High-Efficiency Audio Amplification Using Class-D Audio Power Amplifiers

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Abstract

Audio amplifiers based on a Class-D topology have been implemented in various high power systems to take advantage of the topology's increased efficiency. Class-D offers advantages for portable audio applications, but the designer must be aware of potential problems with Class-D audio amplifiers that do not exist when designing with linear audio amplifiers in PDAs, multimedia notebooks, personal communication applications, and other portable, battery-operated equipment.

Introduction

Nearly all the integrated circuit amplifiers available on the market are based on a Class-AB architecture. This architecture offers very good total harmonic distortion plus noise (THD+N) performance, with fairly low supply currents, IDD, sometimes referred to as quiescent current. Class-AB amplifiers are a subset of a larger group of audio amplifiers collectively called linear audio power amplifiers. These amplifiers are notoriously inefficient, with the maximum usable output power typically being constrained by the ability to remove heat from the IC as a result of internal power dissipation in the IC. This excess heat is generated by power dissipated in the amplifier, instead of being delivered to the load.

In applications where thermal performance or battery life is important, a different amplifier topology is needed. Class-D APAs overcome the shortfalls of Class-AB amplifiers by being highly efficient APAs. This allows extended run-times in battery-operated equipment.

Analogy between audio power amplifiers and power supply regulators

An analogy can be made between Class-AB audio power amplifiers (APAs) and linear regulators used in power supplies. In a linear regulator, the output voltage is less than the input voltage by some voltage, V_{DROP}, which is merely the difference between the input voltage and the output voltage:

$$V_{DROP} = V_{IN} - V_{OUT}$$

This voltage, V_{DROP}, is dropped across some kind of pass element, usually either a bipolar or a MOSFET transistor, as shown in Figure 1.

The power dissipation in the linear regulator is equal to the load current multiplied by the voltage across the pass element, V_{DROP}. The useful range of linear regulators is limited by the

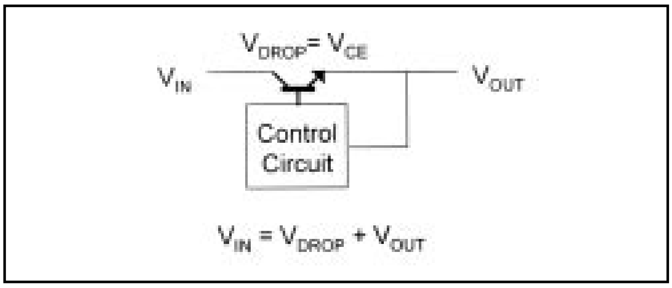

Figure 1. Linear regulator block diagram

ability to remove heat from the pass element. For example, if we have a 5-V power supply, and want to generate a 1-A, 3.3-V supply voltage to power some 3.3-V logic circuits, the V_{DROP} is equal to 1.7 V, and the power dissipated in the pass element will be:

$$\begin{aligned} PD &= V_{DROP} * I_{LOAD} \\ &= 1.7\ V * 1\ A \\ &= 1.7\ W \end{aligned}$$

which is a significant power dissipation. This is energy supplied from the power supply that is dissipated as heat instead of being used to actually power the circuit. Looking at the power consumed by the load:

$$\begin{aligned} P_{LOAD} &= V_{LOAD} * I_{LOAD} \\ &= 3.3\ V * 1\ A \\ &= 3.3\ W \end{aligned}$$

The total power delivery by the supply is the sum of the power dissipated in the pass device and the power delivered to the load:

$$\begin{aligned} P_{SUPPLY} &= P_D + P_{LOAD} \\ &= 1.7\ W + 3.3\ W \\ &= 5.0\ W \end{aligned}$$

Calculating the efficiency:

$$\begin{aligned} \text{Efficiency} &= P_{LOAD}/P_{SUPPLY} \\ &= 3.3\ W / 5.0\ W \\ &= 66\ \% \end{aligned}$$

which is quite poor. It is important to note that 1 A of current is consumed from the input power supply, and that same 1 A of current is delivered to the load. The power, however, is not the same.

To increase this efficiency, a basic change in the way power conversion is accomplished is needed. By using a DC/DC converter (also known as a switching regulator), the efficiency can be significantly increased.

A DC/DC converter works by moving pulses of power from the input power supply to an energy storage component, usually an inductor. The inductor is then connected to the load, and acts to smooth out the power being applied to the load.

Unlike a linear regulator, a DC/DC converter can be designed to have the output voltage be greater than the input voltage (called a boost regulator), have the output voltage be less than the input voltage (called a buck regulator - provides the same functionality as a linear regulator), or even designed to operate in both modes, depending on whether the input voltage is greater than, or less than, the desired output voltage (called, appropriately, a buck-boost regulator).

