  - **Clarity**: A high SNR ensures that the amplified audio signal is clear and free from background noise. This is especially important in high-fidelity audio systems where the listener expects pristine sound quality.
  - **Detail preservation**: Higher SNR preserves the subtle details in the audio signal, making it essential for applications like music production, broadcasting, and high-end audio equipment.
  - **Dynamic range**: A high SNR allows for a greater dynamic range, which is the difference between the quietest and loudest parts of the audio signal. This is crucial for applications that require accurate reproduction of audio dynamics, such as live sound reinforcement and recording.
- **User experience:**
  - **Listening comfort**: Low residual noise contributes to a more comfortable listening experience by minimizing unwanted noise that can be fatiguing over extended periods.
  - **Professional standards**: Meeting professional audio standards often requires achieving specific SNR and noise floor levels. This ensures compatibility and performance consistency across different audio systems and environments.

In Figure 1, (V_i) refers to the signal into to the amplifier. (V_o) refers to the signal output. (V_{ni}) refers to the amplifier input noise. (V_{no}) refers to the amplifier noise seen at the output.

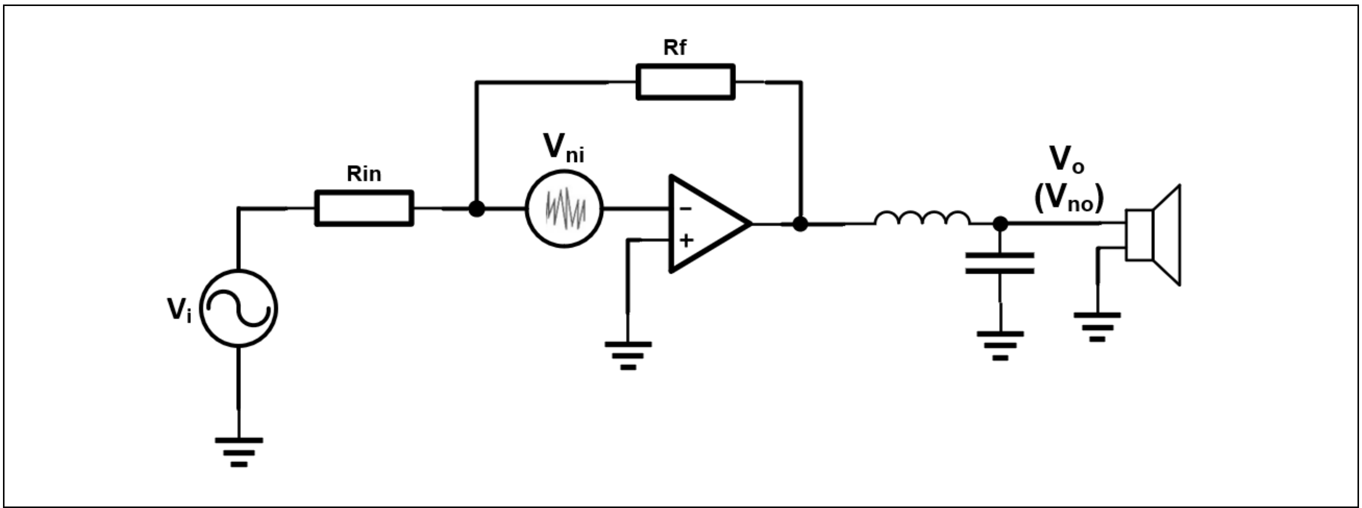


Figure 1 **Class D gain stage**

Lowering the noise gain in the power amplifier stage results in a reduced noise floor. The noise floor in an amplifier system is influenced by the gain settings of the various stages.

The signal gain of the Class D amplifier can go down to zero while the noise gain asymptotically approaches 1 as the signal gain is reduced. This means that the residual noise improvement saturates at some point of reduced gain.

Reducing Class D amplifier gain and compensating the gain with a preamp that is lower noise compared to the noise level of the Class D stage is preferred. By using multiple amplifier stages, you can distribute the total gain across the stages. This can help in preventing noise from being amplified at each stage, resulting in improved SNR.

