by **Jihad Hammoud**

THERMAL MANAGEMENT FOR CLASS-D AUDIO AMPLIFIERS

Linear audio amplifiers can provide excellent sound fidelity, but they consume a great deal of power and present significant thermal management challenges, especially in automotive audio systems. However, highly efficient digital audio amplifier ICs suitable for automotive applications are emerging as an alternative to linear amplifiers and their significant thermal-design requirements.

A relatively new technology called the pure digital or Class-D amplifier has been introduced into the audio world. The Class-D architecture allows the input audio signal to stay in its digital format throughout the audio signal path.

While the theory behind Class-D amplifiers has been around for some time, their distortion levels were generally considered to be too high for standard audio applications. However, the technology has now matured to the stage where a Class-D amplifier can be fully implemented within a single device capable of producing high-quality audio. This significantly lowers manufacturing costs while also providing tremendous gains in power efficiency. This, in turn, has led to smaller, lighter and more efficient audio systems based on the Class-D architecture. Not surprisingly, these systems are emerging as possible replacements for the inefficient linear amplifiers that have dominated the audio market, including those suited for automotive applications.

EVOLUTION OF AUDIO AMPLIFICATION

Audio signals have been electronically amplified since 1925, but the goal has always been to reproduce the input audio signal at the output with low distortion. This function was first performed by audio amplifiers that employed vacuum tubes, but though this was a functional approach, the vacuum tubes in these first audio amplifiers made them fragile and unreliable.

However, audio amplifier technology advanced when transistors replaced vacuum tubes as the main amplifying component. The result was the proliferation of the now-familiar linear amplifier architectures, including Class A, Class B, and Class AB. Yet, while more reliable than vacuum-tube technology, these transistor-based analog architectures were still highly inefficient, and required bulky heatsinks (unlike the vacuum tubes they replaced). Furthermore, audio quality in the transistor-based architectures was still affected by the susceptibility to noise inherent in any analog system. While audio quality was significantly improved in systems using digital audio signals that could be stored on CDs, these audio signals still had to be fed into a DAC and converted into analog signals that were then boosted by analog audio amplifiers in order to produce sound. Therefore, inefficiency remained a concern in these first digital audio systems.

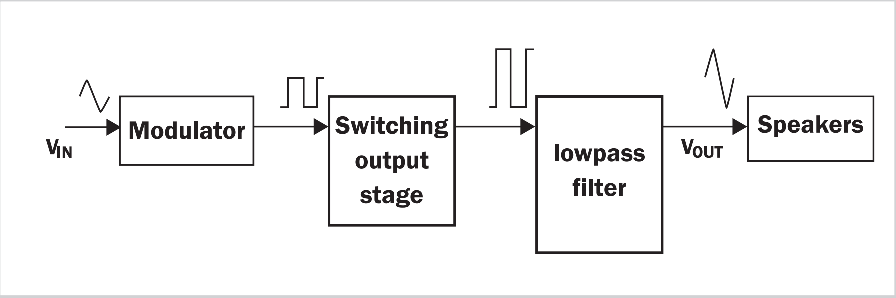

Figure 1. Block diagram for Class-D amplifier.

COMPARISON OF AMPLIFIER ARCHITECTURE CLASSES

A Class-A amplifier is known for its high sound quality. In this architecture, the output-stage transistors operate continuously in return for excellent linearity. Therefore, this architecture always consumes current, even when there is no audio signal, because a dc-bias current component continuously flows in the two output transistors but bypasses the speaker completely. Therefore, this amplifier has a high power dissipation and low efficiency (approximately 25%), which causes the amplifier to generate significant heat.

The output transistors in the Class-B amplifier operate alternately in a swing mode, and together alternately source positive current to the speaker and synch negative current from the speaker. This action eliminates the bias current in the Class-A amplifier. The Class-B amplifier, therefore, has much higher efficiency (approximately 65%). However, this gain in efficiency comes at the expense of audio quality, and the Class-B amplifier has a much higher distortion than a Class-A amplifier.

