John Caldwell Dec 21, 2015

Other Parts Discussed in Post: OPA1622

This post is co-authored by Bharath Vasan.

When we set out to create an operational amplifier (op amp) for headphone applications (which became the OPA1622 op amp), one of the first questions we needed to address was just how much power headphones need.

Think of headphones and loudspeakers as a transformer that converts an input electrical power to acoustic output power. Like all processes, this conversion of electricity to sound has an efficiency associated with it. And as you might expect, different headphone styles have different efficiencies. In general, over-the-ear headphones have lower efficiencies than in-ear headphones.

Headphone manufacturers usually provide the efficiency of their headphones in terms of the sound-pressure level ([SPL], given in decibels) produced for a certain input power (typically 1mW). For example, a headphone manufacturer may specify that their headphones have an efficiency of 100dB/mW, which you should read as “100dB at 1mW.” Using the reference efficiency provided by the manufacturer, you can use Equation 1 to calculate the SPL produced for other power levels:

$$SPL(dB) = \eta + 10\log\left(\frac{P_{IN}}{1mW}\right) \quad (1)$$

In Equation 1, P_{IN} represents the input power to the headphones, and η is the efficiency given at a 1mW reference level. Figure 1 shows the output SPL for increasing input power for a range of common headphone efficiencies.

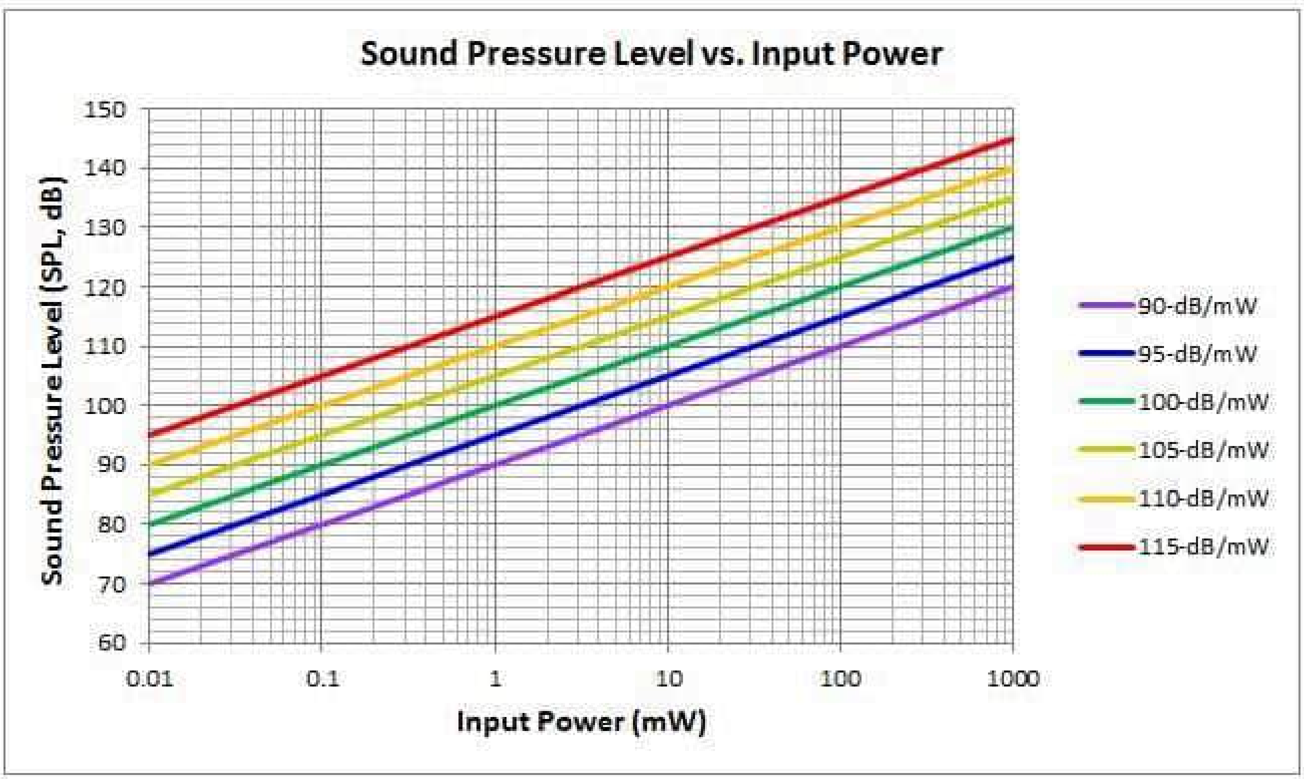

Figure 1: SPL produced vs. input power for various headphone efficiencies

Equation 1 and the plots in Figure 1 include the assumption that the drivers in the headphones are operating in a linear fashion. Of course, you can't keep increasing the input power to the headphones and expect the output SPL to increase forever (don't try). At high input powers, nonlinear effects in the drivers themselves will limit the maximum SPL.

Once you've established a target SPL goal, determining the signal levels only requires some fundamental electrical engineering equations (Equations 2 and 3):

$$V_{RMS} = \sqrt{P_{IN} \times R_{HP}} \qquad (2)$$

$$I_{RMS} = \sqrt{\frac{P_{IN}}{R_{HP}}} \qquad (3)$$

Both of these equations include the nominal headphone impedance, R_{HP}, also given by headphone manufacturers. Headphones designed for portable electronics have low impedances (as low as 16Ω) because a low voltage signal at the headphones will still deliver sufficient power. Headphones not intended for portable applications, such as those used in professional recording studios, may have impedances as high as 600Ω.

· Let's apply all of this information to a design example, calculating the signal voltage and current necessary to reach a certain SPL for a popular pair of over-the-ear planar-magnetic headphones. Table 2 lists the design goals and headphone specifications.