The signal gain for in inverting amplifier, (A_v), is given by the following:

$$Av = -\frac{Rf}{Rin}$$

Equation 1

Noise gain for in inverting amplifier, (A_n), is given by the following:

$$An = 1 + \frac{Rf}{Rin}$$

Equation 2

1.2 Residual noise vs. signal gain

Figure 2, Figure 3, and Figure 4 illustrate the relationship between different signal gain levels in the Class D amplifier and the resultant residual noise with three different Class D ICs. The test conditions are:

- Supply voltage: ±35 V
- Switching frequency: 400 kHz
- Load impedance: 4 ohms
- Gain variation: Controlled by changing the input resistance (R_{in}) referenced in Figure 1.
- Audio analyzer bandwidth: 20 kHz AES-17, A-weighted

Figure 2 graph shows how the residual noise varies with the amplifier gain in an Infineon MERUS™ multi-chip module IR4301M (MCM) Class D IC. Initially, the residual noise remains low, but as the gain is increased, the residual noise increases as well. This indicates that while the multi-chip module can maintain low noise at moderate gain settings, higher gain settings lead to an increase in residual noise.

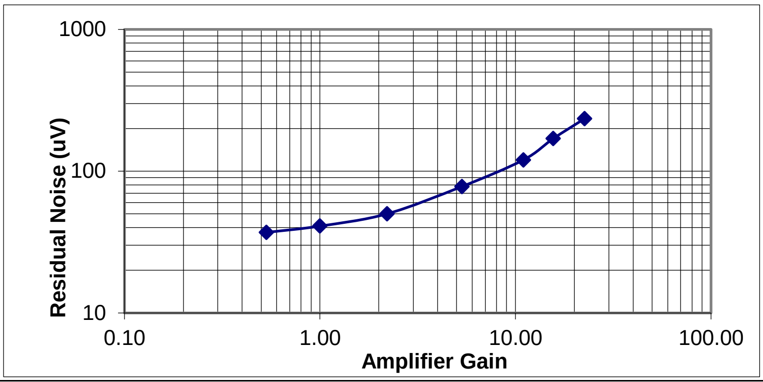


Figure 2 Residual noise vs. IR4301M gain

Figure 3 shows that the IRS2092SPBF Class D IC tested exhibits a similar noise trend as the MCM device. The residual noise remains low at lower gain settings but increases as the Class D gain is increased above 1. This rise indicates that while the IRS2092SPF performs well at low to moderate gains and its residual noise increases at higher gain settings.

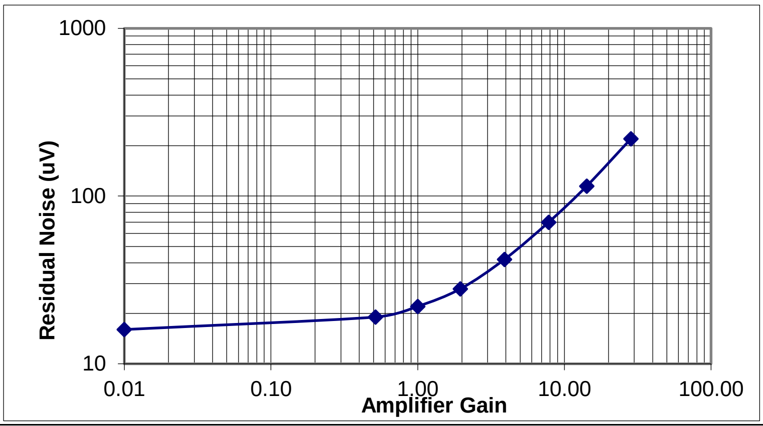


Figure 3 Residual noise vs. IRS2092 gain

As seen in Figure 4, the combination of a TLC081 opamp and IRS20957SPBF exhibits a similar behavior. As observed previously, the noise introduced by the Class D amplifier increases with amplifier gain. You also observe that as the noise gain approaches unity, the noise gain reduction has a negligible impact on residual noise. Consequently, the improvement in residual noise reaches a plateau at a gain of 1, as is the case with the previous examples.