Class-AB amplifiers allow current to run through the output transistors when there is no audio signal, but only at a very low level. The small bias current improves linearity and thus lowers distortion, yet remains relatively efficient, enabling both good sound quality and low power dissipation. As such, this architecture provides a good engineering compromise between the audio performance of the Class-A amplifier, and the power efficiency of the Class-B amplifier.

In contrast to these linear amplifiers, the Class-D amplifier (Figure 1) is a switched-mode design based on a digital-modulation technique that operates the output transistors as switches—rather than as variable resistors—to control power distribution. This provides high efficiency, because an ideal transistor has no voltage drop in the on state, and no current flow in the off state. By the equation P = I x V, no power is dissipated by an ideal transistor in either state.

Because, the output transistors are either on or off, losses in a digital audio system are relatively small and mainly due to the non-ideal nature of the components. Specifically, the main contributors of power loss are transistor on resistances, transistor switching losses, and the parasitic resistances of the circuit elements (i.e., interconnects, lead frame and PCB traces). Therefore, Class-D amplifiers exhibit much greater power efficiency than linear amplifiers, resulting in reduced heatsink requirements, smaller PCB sizes and lower costs.

Unfortunately, Class-D amplifiers also produce higher distortion than Class-AB designs due to the high switching frequencies of the transistors (usually outside the audio range). However, this distortion is easily removed by a low-pass filter. The filter's cut-off frequency is selected to suppress the distortion and noise over a frequency threshold that is just above the desired audio bandwidth. The result is that the instantaneous voltage at the output of the low-pass filter becomes the supply voltage (the specific voltage feeding the transistor output stage) multiplied by the duty cycle of the transistor-switching signal. Therefore, the duty cycle can be modulated as a function of the audio input signal, replicating a scaled, low-distortion version of this input signal at the output of the low-pass filter.

AUDIO POWER RATINGS

It is important to note that ratings for audio power and continuous output power are not identical. Figure 2 illustrates the difference. The audio power is the peak power that the amplifier can supply for about 10 ms. It is real, instantaneous and higher than the continuous power. Continuous output power is the averaged electrical power of the output signal. Practically, the amplifier cannot continuously maintain its full-rated peak power. Therefore, an amplifier's performance should not be based on its peak power rating.

A common method of evaluating an amplifier is to connect it to a known resistive load, apply a continuous sinusoidal input signal, and then monitor its power output. The continuous output power is the resulting product of the rms voltage and the rms current at the output, taken over the measurement time interval. The rms value for any ac voltage or current signal is the

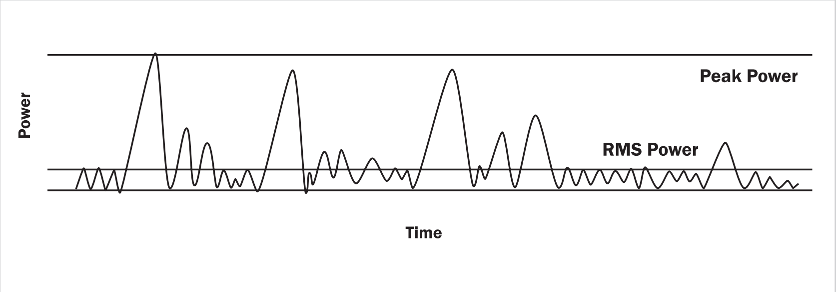

Figure 2. Peak power vs. average power for a complex signal.

equivalent dc signal that dissipates the same power in the same load (in this case, a fixed resistor). Therefore, a dc signal has an rms factor of one by definition. However, the rms value for an ac signal depends on the shape of the input signal, and a sinusoidal waveform is often selected because it is a convenient waveform to generate and analyze. Specifically, for a sine wave, $V_{RMS} = V_{PEAK}/\sqrt{2}$, and $I_{RMS} = I_{PEAK}/\sqrt{2}$, so the peak power is twice the rms power, or $P_{RMS} = P_{PEAK}/2$.