A conceptual circuit schematic for a buck regulator is shown in Figure 2. When the controller determines the load needs more

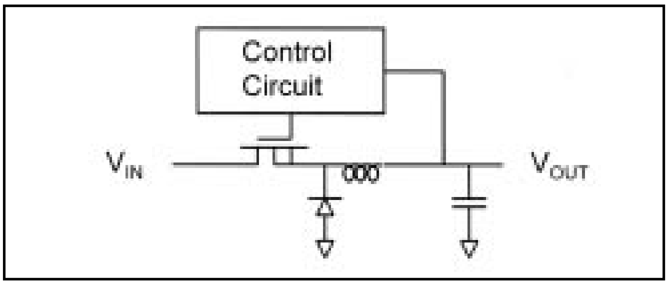

Figure 2. Block diagram of a buck regulator

power, the switch is closed, drawing power from the input supply. Once the desired output power level is reached, the switch turns off, and the inductor supplies current to the load. Once the output voltage drops below a threshold value, the switch is again commanded to close, and the whole cycle repeats itself.

If the output voltage is a DC-level, the circuit is simplified in that the input and output voltages are related by the duty cycle of the switch:

$$V_{OUT} = V_{IN} * D$$

Where D is the duty cycle of the switch.

The efficiency of this converted is calculated again using the equation:

$$\text{Efficiency} = P_{LOAD}/P_{SUPPLY}$$

Where the difference between P_{LOAD} and P_{SUPPLY} is the power dissipated, P_D, in the regulator. The PD of the regulator has two components, one being switching loss, and the other being conduction loss. Typical values are in the range of 90 to 97% efficiency.

Two pages into the paper, and I have not yet written "Class-D," you might start wondering if this is a paper on power conversion. Well, audio amplification IS power conversion, but instead of supplying a constant voltage under conditions of changing load current to the load, we need to supply a changing voltage to a constant (more or less) resistance (a speaker).

Class-AB APAs are analogous to linear regulators, but instead of a fixed voltage that is dropped across an element, the voltage drop follows the music waveform. As the output signal nears the rails, the voltage drop becomes small (thus, giving good efficiency), but when the output signal is moving about the mid-rail level, the voltage drop is quite large (giving poor efficiency). For maximum output level sine waves, the efficiency can be quite good as the amplifier spends a considerable portion of the period with a small voltage drop across it. However, for real music waveforms, the output level is usually much lower, leading to quite poor efficiency. A simplified Class-AB output stage is shown in Figure 3, which details the voltage drops in the system.

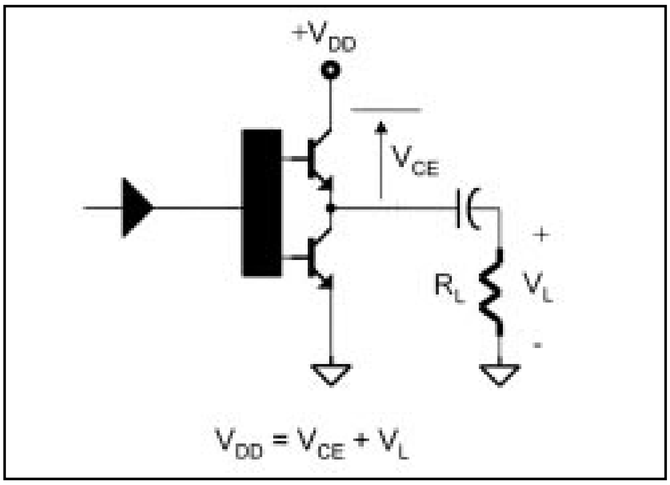

Figure 3. Class-AB output stage

Many years ago, engineers noted the similarities between power conversion, and audio amplification, and set out to develop an APA that is analogous to the DC/DC converter. The result of this work was the Class-D topology shown in conceptual form in Figure 4.

The basic operation of the Class-D architecture shown in Figure 4 is explained in the following section.

