Power Efficiency and Distortion in Class D Audio Amplifiers

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Introduction

Class D amplifiers (CDAs) have recently dominated the audio amplification industry, finding their place in headphones, speakers, stereos, Bluetooth-enabled audio devices, subwoofers, etc. The rationale for using a CDA is straightforward—more power efficiency, less heat produced, longer battery life, less external components, smaller—compared to their linear counterparts (class A, B, AB, and C amplifiers). Additionally, CDAs achieve similar levels of audio quality and sound fidelity compared to class AB amplifiers, and these parameters can be further improved with additional circuitry.

Overview of Class D Amplifiers

CDAs were developed as a solution to the lackluster power efficiency rates of existing amplifiers. All amplifiers are made using transistors, an electrical component that acts as a switch that regulates, controls, and sometimes amplifies voltage and/or current signals. Transistors dissipate the majority of their power when they switch in between their conducting and non-conducting (on vs off) states. CDAs, by using a different transistor than linear amplifiers, are able to switch between their on and off states almost instantly, providing significantly less overall power dissipation.

This near-instantaneous shift between states in a CDA results in very little time for the output voltage to gradually build up or fall. Instead, the transistor's output voltage appears as a pulse waveform that alternates between the maximum positive and negative voltages, with no in-between voltages. Thus, the CDA always appears either on or off, effectively eliminating the pesky power-consuming in-between stage. Next, let's examine how exactly CDAs amplify a signal, using their three main components—a comparator, a push-pull transistor configuration, and a low-pass filter.

Comparator

A comparator does exactly what it sounds like: compares two signals. A CDA compares a triangle waveform to its input signal. Every time the triangle wave is above the input signal, the comparator records a 'high'. Every time the triangle wave is below the input signal, the comparator records a 'low'. Thus, the output of the comparator becomes a pulse wave. The width of each pulse corresponds to the instantaneous signal level—narrower pulses represent a higher input voltage, and wider pulses represent a lower input voltage. This entire process is referred to as pulse-width modulation (PWM).

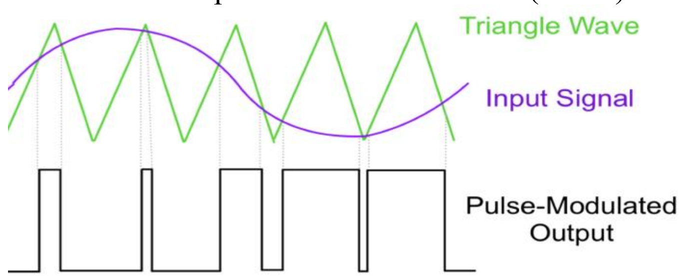

Figure 1. Comparator pulse-modulation process

Push-Pull Configuration

Next, this pulse wave is sent into 2 transistors in a push-pull configuration, in which one transistor ‘pulls up’ the input voltage to a higher value, and the other ‘pushes down’ the input voltage to a lower value. These higher and lower values are specified by the positive and negative DC voltage rails connected to each transistor. Thus, the signal profile stays the same (that is, the effects of PWM are kept constant), but the high and low the comparator had originally created are now increased to the high and low of the DC rails, resulting in amplification.

Low-Pass Filter

Finally, the positive and negative signals are added together and sent into a low-pass filter. This takes the amplified transistor output, which is still a pulse wave, and smooths it back into its original sinusoidal form, effectively converting a digital signal into analog. Now, we have our amplified signal!

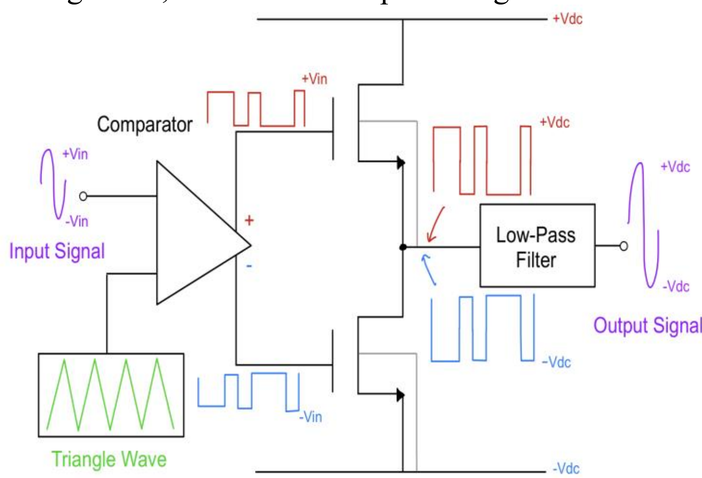

Figure 2. Class D amplifier circuit diagram

Modulation Schemes and Common Problems

The above explanation describes what is known as a PWM CDA, or a pulse-width modulated class D amplifier. CDAs have four main modulation schemes, all of which will be covered briefly below, including the benefits and drawbacks of each scheme.