As a review exercise, consider the following comparison for a dc signal and a sinusoidal signal applied across the simplest load, a fixed resistor. To evaluate the difference between a dc and sinusoidal input signal, apply 12 Vdc across a 15 Ω resistor. The continuous power will be V^2/R, or (12 V)2/15 Ω = 9.6 W. However, if a sine wave with the amplitude of 17 V is applied to the 15 Ω resistor, the corresponding continuous power is (17 V)2/(2 x 15 Ω), which is also 9.6 W. Hence, a 17 V amplitude is required for a sine wave to produce the same output power generated by 12 Vdc for the case of this simple load (and any other constant resistive load).

For an ac signal other than a sine wave, such as a real audio signal, the rms voltage and current must be measured to obtain the true rms power reading. In general, a real audio signal will have a higher peak power than a sinusoidal signal, but its true rms power is usually only about half that of a sine wave with the same average amplitude. Therefore, the thermal effect of a real audio signal on a Class-D amplifier are much lower than that produced by a sine wave. Yet, it is a common engineering practice to use a continuous sine wave to evaluate an audio amplifier's audio performance, since all waveforms are composed of sine waves having distinct frequencies, amplitudes and phases (as defined by the Fourier series). However, a sinusoidal signal is more likely to drive the Class-D amplifier near its maximum output power (where the amplifier enters into a thermal shutdown) than a real audio signal. Therefore, it is imperative to test the amplifier performance with a realistic audio signal instead of a sinusoidal signal.

THERMAL DISSIPATION

Designers of multimedia products are faced with demands to provide versatile, high-quality audio functions, including high-output speaker modes. To make this possible, high performance is required of the audio amplifiers. However, the linear amplifier efficiency in most practical situations is around 50%, and a small increase in output power comes at the cost of a relatively large increase in current consumption. This often leads to significant heat dissipation that requires system-level cooling measures to spread and remove heat. Typically, bulky heatsinks are attached to audio amplifiers for this purpose. For automotive audio systems, where space and cost are at a premium, these measures can be quite expensive and even disruptive to the design flow of the entire automotive platform.

By using a Class-D amplifier, less heat is generated. This permits the use of a smaller heatsink, and head units can be offered with extra output channels without the need for an expensive external amplifier. Therefore, a Class-D amplifier provides tremendous advantages to automotive OEMs. Specifically, it can deliver high sound quality, while minimizing packaging costs. It can also reduce the capacity ratings needed for the thermal management components as well as the power supply.

On average, a realistic audio signal (such as that for music) applied to a Class-D audio amplifier spends a very short time at peak output power. This results in a much lower rms output power for a continuous audio signal. This property allows for a much smaller heatsink than that required for linear amplifiers rated to support a continuous sine wave. As a rule of thumb, the heatsink can be sized to accommodate a steady-state power value that is half the peak output power value for which the Class-D amplifier is rated.

However, it is ultimately up to the system design engineer to determine the thermal management approach for a specific application based on size and cost, including the use of techniques that compliment an external heatsink. For example, the amplifier's PCB can also assist in removing heat from the amplifier IC. Specifically, using large IC copper pads and maximizing the widths of all traces that connect to the IC are effective measures that can be implemented at relatively low cost.

EFFICIENCY

Efficiency is the ratio of output power across the load to the input power drawn from the supply, defined in the following equation, which expresses efficiency as a percentage: $\eta\ (\%) = (P_{LOAD} / P_{SUPPLY}) \times 100$. As stated previously, linear audio amplifiers are highly inefficient, since they often produce more power as heat dissipated into the ambient environment than as electricity delivered to the speaker. This is because a linear amplifier uses the resistance of the driving transistors to produce the desired output voltage. The power dissipated by each of the transistors is then partly a function of the voltage difference between the output and the connected power rail (either positive or negative) developed across the transistor.

One crude method for improving the efficiency of a linear amplifier is to minimize this voltage difference by expanding the output voltage signal to be mainly at the supply-rail voltages. While this produces a type of switching action that is similar to that of the Class-D audio amplifier, this method also causes severe distortion, because the voltage of the audio signal is being clipped. Distortion severely degrades the sound quality and can permanently damage the speaker, so this method is usually not a viable option. Therefore, a high-efficiency amplifier such as a Class-D amplifier nearly always requires far less power than a linear amplifier for a given audio application.