Specification	Value
Headphone efficiency	90dB/mW
Headphone impedance	45Ω
Maximum SPL goal	110dB

Table 2: Specification goals for design example

Using either Equation 1 or Figure 1, first determine the necessary input power to reach your SPL goal:

$$SPL(dB) = \eta + 10\log\left(\frac{P_{IN}}{1mW}\right) \rightarrow P_{IN}(mW) = 10^{\frac{SPL(dB)-\eta}{10}} = 10^{\frac{110dB-90dB/mW}{10}} = 100mW$$

Next, calculate the voltages and currents required to deliver this amount of power to the headphones:

$$V_{RMS} = \sqrt{P_{IN} \times R_{HP}} = \sqrt{100mW \times 45\Omega} = 2.12V_{RMS}$$

$$I_{RMS} = \sqrt{\frac{100mW}{45\Omega}} = 47.14mA_{RMS}$$

The combination of a low-impedance headphone with low efficiency and a very loud maximum SPL goal in this design example illustrated to our team the challenges ahead in the OPA1622 design. It was apparent that the amount of current our amplifier would need to deliver to some headphones would be significant (by op amp standards). With this in mind, we turned our focus to the output circuitry of the OPA1622. It would need to be capable of delivering large amounts of current without distortion

In the next three installments of this series, we'll examine some of the other challenges we encountered in headphone applications, and how we overcame them in the design of the OPA1622.

Additional resources

- Watch on-demand training courses on stability and more in the TI Precision Labs – Op Amps Low-Distortion Design and Noise video series.
- Download the *Analog Engineer's Pocket Reference* e-book for frequently used system- and board-level design formulas (myTI login required).
- Learn more about TI's precision-amplifier portfolio and find technical resources.
- View TI's entire audio portfolio with the audio selection tool.

- Learn about TI’s entire portfolio of amplifier ICs and find more technical resources.

1 comment 0 members are here

allan guan *over 9 years ago*

thank you for sharing，it helps me a lot。

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Bharath Vasan Jan 22, 2016

Other Parts Discussed in Post: OPA1622

This post is co-authored by John Caldwell.

In the first post in our "Amp up your cans" blog series, my colleague John Caldwell and I used a nominal value of headphone impedance to calculate the output voltage and current requirements of headphone amplifiers. The impedance of most headphones is not purely resistive, however. Headphones are notorious for being a difficult load for amplifiers, necessitating proper compensation to avoid stability issues, such as ringing and oscillations.

Numerous compensation techniques exist to address this issue using external components, but wouldn't it be nice if the op amp didn't need these additional components? During the development of the OPA1622, a high-performance, low THD+N, bipolar-input audio operational amplifier (op amp), we took on this challenge. Our goal was to minimize, if not eliminate, the need for additional components to maintain stability.

Figures 1 and 2 show the impedance magnitude and phase of several popular headphones. The magnitude plot clearly reveals a resonant peak around 1MHz. This peak results from the cable capacitance and inductance. Beyond this point, the headphone load is dominantly capacitive, as is evident from the phase shift at these frequencies, illustrated in Figure 2. On extracting electrical models for the headphone impedance, the value of this capacitance can be almost 500pF!