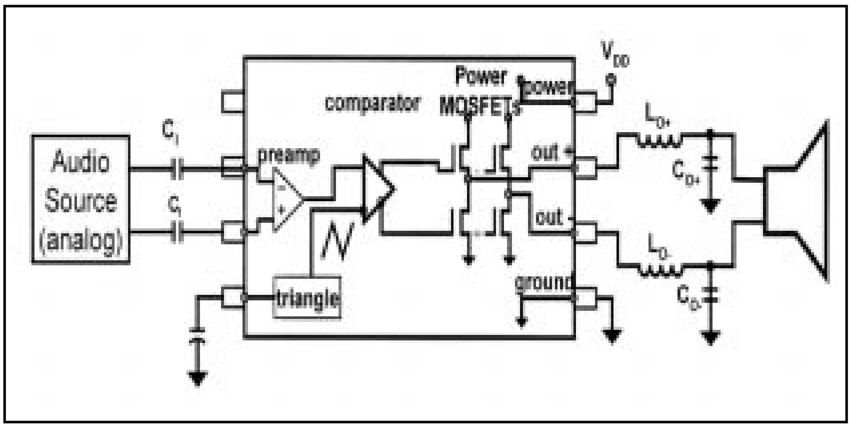

Figure 4. Class-D conceptual block diagram

Basic Class-D Theory of Operation

An analog audio input signal is applied to the input terminals of the amplifier, and undergoes a differential-to-single-ended conversion (single-ended designs are also possible, but this is

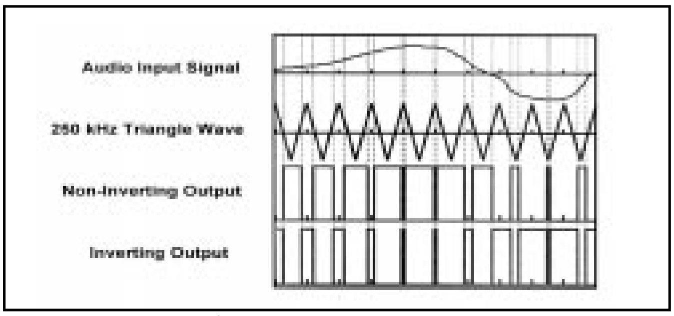

Figure 5. Comparator waveforms

the most general case). The audio signal is then fed into the positive input of a very high-speed comparator, along with a ramp signal to the negative input of the comparator. As shown in Figure 5, each time the input signal crosses the ramp waveform, the outputs of the comparator change state. The outputs of the comparator are connected to gate drive circuitry which provides level-shifted, low-impedance drive signals for the output power transistors.

Class-D APAs in Portable Equipment

The improved efficiency of Class-D makes it an obvious choice for use in portable, battery-powered equipment. Using an audio power analysis software tool developed by Texas Instruments, it has been shown that a Class-D amplifier is capable of running at much higher efficiencies than a Class-AB amplifier. For a 1 kHz tone at full-scale output power, a typical Class-AB amplifier will run at approximately 63% efficiency. For a similarly-rated Class-D amplifier that has output transistors with an $r_{DS(on)}$ of 0.300Ω, its efficiency is approximately 86%. But, most audio amplifiers are not used to drive tones into speakers, they are used to drive music or voice-band signals.

A signal's crest factor is defined as its ratio of peak power to RMS power. Tones therefore have a crest factor of 3 dB. Typical music pieces have crest factors of approximately 15 dB. When comparing Class-AB and Class-D APAs with such real-world signals, the difference in efficiency becomes startling. For a typical Class-AB APA amplifying music with a crest factor of 15 dB (125 mWRMS with 4 Wpk), an efficiency of approximately 20% will result. In other words, 80% of the energy supplied by the battery will be dissipated inside the APA. In comparison, a Class-D APA under the same conditions will have an efficiency of nearly 75%, greater than a three and a half times improvement in efficiency!

This improvement could be used to extend run-times of battery-powered equipment, or for a given amount of acceptable power dissipation, the output power could be increased 3.5 times using a Class-D APA in place of a Class-AB APA.

The above data points were generated using TI's Audio Power Analysis Program, the input file being a jazz track, JZZ_2_M, playing on 5 V BTL amplifiers.

To confirm these software simulations, a laboratory test was performed using two commercially-available APAs, the Class-AB APA was a TPA0202, and the Class-D APA was a TPA005D02, both available from Texas Instruments. These are 2 W, 5 V, BTL amplifiers. For detailed information on this test, please refer to the section title, Efficiency.

Implementing class-D APAs in portable equipment

Using a Class-D APA in place of a Class-AB APA presents some challenges to the designer. There are three primary areas that are significantly different for Class-D APAs than for Class-AB APAs. Perhaps the most obvious difference is the need for an output filter for use with Class-D APAs. The design criteria and procedure for the output filter are discussed in a following section titled, Output Filter Design. The second area that requires extra design effort is the supply decoupling and bypass capacitance as the amplifier is now working in a switching configuration, which leads to high frequency, high current pulses being demanded from the power source. These considerations are discussed in the section titled, Power Supply Decoupling. The switching nature of Class-D APAs makes the PCB layout critical, and is discussed in the section titled, PCB Considerations. EMI considerations are discussed in the section with that name. A section detailing the efficiency gains achievable with Class-D APAs is in the section titled, Efficiency. Finally, the performance of a commercially-available Class-D APA is discussed in the section titled, Commercially-Available Class-D APA.