While the ideal Class-D amplifier is 100% efficient, this is not quite achieved in reality due to the non-zero on-state resistance, $R_{DS(ON)}$, in each of the output transistors. Moreover, other circuit elements in the output path have non-zero resistances that also contribute to the overall power loss of an audio amplifier. This is illustrated in Figure 3, which shows a dc equivalent circuit with all major resistive losses for a typical Class-D amplifier having a double-ended output stage configured as an H-bridge. The circuit represents a steady state where two complimentary transistors on opposite sides of the bridge are turned on to power the load.

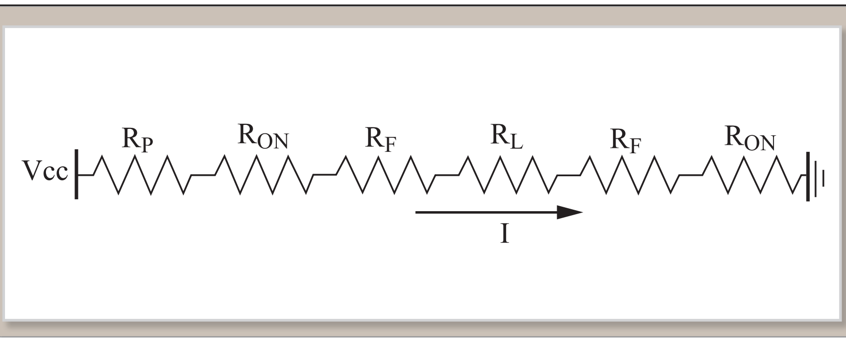

Figure 3. Resistive circuit model for a typical Class-D amplifier in the on state.

In the Figure 3 circuit, $R_{DS(ON)}$ is the output on resistance for a transistor in the on state, $R_{PARASITIC}$ is the parasitic resistance in the output circuit path (metal interconnects, bond wires, lead frame, and PCB traces), R_{FILTER} is the combined series resistance of the low-pass filter used for the output path, and R_{LOAD} is the load resistance. From this circuit, the efficiency of the Class-D amplifier system can be estimated by the formula:

$$\eta = \frac{P_{LOAD}}{P_{SUPPLY}} = \frac{I_{OUT}^2 \; R_{LOAD}}{I_{OUT}^2 \; \left(R_{LOAD} + 2\left(R_{ON} + R_{FILTER}\right) + R_{PARASITIC}\right)}$$

Which simplifies to the following when R^{FILTER} and $R_{PARASITIC}$ can be neglected:

$$\eta = \frac{R_{LOAD}}{R_{LOAD} + 2R_{ON}}$$

Another contributor to overall system power loss is the combined switching losses from the output transistors (P_{SWITCH}). These are caused by rise and fall times that are greater than zero (Figure 4), leading to brief intervals of voltage-current products in the transistors that result in power pulses that must be dissipated by the devices. The switching losses can be ignored at high power levels, but they must be taken into account at low power levels.

The system efficiency can then be estimated with greater accuracy by this formula:

$$\eta = \frac{P_{LOAD}}{P_{SUPPLY} + P_{SWITCH}} = \frac{I_{OUT}^2 \; R_{LOAD}}{I_{OUT}^2 \; \left(2\left(R_{ON} + R_{FILTER}\right) + R_{PARASITIC} + R_{LOAD}\right) + P_{SWITCH}}$$

Which simplifies to:

$$\eta = \frac{P_{LOAD}}{P_{LOAD} + P_{DISS}}$$

Where PDISS is the total power dissipation contributed by parasitic losses, and by the conductive and switching losses in the output transistors of the Class-D amplifier stage of the audio system.