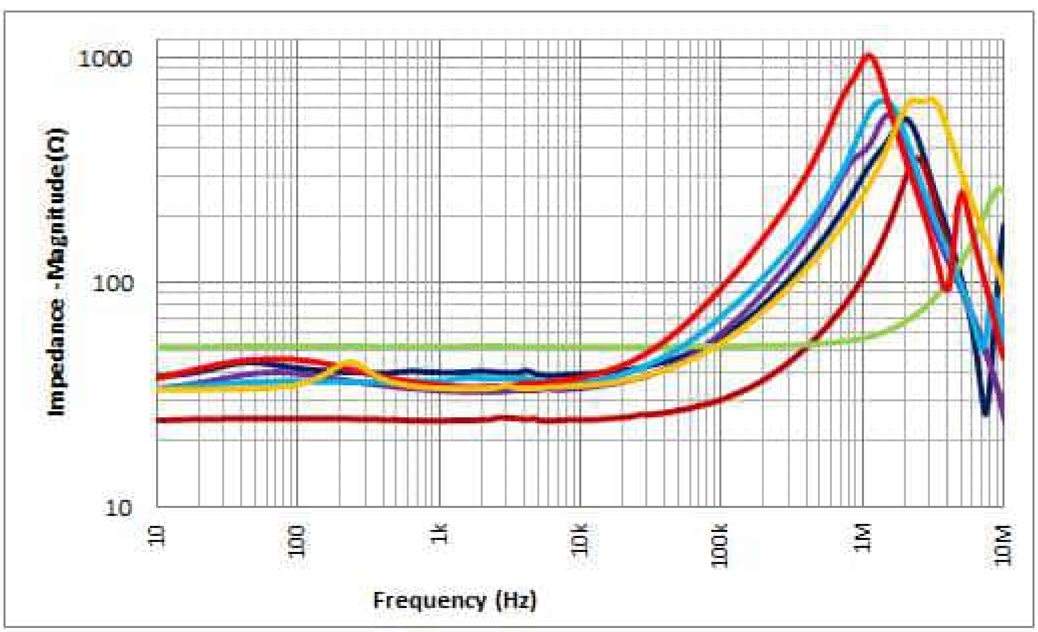

Figure 1: Impedance magnitude of several headphone models

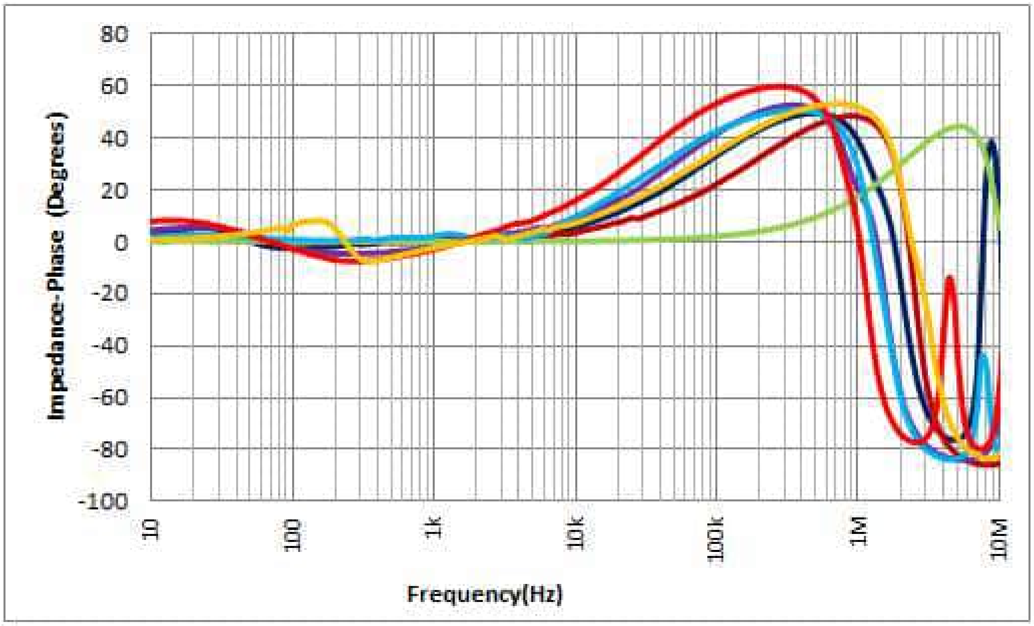

Figure 2: Impedance phase of several headphone models

Op amps are not usually designed to drive a large capacitive load. The capacitance interacts with the open-loop output impedance, R_O, of the amplifier to introduce a pole, fp_{O1}, in the amplifier's open-loop gain curve, as shown in Figure 3. This pole causes excessive phase shift in the feedback loop, severely degrading phase margin. The reduced phase margin results in increased ringing in the amplifier's step response and could potentially cause the amplifier to oscillate. The effect is worse in a unity-gain configuration.

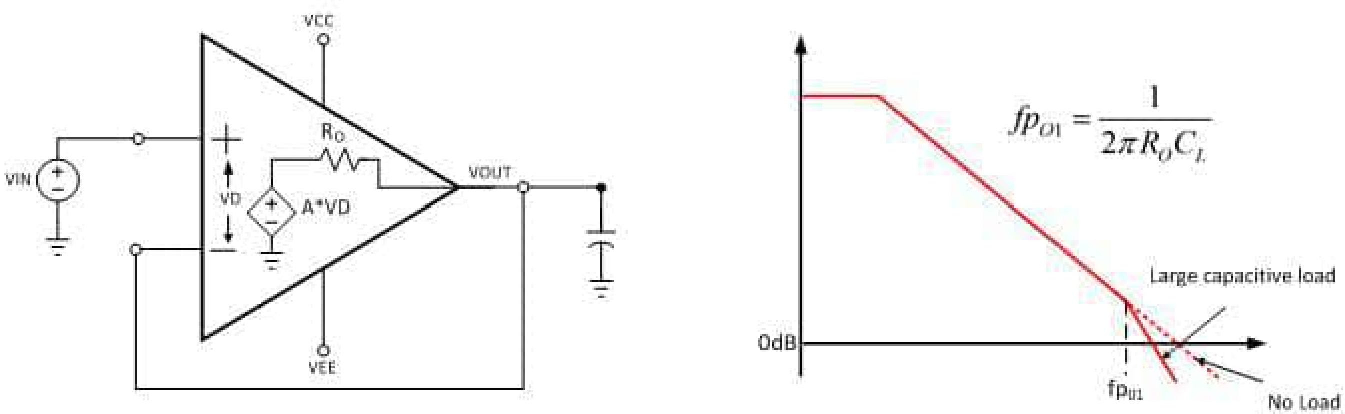

Figure 3: The effect of op amp open-loop output impedance, R_O, on capacitive load drive

A common solution is to use an isolation resistor, R_{ISO}, between the amplifier and the headphone load (Figure 4), but this heavily degrades audio performance, along with other penalties like reduced output voltage range. John's article, "Stabilizing difference amplifiers for headphone applications," examines in further detail the negative effects of series isolation resistors in headphone amplifiers.

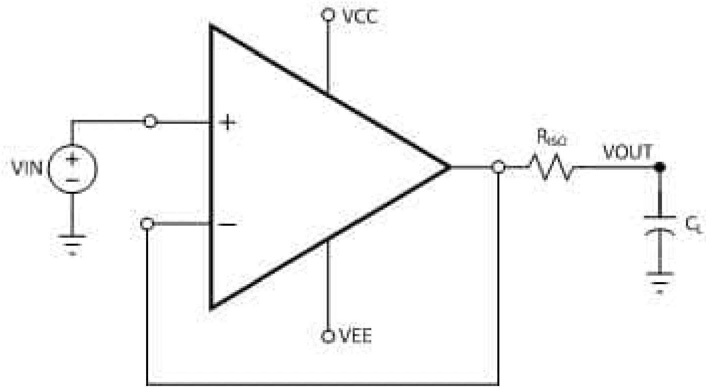

Figure 4: Isolation resistor to improve capacitive load drive

With the OPA1622, we took a different approach. We developed an output stage with very low output impedance that pushes the second pole (created by the capacitive load) to a higher frequency. We added additional poles and zeros to the open-loop gain curve at frequencies fp_A and fz_A (shown in Figure 5), choosing the location of the pole-zero pairs and the pole-zero separation to:

- Provide high gain bandwidth (GBW) in the audio frequency range, resulting in a large loop gain that suppresses harmonic distortion over the audio frequency range.
- Roll off the open-loop response to cross unity-gain well below the output pole, fp_{O2}, resulting in sufficient phase margin with a large capacitive load. See Figure 5.