Output filter design

Class D amplifiers require special filtering at the output to remove the high-frequency switching component and accurately reconstruct the audio signal. The output filter is a low-pass filter (LPF) which sets the high frequency -3-dB point of the bandwidth. The major consideration here is how to choose the components and set the desired -3-dB point.

Filter design goals

A second-order low-pass filter is commonly used for the output filter. A popular filter topology commonly used in Class-D APAs is the Butterworth filter, which is characterized by a flat response over the pass band, good phase response, but with less attenuation after the cutoff frequency than other filter topologies. The order of the filter determines how many poles exist at the same frequency, with each pole providing -20 dB per decade of signal attenuation. Thus, a second-order Butterworth filter provides -40 dB of signal attenuation per decade. The cutoff frequency, f_c, can be determined using the equation

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

where L is the inductance and C is the equivalent capacitance. Take as an example a filter design with the following component values: 15 µH for the inductors, and 0.22 µF and 1 µF capacitors in parallel for an equivalent capacitance of 2.22 µF, setting the cutoff frequency to 27.5 kHz. The main purpose of this filter is to reduce the switching frequency to an acceptable level while not attenuating the audio band. The 250 kHz amplifier output square-wave signal is then reduced by -40 dB to one percent of its pre-filtered value, while passing the audio information with little attenuation. The considerations for inductor selection are inductance, continuous and peak current ratings, dc series resistance, and package form factor. The inductance of 15 µH was chosen based on commonly available inductance and capacitance values.

Output filter components

The output inductors are key elements in the performance of the Class-D audio amplifier system. It is important that these inductors have a high enough current rating and a relatively constant inductance over frequency and temperature. The current rating should be higher than the maximum current expected to avoid magnetically saturating the inductor. When saturation occurs, the inductor loses its functionality and looks like a short circuit to the PWM signal, which increases the harmonic distortion considerably. A shielded inductor may be required if the Class-D amplifier is placed in an EMI-sensitive system; however, the switching frequency is low for EMI considerations and should not be an issue in most systems. While the output square wave has fast rise and fall times, if the length of the traces between the IC and the inductors is kept to a minimum, the EMI generated by those traces is also minimized. The DC series resistance of the inductor should be low to minimize losses due to power dissipation in the inductor, which reduces the efficiency of the circuit. Capacitors are important in attenuating the switching frequency and high frequency noise, and in supplying some of the current to the load. It is best to use capacitors with low equivalent-series-resistance (ESR). A low ESR means that less power is dissipated in the capacitor as it shunts the high-frequency signals. Ceramic capacitors are selected because of their low ESR. Placing these capacitors in parallel also parallels their ESR, effectively reducing the overall ESR value. The voltage rating is also important, and, as a rule of thumb, should be 2 to 3 times the maximum RMS voltage expected to allow for high peak voltages and transient spikes. These output filter capacitors should be stable over temperature since large currents flow through them, leading to self-heating.

A final note on the output filter - this is a source of not immediately obvious energy loss. Take the case of zero input signal where the outputs are switching with 50% duty cycle. Each half cycle some charge is delivered to the 0.22 μF capacitors to ground, and during the other half cycle, some charge is removed from the 0.22 μF capacitors to ground. This looks like an increase in supply current to the device, when in fact, the current is going to the load. Perhaps with judicious selection of switching frequency, and output filter component values, this current can be minimized, allowing even higher efficiencies. This would provide a good topic for a future paper.

Class-D output filter design methodology

The normalized transfer function, H(s), for the Butterworth filter is

$$H(s) = \frac{1}{s^2 + \sqrt{2s} + 1}$$

The next step is to realize the circuit and develop a transfer function. The filter for a single-ended application is shown in Figure 6.

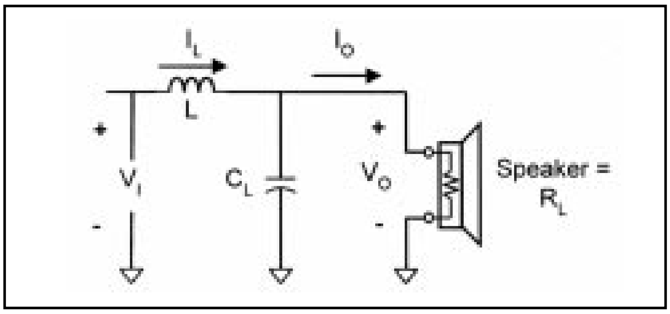

Figure 6. Single-ended class-D output filter

The transfer function is easily derived by using a voltage-divider equation with the load voltage being a parallel combination of RL and CL . This transfer function is:

$$\frac{V_O(s)}{V_I(s)} = \frac{\frac{1}{LC_L}}{s^2 + \frac{1}{R_L C_L} \cdot s + \frac{1}{LC_L}}$$