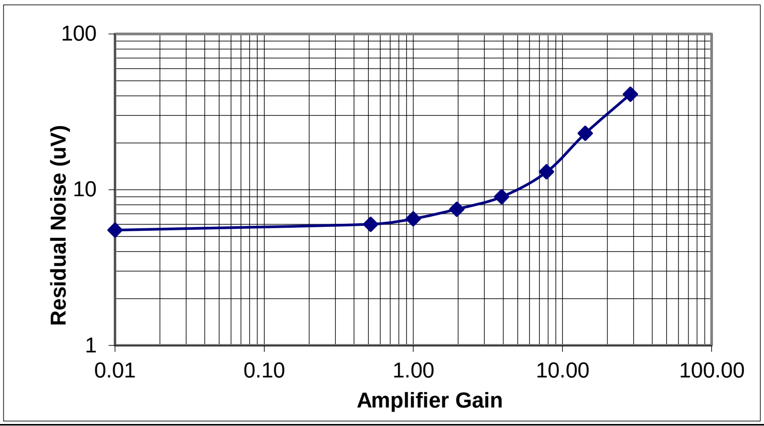


Figure 4 Residual noise vs. TLC081 + IRS20957 gain

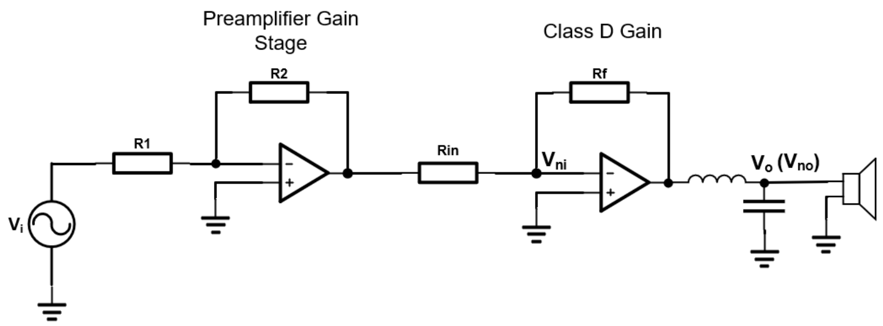
2 Optimizing system gain

2.1 Overview

In audio amplification systems, achieving a full-scale output requires adequate signal gain. This section describes how to utilize a preamp gain stage to ensure that the system gain is high enough to drive the power amplifier output to its full potential, particularly when the Class D amplifier gain is intentionally set low to minimize noise.

Most signal sources (analog or digital) output low voltage levels. If driving the Class D directly with low-level signals, the Class D gain typically needs to be set high to achieve its full output potential. This in turn increases the noise generated by the Class D amplifier. By incorporating a preamp gain stage, the input signal into the Class D stage can be set to an amplitude much greater than that of the signal source. This allows the amplifier to reach its full output potential while keeping the Class D gain as low as possible.

In Figure 5, utilizing a preamp gain stage allows you to apply gain to the input signal prior to the Class D stage, thus increasing the signal amplitude into the Class D amplifier. Multiplying the gain of each stage together gives us the total system gain $A_{v(total)}$. Total system gain typically needs to be set high enough to allow the amplifier to achieve its full-scale output when the source signal output level is at its maximum.



$$Av(total) = Av(preamp)\ \mathrm{X}\ Av(Class\ D)$$

Figure 5 **Preamp and Class D amplifier gain stages**

2.2 Design example 110 dB with MA5302MS

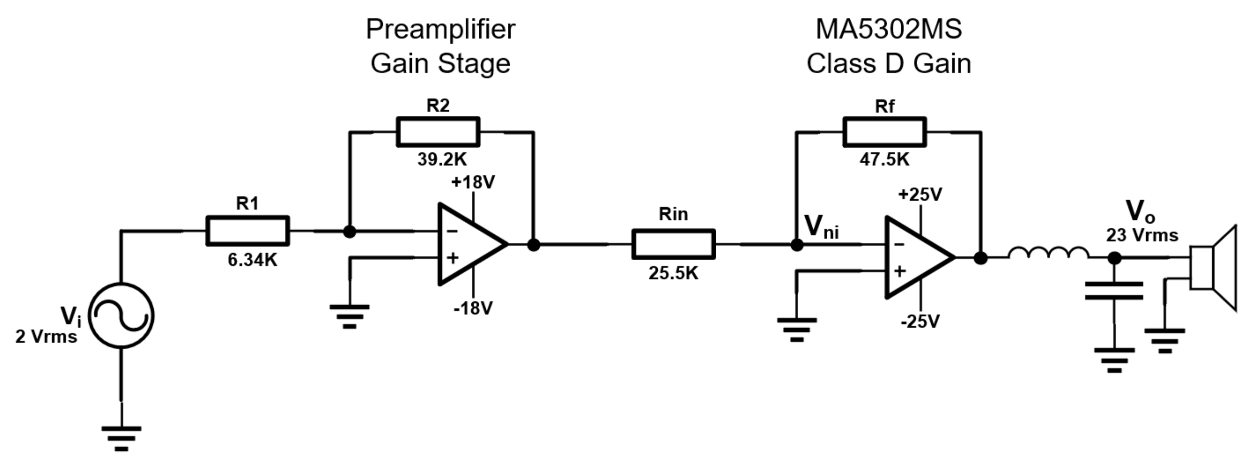
In most applications, source output voltage and target amplifier output voltages are known. The task is to determine how much gain to apply to the preamp and amplifier stages to achieve the best possible SNR.