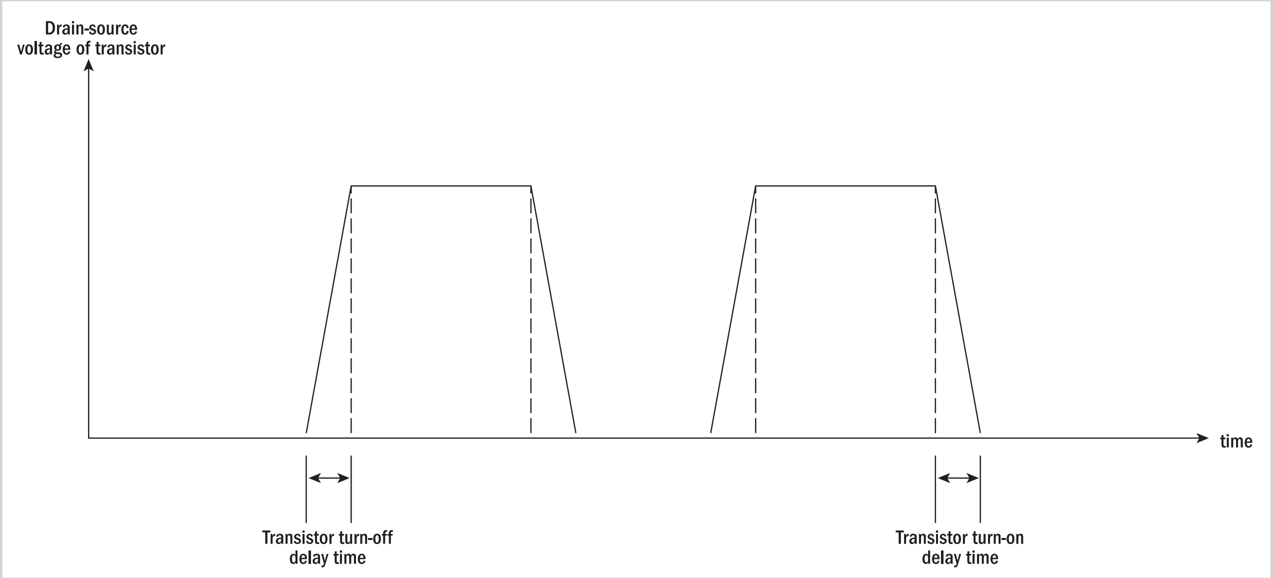

Figure 4. Switching losses in a transistor are caused by delays in transitions between the on and off states.

DESIGN EXAMPLE

A few basic calculations can help to estimate a Class-D amplifier thermal load, and thus the die temperature. For example, consider using a two-channel Class-D amplifier with a full-power efficiency of 90% that drives two 4 Ω subwoofers, operating at 60 °C ambient. The supply voltage is 14 Vdc, and the thermal resistance from the packaged die to ambient air (Θ_{JA}) is specified at 5 °C/W. The output peak current limit occurs at $I_{PEAK} = V_{PEAK}/R_{LOAD} = 3.5$ A. This corresponds to an output peak power of $P_{PEAK(LOCAL)} = (I_{PEAK})^2 R_{LOAD} = 49$ W per channel. Although the subwoofers are modeled as fixed resistors, their system impedance varies with frequency; the 4 Ω value is considered as a nominal value that is present within a narrow frequency band. The rms output power delivered to each speaker for a sinusoidal signal is then $P_{RMS(LOCAL)} = P_{PEAK(LOCAL)}/2 = 24.5$ W per channel. The total peak output power of both channels is then 98 W.

Efficiency for the audio amplifier can then be defined as follows:

$$\eta = P_{LOAD(RMS)}/(P_{LOAD(RMS)} + P_{DISS})$$

Where $P_{LOAD(rms)}$ is the average power delivered to the load, and P_{DISS} is the total heat dissipation from the amplifier. The value for P_{DISS} is then found to be:

$$P_{DISS} = (1 - \eta)\ P_{LOAD(rms)} = (0.10)(49\ W) \approx 5\ W$$

The maximum junction temperature $T_{J(MAX)}$ is a parameter that is not directly related to the amplifier performance. However, junction temperature is significant in defining heatsink size, because a higher $T_{J(MAX)}$ reduces overall heatsinking requirements. The thermal power dissipation is used to calculate the junction temperature at the die, T_J, as follows:

$T_J = T_A + P_{DISS} \times \Theta_{JA} = 85$ °C, which is well within the device's $T_{J(MAX)}$ rating of 150 °C.