The next step is to set the terms of the circuit transfer function equal to the terms of the normalized 2nd-order Butterworth low-pass filter and solve for L and C_L in terms of RL. This yields:

$$C_L = \frac{1}{\sqrt{2} \cdot R_L}$$

$$L = \sqrt{2} \cdot R_L$$

These values give a cut-off frequency at ωo= 1 radian/second, which means that the components must be frequency scaled.

To frequency scale, each component is divided by $\omega_o = 2.\pi.f_c$ (f_c is the desired cut-off frequency in Hertz):

$$C_{SE} = \frac{1}{\sqrt{2} \cdot R_L \cdot \omega_0}$$

$$L_{SE} = \frac{\sqrt{2} \cdot R_L}{\omega_0}$$

$$\omega_0 = 2\pi \cdot f_c$$

For BTL amplifiers, this filter structure is needed at both the positive and negative output. This means that R_L must be split between each filter, so for a bridged application, R_L must be divided by two in the component calculations. In other words, if designing a BTL filter for a 4-Ω loads, use RL=2 Ω in the equations, or use the modified equations below. One capacitor can be used in place of the two capacitors in the output filters if the capacitor is placed across R_L instead of from each side of R_L to ground. This circuit is shown in Figure 7.

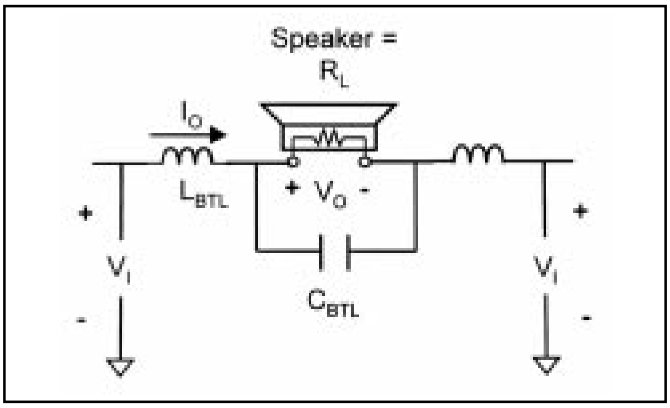

Figure 7. Low-pass filter for bridged-tied load

The component equations adjusted for bridged amplifiers are (substituting $R_L/2$ for R_L in the above equations):

To find component values, let f_c = 30 kHz, which yields ω_o = 188500 radians/ second. If a 4-Ω speaker is used, then R_L = 4 Ω.

$$C_{BTL} = \frac{1}{\sqrt{2} \cdot R_L \cdot \omega_0}$$

$$L_{BTL} = \frac{\sqrt{2} \cdot R_L}{2 \cdot \omega_0}$$

This yields L_{BTL} = 15 μH and C_{BTL} = 0.94 μF. Additional capacitors can be added from each side of R_L to ground to provide a high-frequency short to ground. These additional capacitors should be approximately 10% of 2ºC$_{BTL}$. The resulting output filter is shown in Figure 8 with commonly-available components selected.

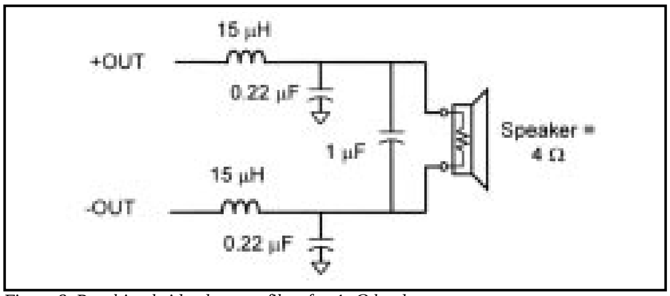

Figure 8. Resulting bridged output filter for 4- Ω loads

Power supply decoupling

Power supply considerations include power supply decoupling and high frequency bypass loops. Electrolytic capacitors are used for decoupling and ceramic or mica capacitors are used for high frequency bypass applications.

Decoupling capacitors serve to smooth the input voltage and assist the amplifier by providing current when needed. These capacitors may shunt relatively large ripple currents to ground and must have a low equivalent series resistance (ESR) to reduce power and heat dissipation in the capacitor. The ESR combines all losses, both series and parallel, in a capacitor at a given frequency in order to reduce the equivalent circuit to a simple RC series connection, valid only for low frequencies (less than 1 MHz). Other considerations are the voltage rating, capacitance, physical size, and the specific type of capacitor.