Figure 1 displays an open-loop PWM CDA, which is preferred for low-fidelity (in this context meaning less precise) applications due to its simple implementation. A closed-loop PWM CDA is an open-loop PWM CDA with a feedback system to decrease the CDA’s distortion. This modulation adds an integrator to increase amplification and filter unwanted loop noise.

The next modulation scheme is the Delta-Sigma CDA, which replaces the comparator with a quantizer. This scheme is used to achieve more musicality (lower output noise, decreased distortion) but causes increased hardware complexity and power dissipation.

The third scheme is a bang-bang CDA, which has the most simplistic configuration and decreases power dissipation by lowering the typical switching frequency—the rate at which transistors switch on and off—associated with other CDAs.

Finally, the last modulation scheme is called self-oscillating, and it functions in a similar manner to a normal oscillator. The advantages of this scheme are that the feedback network is reworked to reduce the noise and distortion fed into the filter. However, this scheme has added hardware complexity as a drawback.

Modifications for Optimized Efficiency and Sound Fidelity

While all schemes do have their individual pros and cons, CDAs generally suffer from distortion increasing alongside power efficiency. References [3] – [8] each examine optimization of either efficiency or sound fidelity in a class D amplifier. Let’s examine some potential implementation ideologies that overcome the shortcomings of CDAs.

Optimizing Sound Fidelity

References [3] and [4] deal exclusively in distortion reduction. Reference [3] uses signal processing and two specific modulators (delta-sigma and ‘chopping), to remove noise from the original PWM signal, resulting in an overall distortion/noise reduction of ~25 - 45 dB, depending on the methodology used. For context, the range of 20 – 40 dB is around the sound of a whisper or rustling leaves, making for a noticeable decrease. Reference [4] describes a solution that uses a digitally-controlled delay that realigns the PWM signal’s edges to alter the width of the pulses. This was implemented as a feedback loop and was created specifically to find a solution that doesn’t use signal processing or overly complex hardware. Overall, [4] demonstrated a decrease in distortion by ~ 50 dB, which is just below the noise level of a typical conversation.

Optimizing Power Efficiency

References [5] and [6] focus on increasing efficiency. Reference [5] uses an optimization that gives a final efficiency output of 91.8% by utilizing a specially designed pre-amplification stage as well as their own comparator and circuit designs. Reference [6] analyzes the power efficiency of specifically output stages, demonstrating how most power loss occurs there. This paper proposes using a different chip layout design which would allow for massive power dissipation reduction (42% less dissipation) and chip area reductions (only 1/6 of the chip area utilized).

Optimizing Both

Lastly, references [7] and [8] depict separate methods of increasing power efficiency while preserving distortion reduction. Reference [7] proposes a combination of a class D and an AB amplifier, using the AB amp to keep distortion low and do most of the CDA filtering (with little extra power dissipation). Reference [8] employs an additional feedback loop onto a closed-loop PWM CDA which allows for better overall performance.

CDAs in Connection to Senior Project

Regarding our digital multi-effect guitar pedal, we decided, due to time constraints, that buying a pre-built amp would better serve our interests instead of building one. While we never formally created a CDA, the knowledge gained from this study allowed us to better understand the innerworkings and importance of an integral pedal component.

Conclusion

CDAs have a plethora of uses in audio amplification due to their high efficiency, low distortion, and low heat/power dissipation. These qualities make CDAs perfect for small applications that need long-lasting, quality audio. While these amps do have a trade-off between power dissipation and distortion, this drawback can be avoided by implementing proper circuitry as demonstrated by the reference papers discussed. Overall, CDAs have been so rigorously studied and tested that there, without a doubt, exists a configuration to meet all your audio needs.

References

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