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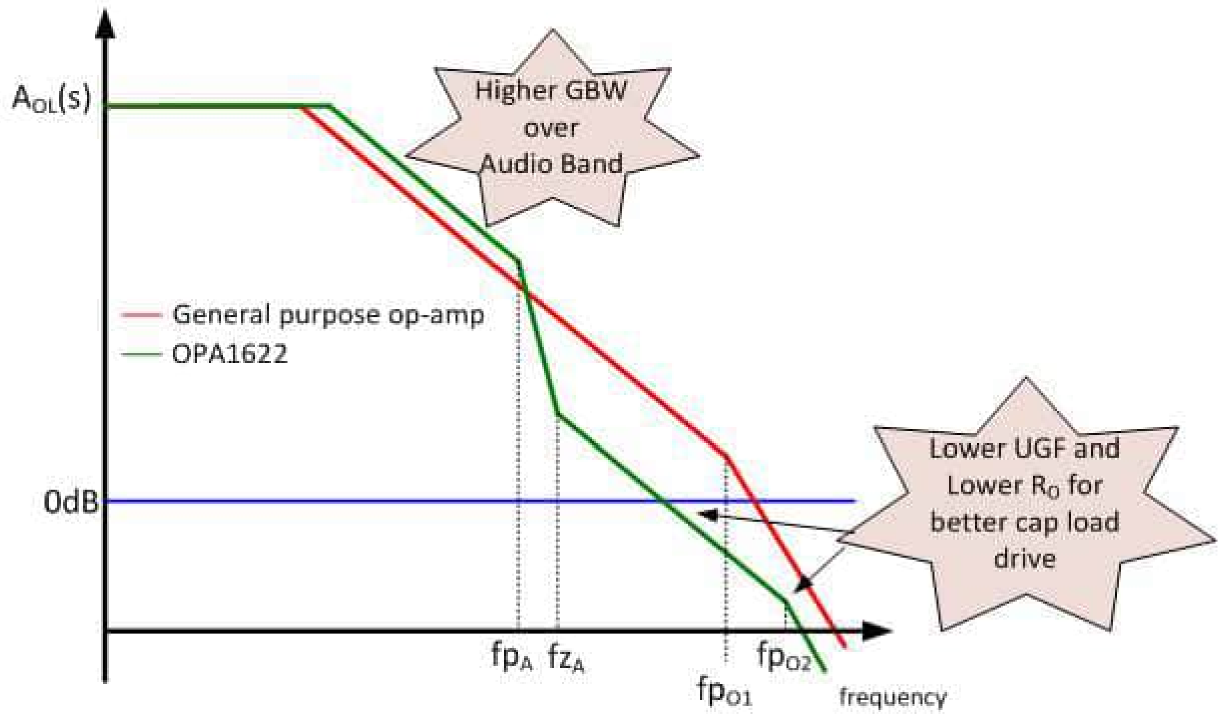

Figure 5: OPA1622 open-loop response vs. general-purpose amplifier for large capacitive load

Figure 6(a) shows the measured gain and phase response of the OPA1622. The pole-zeros in the response enable the gain to roll off faster with only minor changes in the phase response, allowing adequate phase when gain crosses 0dB. The gain bandwidth in the audio band is around 32MHz, with a unity-gain frequency (UGF) of 8MHz. Figure 6(b) shows the open-loop output impedance of the OPA1622.

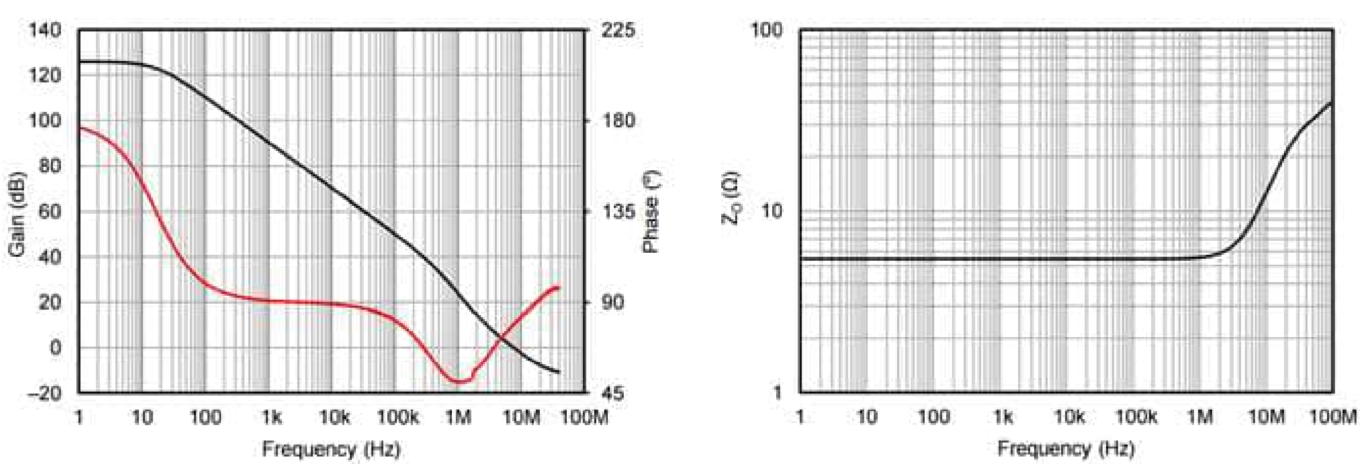

Figure 6: OPA1622 open-loop gain and phase (a) and output impedance (b)

· We designed the OPA1622 to have a low output impedance of 5.5Ω over a wide frequency range. This allows it to drive capacitive loads over 800pF in a unity-gain configuration, requiring no external components for compensation. See Figure 7.

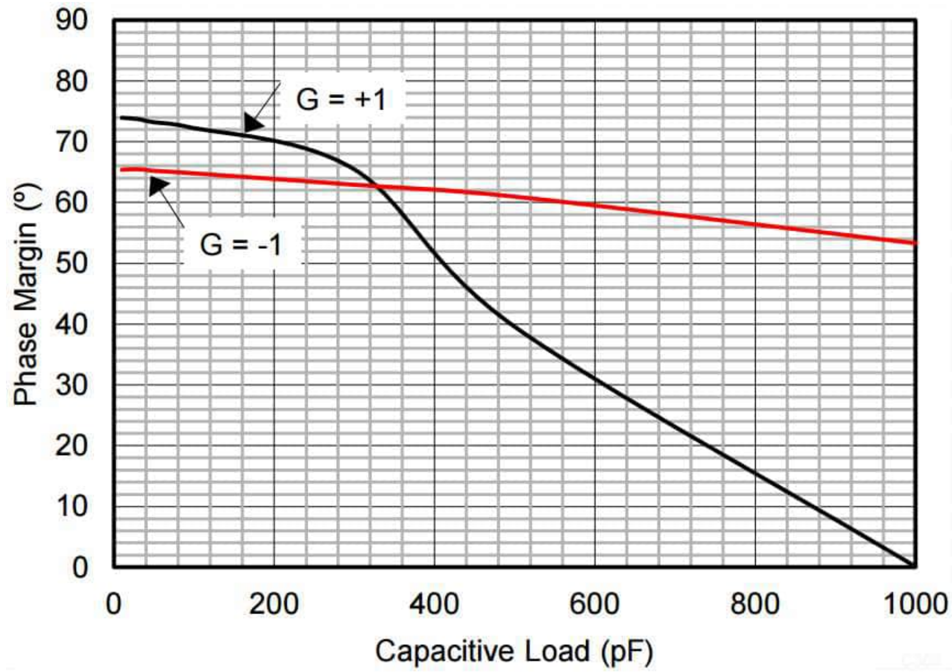

Figure 7: OPA1622 phase margin vs. capacitive load

We demoed the device at the 2016 Consumer Electronics Show (watch John's video of the demo) in a circuit that did not include any series isolation resistors. The OPA1622 was stable regardless of the headphone the attendees chose and we received overwhelmingly positive feedback regarding the sound quality.