For portable equipment, the focus is to get the largest capacitance possible yet keep the size to a minimum, tantalum capacitors, instead of aluminum electrolytic capacitors, are the preferred type of capacitor. Tantalum capacitors provide a higher capacitance value in a smaller package and have lower ESR values than aluminum electrolytic capacitors. SMT packages further reduce the inductance associated with lead lengths. All of these considerations led to the use of a SMT tantalum capacitors as the primary decoupling capacitor.

The high frequency bypass capacitors are usually small in size, limited by the size of the capacitance to approximately 10 µ5F or less. Ceramic capacitors have extremely low ESR and dissipate very little power. Lower ESR means a lower net impedance at higher frequencies, which is more suitable for filtering the higher frequency components of the power supply, especially voltage spikes. Bypass capacitors should be placed as close as possible to the IC power input pins and also as close to the IC power ground pins as possible. The idea is to form the smallest possible loop, or path, over which the high frequency signals can travel, and minimize the impedance. A short path with a high impedance defeats the purpose.

PCB considerations

Class-D APAs are more layout-sensitive than Class-AB APAs due to their switching nature. However, with good internal IC design and pin-out, the user's layout efforts can be reduced. Also, for lower output levels, the board design is less critical, as the currents are fairly small. As the output power level is increased, and thus the switching currents, layout becomes more and more critical. Bypass capacitors must be connected as close as physically possible to the output H-Bridge, and in sufficient quantity to prevent voltage transients from breaking down the output transistors due to voltage transients. Likewise, the tracks on the PCB must be large enough to carry the peak currents, and to prevent extreme voltage drops from occurring during high-current pulses.

But most portable applications demand lower-output power devices because of their limitations on practical speaker size. While laying out a 2-W, 5-V, BTL, Stereo Class-D APA, experimentation with several types of ground planes has shown that a solid ground plane works as well as methods that split the analog and power ground planes as long as good layout practices are followed. This allows a much simpler design that requires less time and is less prone to layout errors. The success of the solid ground plane is partially due to the TPA005D02 IC, which allows the designer to keep the input and output sections of the chip separated, reducing the chance that high- and mid-frequency return currents will make a path to the analog input section of the chip. The traces for the analog circuit grounds are extremely short and are connected to the ground immediately under the chip through vias, while the power circuit grounds are connected to the ground plane slightly further out from the chip and closer to the signal outputs and power inputs. The large current traces of the output are then shielded from the input circuit by the ground plane. The solid ground plane has low resistance compared with the narrow paths to pins and vias that are attached. If a voltage spike or current spike hits the ground plane, the entire plane shifts up or down, unlike a split plane, which has inductance between the halves that dampens the noise and can cause uneven voltage potentials to exist.

EMI issues

Even if the switching frequency of a Class-D APA is not especially high, chances are the rise and fall times of the output squarewave will have content into the MHz frequency range. Care must be taken in the PCB layout and component selection to minimize EMI generated by the APA.

As mentioned earlier, the PCB layout and output inductor selection play heavily on a Class-D APAs ability to meet the end equipment's EMI limits. By using shielded inductors, and placing them physically close to the IC's output to limit the length of PCB trace that is conducting the high-frequency square wave, most EMI issues can be reduced or eliminated. In severe cases were sensitive receivers pick up interference, it may be necessary to shield this portion of the circuit with an EMI barrier. For digital systems without receivers, EMI has not been a significant issue.

TI has EVMs (evaluation modules) available that have a low amount of EMI, and Class-D APAs have been implemented into numerous applications with FM and AM radio receivers, so with proper care, Class-D APAs can be used in place of Class-AB APAs in most applications.

Efficiency

Efficiency is the single driving factor behind the push to Class-D APAs. By improving the efficiency over that of a traditional Class-AB APA, we either extend battery life of portable equipment, or we significantly increase the amount of output power available for a given power dissipation. This power dissipation may be limited by the application's ability to remove heat, or the constantly dwindling power dissipation due to today's devices being smaller and lighter than yesterday's models.