When using a real audio signal, such as music, instead of a pure sinusoidal input signal, it is necessary to consider the dynamic range (the ratio of the peak-power amplitude to the average-power amplitude) of the signal. A standard method of comparing the peak to rms power values of a waveform is to use the crest factor. A typical signal for a music CD has a crest factor ranging from three to 10, and that is expressed in decibels as 10 dB to 20 dB (given that P (dB) = 20 log (V_{PEAK}/V_{REF})), This means the peak power exceeds the true rms power by 10 dB to 20 dB. In contrast, the crest factor for a sine wave is only 3 dB, given that P (dB) = 10 log (P_{PEAK}/P_{RMS}) = 10 log (2).

Therefore, in order for a music signal to pass the loudest portions without distortion, it requires 10 dB to 20 dB of dynamic voltage headroom compared with the average power output. When the Class-D amplifier in this example is operating from a 14 V supply, then 49 W of peak output power is available. Normalizing this peak power (which shall be called $P_{PEAK(NORMALIZED\ 24\ W)}$) in comparison to the rounded-down value for $P_{LOCAL(rms)}$ of 24 W, and expressing the ratio in dB is performed as follows:

$$P_{PEAK(NORMALIZED\ 24W)} = 10\ \log\left(\frac{P_{PEAK}}{P_{RMS}}\right) = 10\ \log\left(\frac{49\ \ W}{24\ \ W}\right) = 3.1\ \ dB$$

Subtracting the crest factor restriction to obtain the average distortion-free average output power level yields:

$P_{NORMALIZED\ \ DISTORTION\ FREE\ \ (dB)}$ = 3.1 dB - 20 dB = –16.9 dB (for 20 dB of dynamic voltage headroom)

and

$P_{NORMALIZED\ DISTORTION\ FREE\ (dB)}$ = 3.1 dB - 10 dB = –6.9 dB (for 10 dB of dynamic voltage headroom)

Converting these normalized power figures back into rms output power gives:

$$P_{DISTORTION\ FREE\ (RMS)} = \left(10^{(P_{NORMALIZED\ DISTORTION\ FREE\ (dB)}/10)}\right)P_{RMS}$$

which yields 490 mW for 20 dB of dynamic voltage headroom, or 4.9 W for 10 dB of dynamic voltage headroom. The specific values of heat dissipation for this design example and maximum junction temperatures are shown in Table 1.

Therefore, the maximum power dissipation for a typical audio CD signal without distortion happens at an average listening level of –6.9 dB. This design example clearly shows that using a sinusoidal signal as a metric for estimating output power levels in an audio amplifier leads to a considerably high power dissipation and junction temperature than a real audio signal. Therefore, it is a good practice to reserve the use of a sine wave for test purposes as a way to evaluate the thermal load that drives the amplifier into thermal shutdown. For a cost-effective design, however, power ratings for the components should be based on power levels produced with a realistic complex audio input signal.

FUTURE CLASS-D IMPLEMENTATIONS

Commercially available Class-D chip designs, such as the TDA5414 from Texas Instruments, now comply with Ford Motor Company's EMC specifications. This will allow the use of these Class-D ICs in stand-alone audio power amplifiers beginning with model year 2009. Given their many advantages, these devices will probably be used for many years to come. ■

ABOUT THE AUTHOR

Jihad Hammoud is the senior thermal engineer at Ford Motor Co. where he is responsible for development of new thermal management techniques to support electronic systems cooling at the vehicle level. These systems include navigation radios, multimedia components, amplifiers, DVDs and entertainment systems. He has 15 years of experience in electronics cooling, and more than 15 publications on thermal management. He received a Ph.D. from the University of Akron in Ohio in 1996. Prior to that, he earned an M.S. in mechanical engineering from Youngstown State University, and a B.S. in mechanical engineering from the University of Toledo, both also in Ohio. He can be contacted at jhammou3@ford.com.

Table 1. Power dissipation levels and junction temperatures for Class-D amplifier in design (TA = 60 °C).

P Peak (W)	Average Output Power (W)	Power Dissipation (W/ch)	Total Power Dissipation (W)	Max. Junction Temp (°C)
49	0.490	0.05	0.1	60.5
49	4.9	0.49	1.0	65