In part three of this series, we'll take a look at slew rate, output drive and how the OPA1622 achieves ultra-low distortion while driving headphone loads.

Additional resources

- View the OPA1622 data sheet.
- Download the OPA1622 TINA-TI™ SPICE macromodel.
- Learn more about TI's audio operational amplifier portfolio and find technical resources.
- Watch on-demand training courses on stability and more in the TI Precision Labs – Op Amps Low-Distortion Design and Noise video series.

John Caldwell Feb 26, 2016

Other Parts Discussed in Post: OPA1688, OPA1622

This post is co-authored by Bharath Vasan.

Pop quiz! Take a look at the total harmonic distortion and noise (THD+N) curve in Figure 1. It's for an OPA1688, a 36V, 10MHz audio operational amplifier (op amp), delivering a $1V_{RMS}$ sine wave to several common headphone impedances. The distortion at high frequency is rising and is worse for low impedances.

Why?

Choose the correct response:

(a) The slew rate of the op amp is insufficient to reproduce the signal.
(b) The op amp's loop gain is decreasing.
(c) The op amp's output stage distorts more with low impedance loads.
(d) Both B and C.

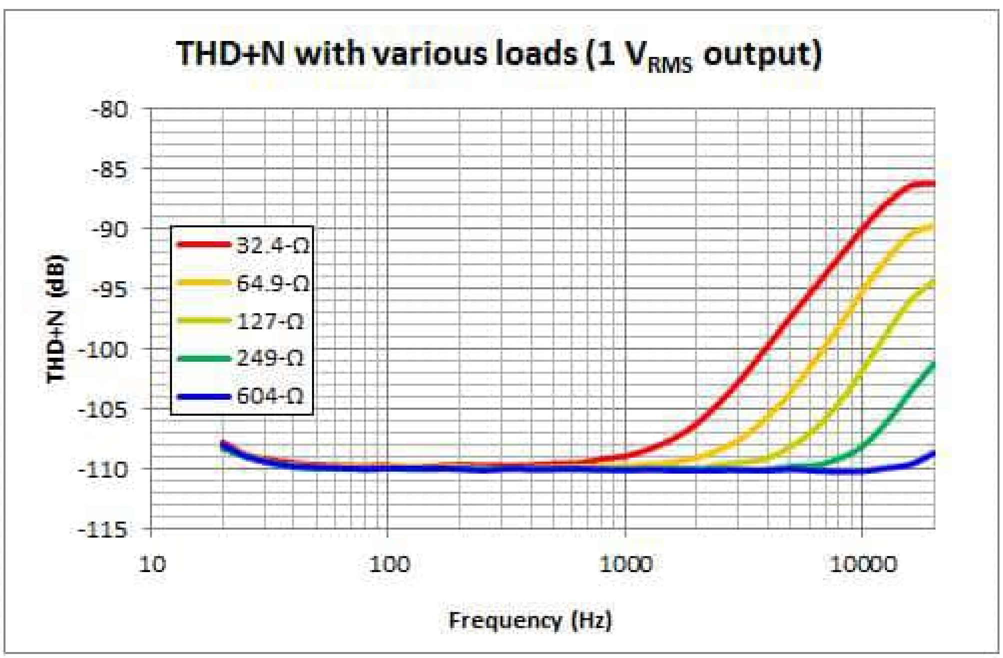

Figure 1: THD+N vs. frequency curve for an OPA1688 with various loads

For those of you who answered "A," slew rate is a measurement of how quickly an amplifier can change its output voltage in response to the input signal. If the amplifier's slew rate is less than the maximum rate of change of the input signal, the amplifier will distort the signal. In the case of a sinusoid, the maximum rate of change depends on the frequency and amplitude (Equation 1):

$$max \frac{d}{dt}[A \cdot sin(2\pi ft)] = 2\pi fA \qquad (1)$$

Insert some numbers from the quiz question into Equation 1 ($1V_{RMS}$ = 1.414Vp, 20kHz), and you can calculate the minimum amplifier slew rate necessary to reproduce the $1V_{RMS}$ signal:

$$max \frac{d}{dt} = 2\pi fA = 2\pi(20kHz)(1.414Vp) = 177688\ V/s \rightarrow 0.178\ V/\mu s$$

This is a modest slew-rate requirement, and the OPA1688's specification of 8V/μs is more than capable of preventing distortion from slew-rate limitations. Sorry, the answer isn't A.

Now let's address answers B and C: amplifier loop gain and output stage distortion. Consider the control system diagram in Figure 2, representing a basic op amp. The input stage of the op amp subtracts the feedback signal from the input voltage (V_{IN}) and amplifies the difference by the open-loop gain: α. β is the feedback factor and represents the portion of the output voltage (V_{OUT}) that is fed back to the input. The output stage of the op amp is the circuitry that delivers current to the load, represented by a simple unity-gain buffer. Figure 2 also includes a distortion source, V_D, summed with the signal inside the control loop.