Limiting factors determine how much gain can be added to the preamp stage are the opamp's power supply voltage rating, its output voltage swing capability, and the available supply voltage. In the example shown in Figure 6, the available supply voltage is +/-18 V, the output voltage swing capability of the opamp is up to within 200 mV of its supply voltage, and the opamp voltage rating is +/-20 V. With this information, you know that the maximum peak output voltage of the opamp is 17.8 V. You also know that Class D signal gain below '1' has negligible effects on residual noise due to its asymptotic nature.

This example uses the Infineon MERUS™ 2-channel analog input Class D audio multichip module MA5302MS. The target SNR is 110 dB, the source voltage is 2 Vrms, and the target output voltage is 23 Vrms. The total voltage gain, ($A_{v(total)}$), needed is approximately 11.5, (*Vout/Vin*) to achieve full output. The target residual noise is approximately 70 µVrms. The maximum in circuit gain capability of the chosen opamp is 6.29. The remainder of the gain will be assigned to the Class D stage. Because gain stages multiply, the Class D stage will need a gain of approximately 1.82. Using standard 1% resistor values you can get close to the target.

The calculations in Figure 6 provide the method to achieving the desired gain.

The chosen resistor values are a balance between minimizing noise and maintaining practical current levels and impedance matching. For instance, 6.34k and 39.2k provide a good trade-off, offering low enough resistance to keep Johnson noise reasonably low while ensuring that the opamp is not excessively loaded.



$$Av(preamp) = -\frac{R2}{R1} = \frac{39.2k}{6.34k} = 6.18$$

$$Av(Class\ D) = -\frac{Rf}{Rin} = \frac{47.5k}{25.5k} = 1.86$$

$$Av(total) = Av(preamp)\ \text{X}\ Av(Class\ D)\ =\ 6.18\ \text{X}\ 1.86 = 11.49$$

$$Vo = Vi\ \text{X}\ Av(total)\ =\ 2\ Vrms\ \text{X}\ 11.45 = 22.98\ Vrms$$

$$An = 1 + \frac{Rf}{Rin} = 1 + \frac{47.5k}{25.5k} = 2.86$$

Figure 6 Example preamp and Class D amplifier gain setting – MA5302MS

In this example, the output capability of opamps is maximized. This gain structure allows full scale output of 23 Vrms with 2 Vrms input and achieves SNR of 110 dB using MA5302MS. With A_n of only 2.86, the gain of this design ensures low amplifier noise contribution.

By understanding and applying these principles, designers can effectively optimize their amplifier designs to meet stringent amplifier noise requirements.

2.3 Impact of preamplifier opamps on the noise floor

Preamp opamps play a role in determining the overall noise performance of an amplifier system. The inherent noise characteristics of the opamps, such as voltage noise density, directly affects the residual noise and SNR of the amplifier system. High-quality opamps with low noise specifications can reduce the overall noise floor. The selection of an appropriate opamp for the preamp stage is essential for optimizing the noise performance of the signal chain.

The voltage noise density (nV/√Hz) specification of an opamp represents the amount of noise voltage generated by the opamp per unit of bandwidth. A higher voltage noise density increases the noise floor, reducing SNR. Noise is typically described as low-level background hiss or white noise. Selecting opamps with low voltage noise density is important for applications requiring high fidelity and low floor noise.