In a head-to-head test of efficiency done at TI, two APAs were pitted against each other - both devices targeted at notebook computer application. The Class-AB device was a TPA0202, while the Class-D device was a TPA005D02. The test bed was the TI Plug-n-Play Evaluation Module which consists of an EVM with the DUT (device under test) on it, a 9-V alkaline battery, a DC/DC switching regulator, and a bass/treble/volume control EVM. Two EVMs were set up side-by-side with 4-Ω load resistors (two each) connected to the outputs of the DUTs. Both were powered by 9-V alkaline batteries which fed DC/DC switching regulators to step-down the voltage to 5 V. The DC/DC switching regulator has under-voltage lockout which turns off the regulator when the input voltage drops below 5.5 V. Both EVMs were adjusted to have a standing current of 44 mA, which includes current for the DUTs, LEDs on the boards, and the bass/treble/volume control EVM. The TPA005D02 has a higher supply current (IDD) than the TPA0202, but in order to show the efficiency possible with the Class-D topology, the supply currents were made identical. Both EVMs were set to have a peak output power of 1.5 W, and fed with the same music signal from a portable CD player. At time zero, both boards were powered up, and the CD player was started.

After approximately 111 minutes (see Figure 9), the Class-AB (TPA0202) board's under-voltage lockout tripped, indicating the 9-V battery's voltage was below 5.5 V. Just to insure

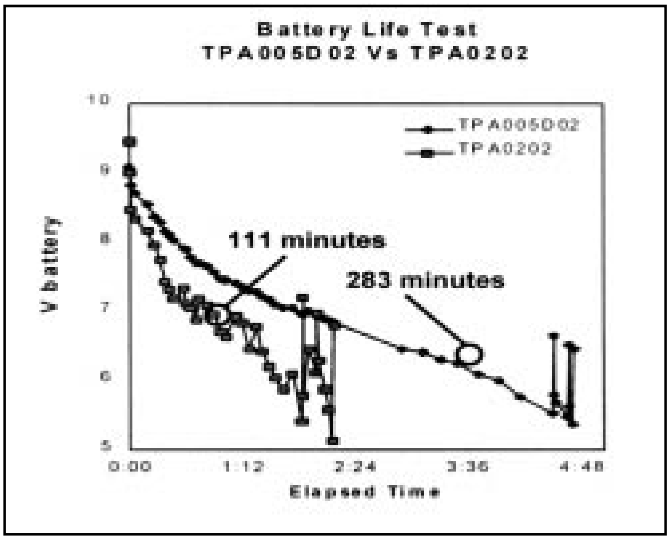

Figure 9. Battery life test, class_D versus class-AB

this was not some anomaly, the power supply was reset, and a few moments later, the under-voltage lockout tripped again. This was repeated a third time to guarantee the battery truly was discharged.

Meanwhile, the board with the Class-D APA on it lasted for 283 minutes, a 2.5 times improvement in battery run-time. Again, the power supply was reset twice to insure an accurate reading.

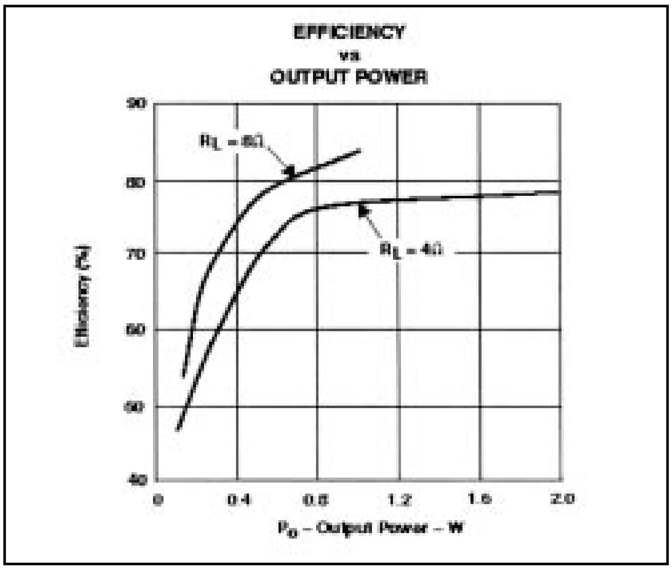

Figure 12. Efficiency versus output power TPA 005D02 driving 4-and 8-Ω loads

Also of interest to note from the above graph is the general shape of the discharge curve - the Class-D APA's voltage curve is much smoother than the Class-AB APA's curve. The author theorizes this can be attributed to the Class-D APA's drawing narrow pulses of higher currents, which the decoupling and bypass capacitors help to satisfy, as well as the inductors' energy-storage characteristics, versus the Class-AB APA's drawing wider pulses of current based solely on the input signal.

Two more comparisons between these two APAs were made, using an efficiency measurement system developed at TI. Figure 10 shows the power supplied from the power supply, versus peak output voltage and peak output power for both the Class-D (TPA005D02) and Class-AB (TPA0202) APAs.

Figure 11 shows the supply current from the power supply versus peak output voltage and peak output power for both the Class-D (TPA005D02) and Class-AB (TPA0202) APAs.