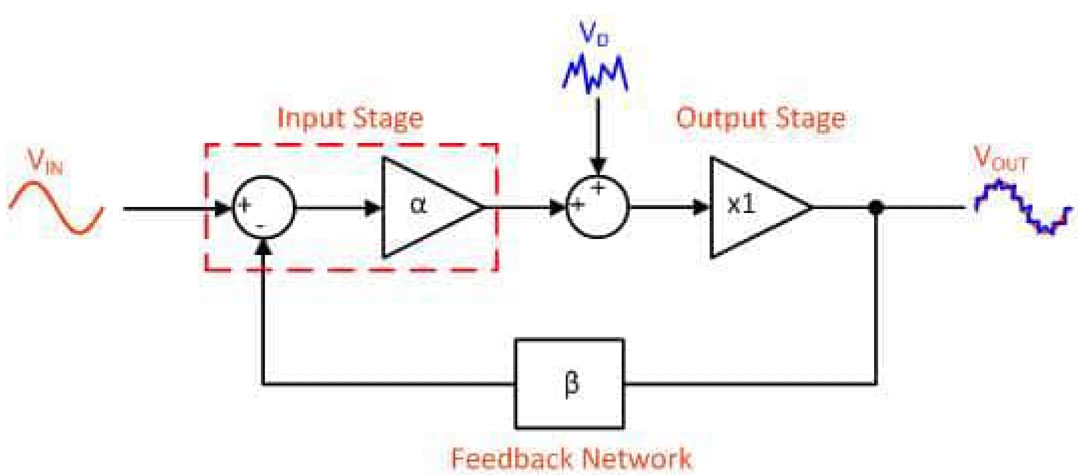

Figure 2: A control-loop diagram of an op amp that includes an internal source of distortion

The output signal of this system consists of two terms: the input signal (now amplified) and some remaining distortion (Equation 2):

$$V_{OUT} = \underbrace{\frac{\alpha V_{IN}}{1+\alpha\beta}}_{\text{Signal}} + \underbrace{\frac{V_D}{1+\alpha\beta}}_{\text{Distortion}} \quad (2)$$

The amount of distortion in the output signal is determined by:

- The amount of loop gain (the product of α and β).
- The amount of intrinsic distortion produced by the amplifier (the magnitude of V_D).

In Figure 1, the loop gain of the amplifier is decreasing at a high frequency, which causes the corresponding rise in distortion (answer B). Now you know why the distortion would increase at high frequencies. This also explains why TI chose to maximize the open-loop gain of the OPA1622 at audio frequencies, as we described in part 2 of this blog series.

But answer B doesn't explain why the distortion would be worse for low impedance loads. To understand this, we need to look at the gain of the output stage, which we assumed to be 1 in Figure 2. We'll tackle that in a post next week, where we'll show how the load impedance affects the gain of the output stage and compare the performance of the OPA1622 to the OPA1688 in the same test conditions.

Additional resources

- Watch our four-part TI Precision Labs training series on op-amp slew rate and low-distortion design.
- Learn more about TI's precision-amplifier portfolio and find more technical resources.
- Download the wildly popular *Analog Engineer's Pocket Reference* e-book for frequently used system- and board-level design formulas (myTI login required).

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John Caldwell Mar 4, 2016

Other Parts Discussed in Post: OPA1688, OPA1622

This post is co-authored by Bharath Vasan.

In part three of this five-part blog series, we introduced a simple control-loop model for distortion in an operational amplifier (op amp), repeated here in Figure 1. We also included a pop quiz that we'll continue discussing in this post, so please read that installment first if you haven't done so already. Everything we discuss here will make more sense that way.

The model in Figure 1 is useful in illustrating how a source of distortion would be attenuated by the loop gain of the system, but it does not reveal anything about the actual mechanism of distortion and why it would increase with low load impedances.

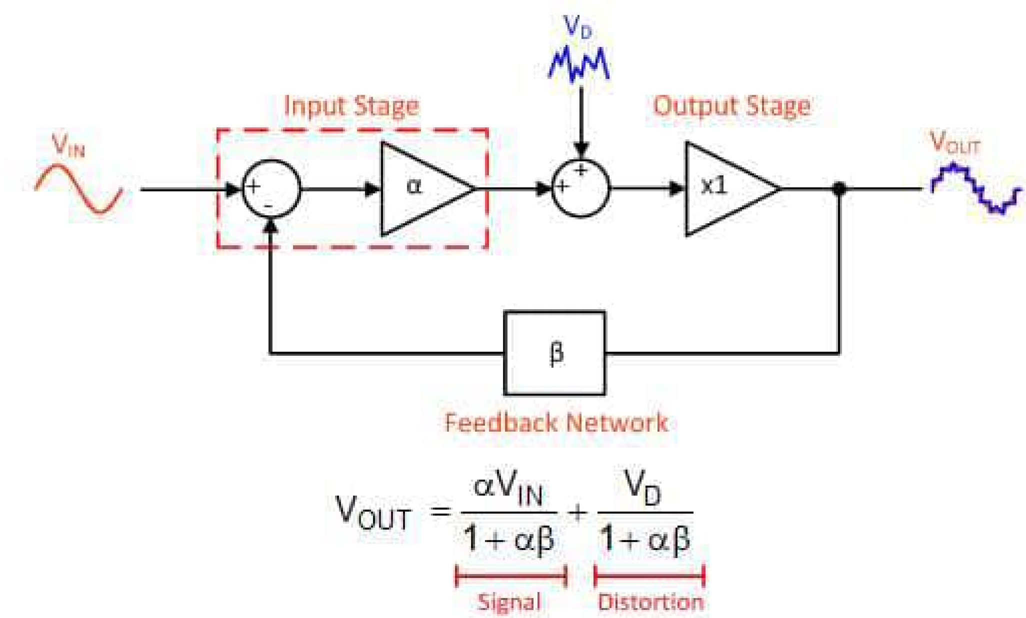


Figure 1: A control-loop diagram of an op amp that includes an internal source of distortion and the resulting transfer function

In an op amp's output stage, the distortion does not come from a separate source injected into the loop; it arises from variations in the impedance of the output stage with the load voltage or current. As illustrated in Figure 2, the actual gain of the output stage (A_{OS}) can be represented as a voltage divider consisting of the load impedance (R_L) and the impedance of the output stage (R_{OUT}).