To demonstrate the impact of preamp opamps on the noise floor, a comparison table of various opamps and their noise performance characteristics is provided in Table 1. This table includes part numbers, their voltage noise density rating, and their impact on noise when the preamp and Class D gain remain common. The opamps chosen are a mix of low, average, and high noise types. By examining these results, the correlation between an opamp's noise specification and the overall noise performance of the amplifier can be observed.

Table 1 Opamps and their noise performance characteristics

Part number	nV √Hz at 1kHz	$Av_{(preamp)}$	$Av_{(Class\ D)}$	Residual noise (µV)	SNR (dB)
LM358DT	55	6.18	1.86	98	107
TL062CDR	30	6.18	1.86	97	107
TL072IDR	18	6.18	1.86	75	109.1
TL082IDR	18	6.18	1.86	78	108.9
NE5532DR	5	6.18	1.86	66	110.3
MC33078DR	4.5	6.18	1.86	66	110.2
LM4562MAX	2.7	6.18	1.86	70	110.4
OPA1656	4.3	6.18	1.86	65	110.5

2.4 The practical impact of speaker types on SNR

Typical SNR measurements for Class D amplifiers are conducted using an audio analyzer with a bandwidth limited A-weighted 20 kHz AES17 filter. This filter is intended to simulate human hearing. However, in practical applications, inherent high-pass and low-pass filter characteristics of different speaker types also influence what the human ear perceives beyond the audio analyzers simulated hearing filters. Subwoofers exhibit low-pass characteristics, midrange drivers act as band-pass filters, and tweeters function as high-pass filters. These intrinsic filters intersect with the analyzer filters and impact the SNR measurements by further reducing unwanted noise frequencies. Considering the impact speakers have on noise in the system is practical when considering the whole audio system noise performance.

In the following figures, how different speaker types and their intrinsic frequency response can impact residual noise and SNR is shown.

Figure 7 shows a typical noise measurement from the previous design example in Figure 6 that yields 110 dB. SNR. The filters applied to the audio analyzer are the typical A-weighted 20 kHz AES17. This is considered the classic analyzer filter set for a residual noise and SNR measurements with 0 dB attenuation at 1 kHz. You can also consider the speaker type these filters represent to be full range with a frequency response of 20 Hz – 20 kHz.

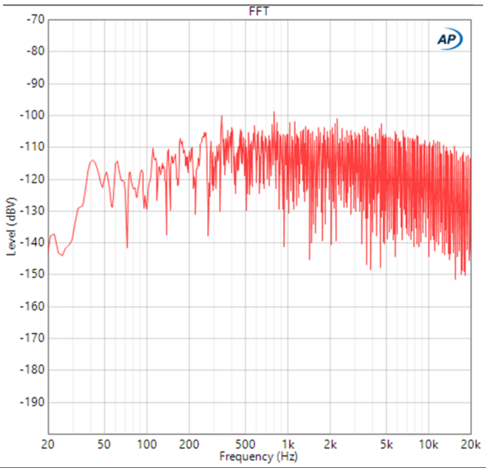


Figure 7 **Example noise measurement A-weighted 20 kHz AES17**

In Figure 8, a typical low pass filter is applied, emulating a subwoofers intrinsic low pass filter. It yields improved noise results. In this case, the superimposed subwoofer filter is a Butterworth lowpass set to 250 Hz with 0 dB attenuation at 200 Hz. Overlaying the speaker filter with the A-weighted AES17 filter yields 129 dB SNR.

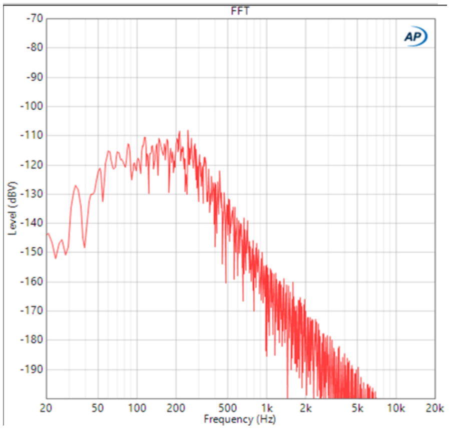


Figure 8 **Example noise measurement with an additional 250 Hz lowpass**

In Figure 9, a band pass filter that represents mid-range speaker characteristics is applied. In this case, the superimposed bandpass filter is a Butterworth set to 250 Hz and 2 kHz with 0 dB attenuation at 1 kHz. Weighting the speakers natural filter on top of the A-weighted AES17 filter yields 117 dB SNR.