And finally, Figure 12 shows the efficiency of the TPA005D02 driving both 4- and 8-Ω loads.

Commercially-available class-D APA

The TPA005D02 was designed specifically for use in notebook PCs, but is finding applications in many different end equipments, even in applications outside

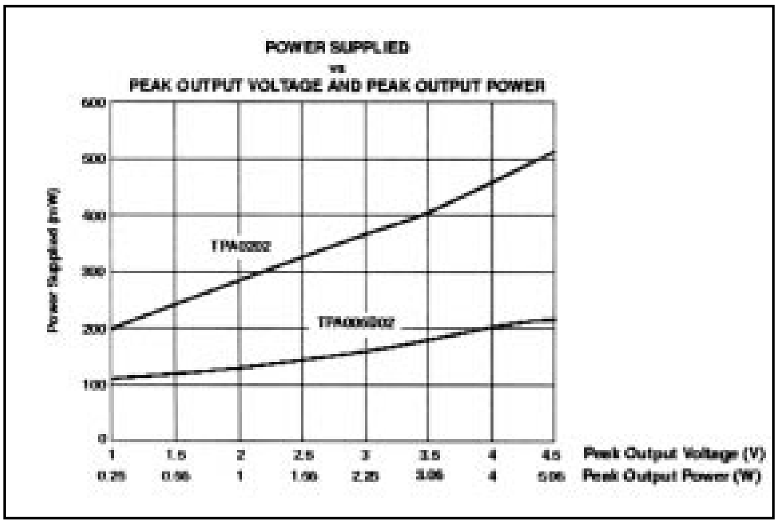

Figure 10. Power supplied versus peak output voltage and power, class-D and class-AB

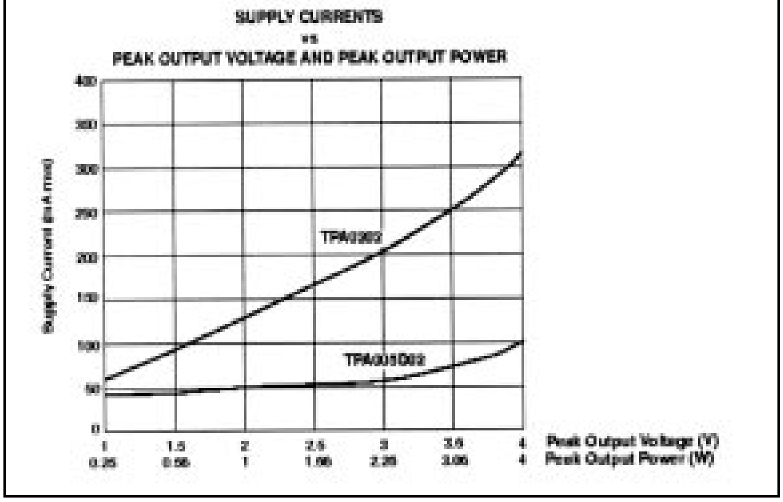

Figure 11.Supply current versus peak output voltage and power, class-D and class-AB

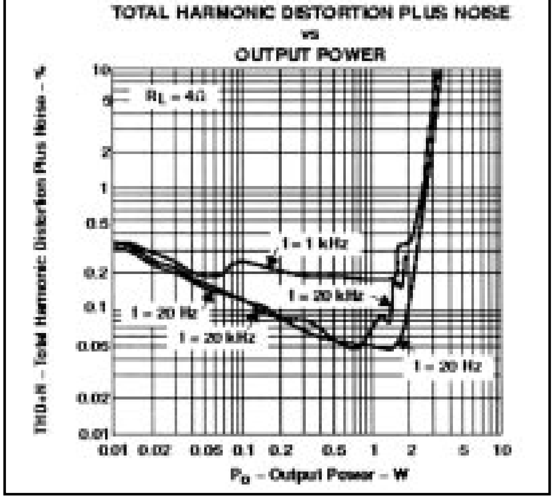

Figure 13. THD vs. output power, TPA005002

of audio - motor drives and driving thermo-electric cooling elements!

An old criticism of Class-D APAs is that they cannot measure up to Class-AB APAs in terms of audio performance, and this has limited their usage until recently to reduced-bandwidth applications like public address systems. However, with recent advances in analog power semiconductor processes, it is now possible to develop Class-D APAs with audio specifications similar to many of the Class-AB APAs on the market today.

For example, Figure 13 shows the Total Harmonic Distortion versus output power for the TPA005D02 driving a 4-Ω load.

Summary

Integrated Class-D APAs are becoming commercially-available from several different IC manufacturers, and provide benefits in battery-powered and/or thermally-limited end equipments.

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