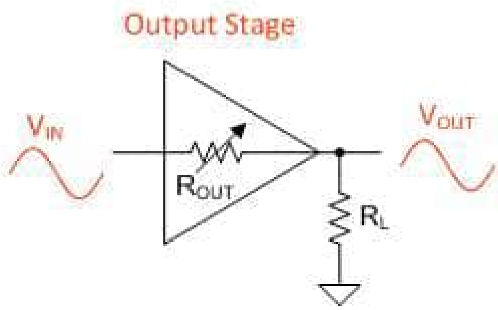


Figure 2: The output stage gain depends on output impedance and load impedance

Therefore, the gain of the output stage can never be exactly 1, and it also depends on the load impedance (Equation 1):

$$A_{OS} = \frac{V_{OUT}}{V_{IN}} = \frac{R_L}{R_{OUT} + R_L} = \frac{1}{\frac{R_{OUT}}{R_L} + 1} \qquad (1)$$

R_{OUT} separates into two terms: a static impedance (R_O) and a dynamic one that varies as a function of the output voltage and output current ($\Delta R[V_O, I_O]$). See Equation 2:

$$R_{OUT} = R_O + \Delta R(V_O, I_O) \qquad (2)$$

It is this varying output impedance that produces distortion. For example, if R_{OUT} decreases when the output stage is sourcing current, then the overall gain of the output stage would be greater for positive voltages compared to negative ones, and would distort the input signal.

Substituting the expression for R_{OUT} back into Equation 1 offers some insight into the role that load impedance plays:

$$A_{OS} = \frac{1}{\frac{R_O}{R_L} + \frac{\Delta R_O(V_O, I_O)}{R_L} + 1}$$

Notice that ΔR_O is divided by the load impedance. Therefore, reducing the load impedance will cause greater variations in the gain of the output stage and produce more distortion (answer C from the pop quiz in part 3 of this series).

· To show this effect, my colleague Bharath Vasan simulated the output stage gain versus the output voltage for the OPA1688, a general purpose audio op amp, and the OPA1622, an audio op amp designed for low impedance loads. He used 604-Ω and 32.4-Ω loads for these simulations.

Figures 3 and 4 show the results. In the 604-Ω load case, both amplifiers displayed stable gain over the range of output voltages simulated. But in the 32.4-Ω case, the differences between the two output stages became apparent. The gain deviation was worst near 0V, where the load current transitioned from one output transistor to another. This is commonly known as output crossover distortion. In the OPA1622, the output crossover region is greatly reduced, and the gain deviation in this region is minimized.

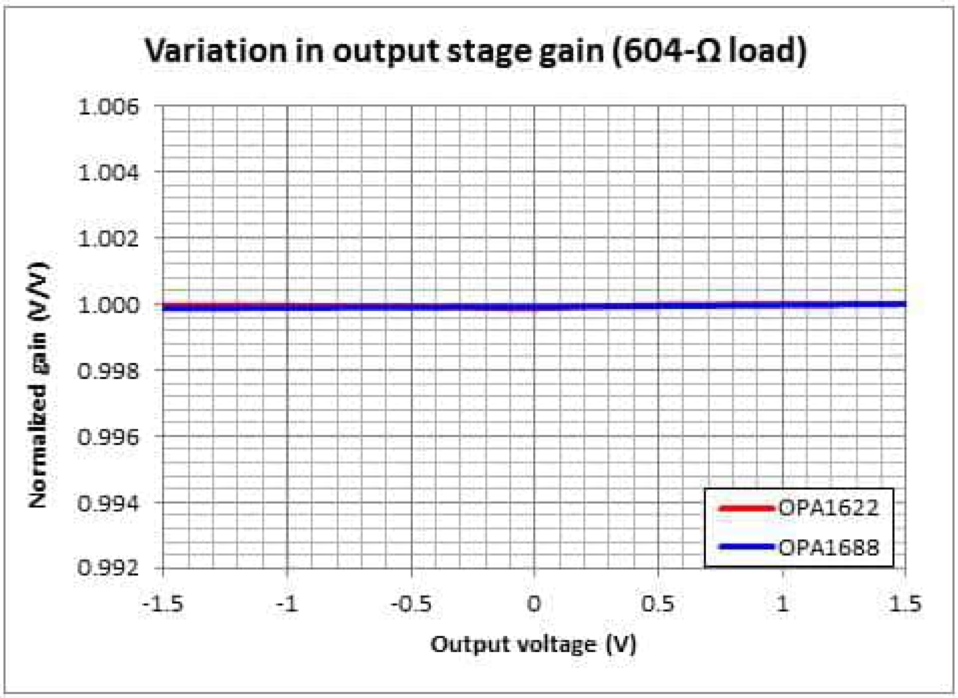


Figure 3: Output stage gain vs. output voltage for a 604-Ω load

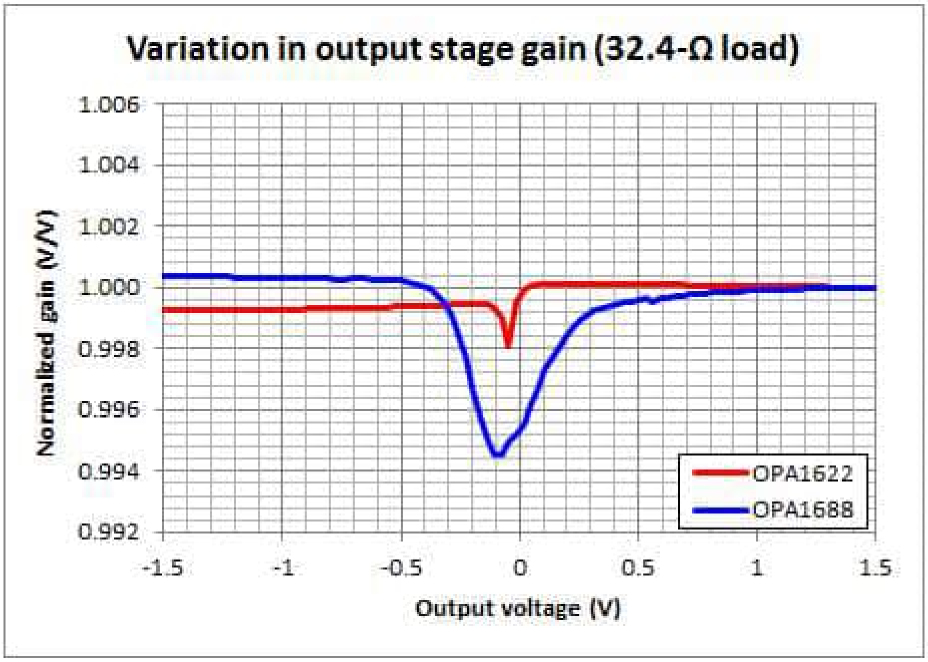


Figure 4: Output stage gain vs. output voltage for a 32.4-Ω load

Congratulations to those of you who answered “D” to the pop quiz in part 3! High-frequency distortion depends on both the loop gain of the amplifier and the distortion of the output stage.

