Power efficiency in mobile audio headphone applications

Introduction

A key for the success of mobile audio resides in power consumption reduction, as the battery must handle more applications and last a longer time. Regarding the analog audio, referred to as the audio CODEC where specifications mainly focus on the stereo playback mode, quiescent power consumption largely felt under 10 mW, rising headphone driver power consumption as a major concern.
In addition to the quiescent power benchmark that does not reflect actual usage case, the power efficiency helps to gauge dynamic power consumption and its significant contribution to the total power consumption bill. The need for low power solution even brings back from the old audio systems the class G architecture and its class H twin brother.
This article will review and discuss these different classes of amplifiers to better understand and calculate power dissipation. Then, low power operation will lead to regulation problematic, audio signal characteristics and system complexity.

Part-1: class AB, G and H: principle

Class AB

Class AB amplifiers, widely used in headphone application, are a trade-off between class A and class B architectures, taking advantages in both of them. The push-pull output stage is designed with two complementary MOS transistors. PMOS and NMOS transistors alternatively provide the current to the load, in addition to a minimum quiescent current needed to prevent zero-crossing distortion.

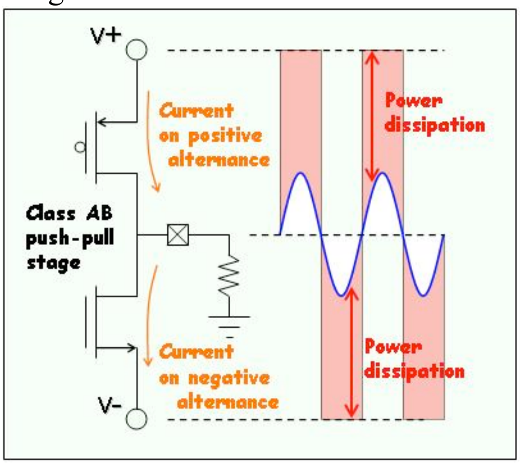

Figure 1. Class AB output stage and signal

The success of Class AB is there: a simple architecture, high audio performances and much lower power consumption than class A. However, dissipation remains substantial, caused by large currents flowing through the ON resistances of MOS transistors, reducing efficiency for low amplitude signals which unfortunately correspond to usual audio operating conditions.

Class G and H

Class G and H have been designed to compensate for the poor low amplitude efficiency of class AB stages. The idea is simple: reducing power dissipation by reducing the voltage across the MOS transistors. It is achieved by adjusting the power supply voltage according to the output amplitude.
Class G generally switches from one power supply to another, based on parallel or serial output push-pull stage. Class H generally uses a unique push-pull stage and scales the power supply, theoretically following the signal without being limited to discrete levels.
Anyway, they are both based on the same principle: adjusting power supply voltage of a push-pull output stage.
Drawbacks are distortion caused by commutation artefact or biasing condition changes during operation and complexity (need for supply regulation and sense circuits).

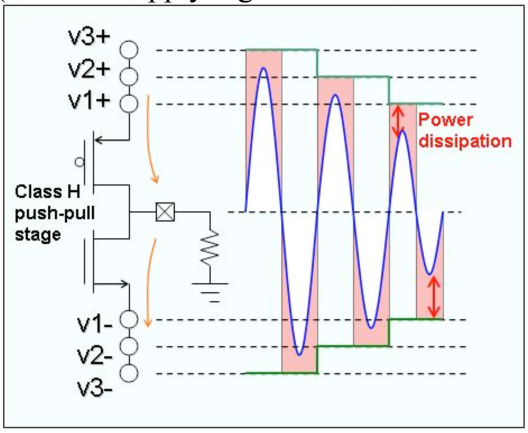

Figure 2. Class G/H output stage and signal

Class D

This class is not detailed in this paper because such amplifier topology is out of focus for low power headphone amplifiers.

Part-2: Amplifier efficiency calculation

Push-pull stage consumption

Class AB, G or H output stage topology are therefore similar, based on a push-pull stage. The efficiency η of an amplifier is the ratio between the output power P_{out}, transferred to the load, and its total power consumption P_{tot}.

[1] $$\eta = \frac{P_{out}}{P_{tot}}$$

Using ideal sine waves, we can estimate output power as:

[2] $$P_{out} = \frac{V_{rms}^{2}}{R_L}$$

- V_{rms}: rms output voltage
- R_L: load resistance

And output stage total power consumption by:

[3] $$P_{tot} = \frac{\sqrt{2}.V_{PS}.V_{rms}}{\pi.R_L}$$

- V_{PS}: power supply range (positive supply - negative supply)

Thus, [1] can be developed as:

[4] $$\eta = \frac{\pi.V_{pp}}{4.V_{PS}}$$

- V_{PP}: peak-to-peak output voltage

The whole power management system also has to be considered, from the battery to the regulated supply.

[5] $$\eta_{total} = \frac{\pi.V_{pp}}{4.V_{PS}}.\eta_{supply}$$

- η_{supply}: supply regulation efficiency

Output power vs. power supply range

These equations, although based on the output stage analysis, give an accurate way to calculate dynamic power consumption. It is remarkable that:

- Efficiency is theoretically limited to 78.5%. It is even worst with real audio signal as sinus peak-to-average ratio is relatively low compared to that of audio signal.
- At given output power, power supply voltage is the only parameter we can act upon to improve efficiency.