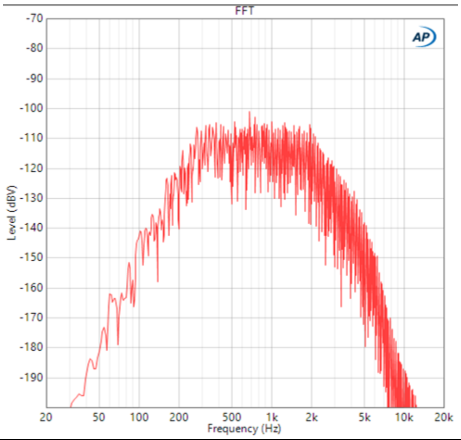


Figure 9 Example noise measurement with additional 250-2 kHz bandpass filter

In Figure 10, a high pass filter that represents a tweeter or other high frequency speaker is applied. In this case, the overlaying speaker filter is a Butterworth high pass set at 2 kHz with 0 dB speaker attenuation at 5 kHz. Overlaying the speaker filter with the A-weighted AES17 filter yields 111 dB SNR.

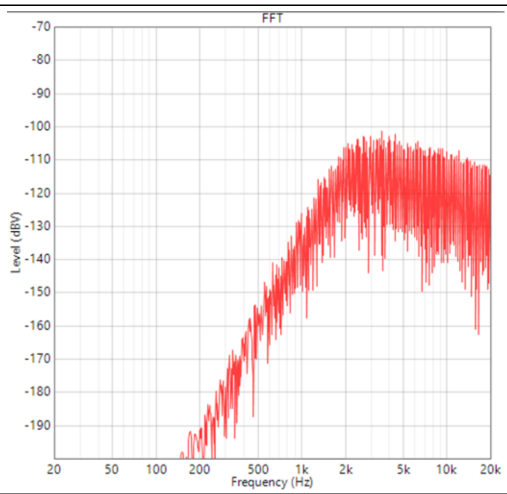


Figure 10 Example noise measurement with additional 2 kHz high pass filter

The inherent filtering characteristics of different speaker types play a role in shaping the practical SNR performance of audio systems.

- Subwoofers, with their intrinsic low-pass filter characteristics, are effective in reducing high-frequency noise, thereby improving SNR substantially.
- Midrange drivers, acting as band-pass filters, provide moderate improvement in SNR by filtering out both low and high-frequency noise.
- Speakers intended for high frequencies, such as tweeters, filter out much of the low frequency noise content, impacting SNR slightly.
- Full-range speakers, while offering a broader frequency response, align more closely with the standard audio analyzer A-weighted SNR measurements due to their less inherent noise filtering.

The impact a speaker's frequency response has on noise is due to the conversion of noise density to rms is in a linear scale. Imagine plotting the noise spectrum on a linear frequency axis. In this representation, the distribution of noise across frequencies provides a clear visualization of how different parts of the spectrum contribute to the total noise. The integration of the noise across the spectrum results in the total rms noise. When this response is weighted with the speaker's frequency response, the total rms noise is reduced. There are three filters to consider; AES17, A-weighting, and speaker frequency response weighting. Speaker frequency response weighting is an additional filter on top of the A-weighted and AES17 filters. Understanding the impact of speaker types on system level SNR performance can inform design decisions and improve overall audio system performance.

3 Conclusion

In summary, optimizing the gain settings in a Class D amplifier system by reducing the amplifiers signal gain while increasing the preamp signal gain is an effective method to increase SNR and minimize residual noise. The careful selection of low-noise opamps for the preamp stage is critical, as their inherent noise characteristics have an influence on the overall noise performance of the system.

The impact of speaker types on SNR further underscores the importance of considering the entire signal chain. Subwoofers, midrange drivers, and full-range speakers each have unique filtering characteristics that affect noise measurements and what is perceived by the listener. By understanding and leveraging these natural filtering effects, audio designers can achieve more accurate and favorable SNR results, ultimately leading to improved audio measurements and performance.

This comprehensive approach to gain optimization, component selection, and consideration of speaker interactions on audio system noise ensures that Class D amplifiers deliver high-fidelity sound with minimal noise, meeting the demands of modern audio applications

Revision history

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V 1.0	2024-09-12	Initial release

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