The real trade-off lies here, between minimum power supply range and needed output power.

Note: other limitations exist (dynamic, parasitic resistances, quiescent consumption…) but depend on architecture and are not relevant to compare architectural efficiency performances. However, they shall be taken into account for the overall system-level efficiency performances.

Part-3: Audio output power delivered by the headphone

Now, to determine the appropriate power supply voltage, we need to consider headphone application more precisely.

Output power vs. SPL

Maximum output power specification is relative to the loudness of sound, the output sound pressure level (SPL) in dBSPL. With modern headphones which generally have sensitivity higher than 100 dBSPL/mW, regular listening condition rarely exceeds 0.01 mW, equivalent to 80 dBSPL. Then, fixing 0.1 mW/ch is an appropriate output power, as 90 dBSPL generally proves to be unpleasant, feeling that the sound is too loud.

Headphone impedance and crest factor

Two more items have to be considered. First, output power depends on headphone impedance (equation [2]). The 1 mW output power requires 506 mVpp with a 32 Ω load, but only 358 mVpp with a 16 Ω load. To cover most headphones, it is worth to consider 64 Ω as a worst case.

Secondly, the audio crest factor (or peak to average ratio) defines the peak to average headroom, generally around 3 or 4, which means that 0.01 mW mean power may reach 0.16 mW peaks without saturation.

Maximum peak-to-peak voltage calculation

This finally gives 905 mVpp max to reach 0.1 mW/64 Ω (considering the crest factor). On regular 16 Ω headphone, it corresponds to 6.4 mW output power (>>100dBSPL). Voltage supply at 1.8 V or 1.5 V is then quite sufficient, showing common 40 mW/ch amplifiers as unnecessarily highly powered.

This result is also consistent with European standard EN50332 for audio portable devices that limits output signal to 150 mVrms, with a maximum crest factor equal to 2.2, giving 933 mVpp max output.

Part-4: (Power supply) Regulation puzzle

Cost of regulation complexity

For Class G/H, as linear regulation gives no efficiency benefit, switching regulation is a must. External versus integrated regulator relies on different trade-offs: PCB congestion, Bill of Material (BoM, external devices and energy storage components), silicon cost (not only area but also process options as deep Nwell required for negative power supply), additional pins and noise consideration (switching regulator may disturb other parts of the system and compel PCB routing).

Capacitor and inductor based regulators are also in balance regarding efficiency, cost, congestion, pining and complexity. Note that open-loop capacitive charge pumps are widely used in class G/H because of their design simplicity and their high efficiency.

The table below gives an idea of comparison between common integrated regulators.

Regulator description	Regulator pins	BoM
"dual mode" charge pump inverting and halving	5 pins - 1 for input - 2 for the flying cap - 2 for the tank caps	1 flying capacitance ~ 100nF 2 tank capacitances ~ 2.2uF
"dual mode" charge pump inverting and dividing by four	7 pins - 1 for input - 4 for the flying caps - 2 for the tank caps	2 flying capacitance ~ 100nF 2 tank capacitances ~ 2.2uF
inductive regulator + inverting charge pump	6 pins - 1 for input - 1 for inductor - 2 for the flying cap - 2 for the tank caps	1 inductor ~ 3.3uH 1 flying capacitance ~ 100nF 2 tank capacitances ~ 2.2uF

Figure 3. Class G/H integrated regulation cost

Power supply transitions

Behind regulation complexity also lays regulation control. During class G/H operation, special care should be taken with power supply transitions. Changing from a high power supply range to a lower one may generate audible pop and click noise on the output.

Soft turn-on/turn-off and detection circuits (envelope detector, delay or output level sensor) could also be required, adding silicon area expense.

Part-5: System considerations

Headphone configuration

Headphone configuration is one more item which strongly impacts cost and power consumption. There are three different configurations: capacitor-coupled, capless virtual ground and capless true ground. Each presents some advantages and some disadvantages that are briefly explained below.

Capacitor-coupled True ground

In capacitor-coupled configuration, the amplifier is supplied between ground and positive power supply voltage. Large blocking capacitors are used to remove DC component on the output signal. Dynamic and quiescent consumption are minimal, as well as silicon area and pin count, but it also increases sensitivity to pop noise and common mode noise.

Capless Virtual ground

In virtual ground configuration, the amplifier is supplied between ground and positive power supply. The headphone reference is connected to the common mode voltage of the amplifier so that blocking capacitors become unnecessary. However, it adds an amplifier and doubles dynamic consumption, also preventing sharing jack ground with other system peripherals (like in headset where ground is shared by the microphone and the headphone).

Capless True ground

In true ground configuration, the amplifier is supplied between positive and negative power supplies. Headphone and amplifier are both referred to ground. No blocking capacitor is needed. Yet, it requires a specific regulation circuit to generate negative power supply voltage, costs silicon area with optional deep Nwell layer and external components. Using a simple power supply voltage inversion, it also doubles dynamic consumption compared to capacitor-coupled configuration.
Those characteristics are summarized in the table below:

Configurations	Characteristics
Cap-coupled	+ Minimal dynamic power consumption - Pop and click noise sensitivity - Long turn-on and turn-off time - VMC noise sensitivity
Virtual ground	+ Suppress DC blocking capacitances - Double dynamic power consumption - Avoid connecting jack reference to shared ground - short-cut sensitivity - Silicon area for supplemental amp - Add noise and quiescent consumption of the supplemental amp
True-ground	+ Suppress DC blocking capacitances + Enable high output power from low power supply voltage + Allow simpler Class G operation - Double dynamic power consumption - Need optional deep Nwell layer - Silicon area for charge pump - Need low ESR charge pump capacitances - Need 3 or 4 pins for charge pump

Figure 4. Headphone configurations summary

Configuration vs. Class

Choosing the adequate class of operation also depends on configuration.

Unipolar Power supply usage

Because cap-coupled and virtual ground configurations only use a positive power supply voltage, class G/H does not fit on these configurations.

Signal common mode is generally half of the power supply level, so adjusting power supply voltage only benefits to half of the signal dynamic, thus making the reduction of consumption less profitable. Moreover, the adjustment range then has to been limited to avoid clipping the output signal: reducing the power supply voltage by two will cause to clip the positive half of the signal.

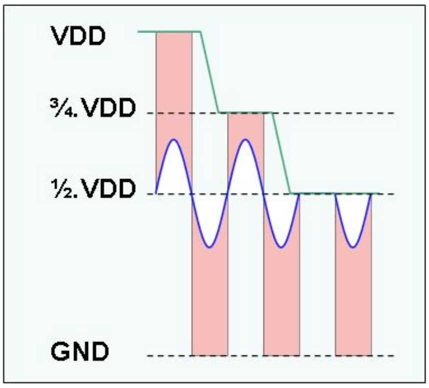

Figure 5. Power supply reduction in capacitor-coupled and virtual ground configuration

Bipolar power supply usage

In opposition, Class G is particularly advantageous for true-ground configuration. The need to generate negative power supply voltage requires a switching regulation so that class G operation can be obtained with minimum supplemental cost.
However, true-ground configuration doubles power dissipation by doubling the power supply range. Class G/H may only be seen as a compensating system, except for low power supply voltage (1.8 V, 1.2 V) where it can be useful to reach sufficient output power while maintaining very low dynamic power consumption. Otherwise, class AB is equivalent.

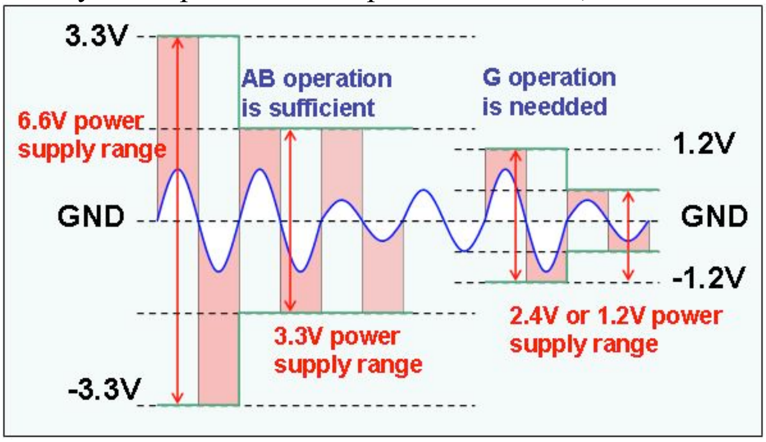

Figure 6. Power supply reduction in true ground configuration

Note: Increasing class G/H complexity may lead to better power consumption performances but price (silicon area, BoM, pinning, and complexity) is generally prohibitive.

Conclusion

In low power audio applications, headphone amplifier efficiency is a major concern. Class G/H and class AB operation are compared, showing that they are both suffering from the same efficiency limitation so that reducing consumption is a simple matter of power supply reduction. However, lowering power supply range of class AB causes to reduce maximum output power while in class G/H the drawback is regulation cost and complexity.

The crucial matter is first to determine the most adequate power supply level, helping by audio signal comprehension, to solve the trade-off between maximum output power and power supply range. Here, it is demonstrated that low supply power range (1.8 V) is sufficient to not over-size output power capability.

However power supply efficiency and headphone configuration should not counteract the amplifier supply optimization. While explaining constraints on power regulation and reviewing headphone configurations, it is shown that class AB stays a better solution for virtual-ground and capacitor-coupled headphone while, for true-ground configuration, especially with low power supply voltage (1.2 V, 1.8 V), class G/H is suitable.

Finally, trying to save power consumption within a class G/H amplifier without defining a balanced power supply strategy is putting the cart before the horse. The root of efficiency lies foremost behind the regulation trade-off.

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After a brief experience in I/O and physical design (2003-2004), Paul Giletti became an analog design engineer in Dolphin Integration. Specialized in delta-sigma converters and audio power amplifiers, its R&D works maily focus on low area and low power design for high performance audio applications.

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