When developing the OPA1622, we took a dual approach to reduce distortion. Not only did we maximize the open-loop gain of the amplifier at audio frequencies, but we reduced the intrinsic distortion of the output stage by addressing the dynamic component of the output impedance.

The result of this improved output stage is instantly recognizable in the distortion measurements. The measurement performed in Part 3 on the OPA1688 is now repeated in Figure 5 with the OPA1622. Notice the improvement in high frequency distortion for all load impedances.

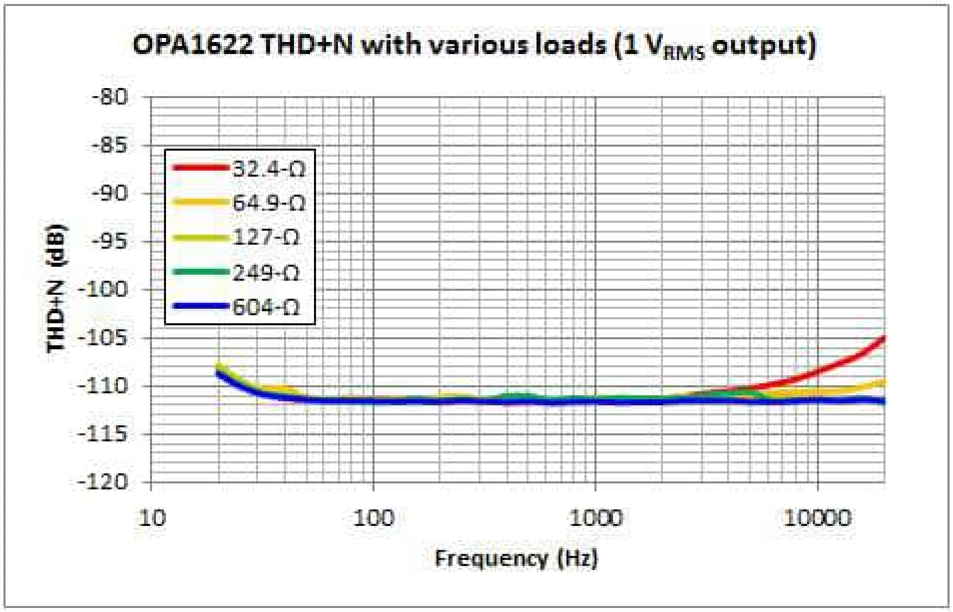


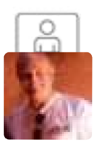
Figure 5: THD+N vs. frequency curve for an OPA1622 with various loads

In the final installment of this blog series, we'll take a look at the shutdown feature of the OPA1622 and how we minimized audible "clicks" and "pops" when the amplifier is enabled and disabled.

Additional resources

- Watch a four-part TI Precision Labs – Op Amps training course on low-distortion design.
- Search TI Designs – Precision reference designs to help get your next design started.
- Read the OPA1622 and the OPA1688 datasheets.

5 comments 0 members are here



Neil Albaugh *over 9 years ago*

Thanks for doing this presentation. I have maintained for a long time that driving very efficient horn speakers, such as Klipsch La Scalas, with high power amplifiers delivers disappointing performance. With sensitivities of 103dB/W, these speakers produce listening-level sound with only a watt or two of amplifier power. At this low power level the amplifier is operating in its cross-over region, thus emphasizing the distortion. A low-efficiency speaker requires far more power so the cross-over region distortion produces much less overall distortion in this higher power output.

Simply speaking, a La Scala, Belle Klipsch, or Klipschorn should be driven with an amplifier that produces low distortion at low power. Do that and the reputed "harshness" of these speakers is overcome.

You have shown the same thing in this presentation, albeit with headphones.

John Caldwell *over 9 years ago*

Great point Neil, since most modern headphones are extremely efficient, the amplifier may operate the vast majority of the time in the crossover region, leading to all sorts of high-order harmonics. There seems to be the same perception in headphone amplifiers that exists in audio power amplifiers that "more power is better". I think the assumption is that if an amplifier can linearly deliver 100W for example, then 1W should be no problem! The reality of the matter is much more complicated, especially in a monolithic amplifier. Big output transistors can often require big compromises.

Torgeir Skomedal *over 9 years ago*

I don't quite get this. Looking at THD+N in 10.3.2 of OPA 1688, it looks like under 0.2 volts the noise is dominating the distortion or the distortion is fixed value at about-110 dBV. So why is crossover distortion a problem? Is it over 1 k?

I just say: Don't try at home to put 1 V HF sine on a pair of low impedance, normal sensitivity headphones. You might or probably will get hearing damages!!! Low impedance dynamic headphones will distort way more than -80db with 1 volt input. I guess -20dB or worse if they are not melted.

Looking at figure 50 of 1688 the sensitivity must only be 99dB/mW to get 115dB at 1V input and 32Ohm. (about 30mW). So how to protect the hearing of the customers is a bigger concern, in my opinion. Consumer health is at risk if a headphone amp is designed to drive both low sensitivity cans AND high sensitivity cans as 30 dB difference in sensitivity can bee seen:

Ultimate Ears TripleFi 10 - Sensitivity: 117 dB SPL/mW, 1 kHz, 32 ohms

HiFiMAN HE-5LE - Sensitivity: 87.5 dB, 1 mW, 38 ohms

(source NwAvGuy)

Altough I can't se any practical differences between 1688 and 1622 for cans over 95db/mW, the V/V curve was interesting, but he signal frequency would be useful to know.

Else thank you for enlightening the HFside of cans in part 1 and 2!

Regards Torgeir

TinderSmith *over 8 years ago*

John Caldwell Could you give me way to communicate with you? I wish have a chance to talk about an the article "Sing-supply, Electret Microphone Pre-Amplifier Reference Design", thank you!

John Caldwell *over 8 years ago*

TinderSmith, If you would like to ask a question about the details of a TI Precision Design (such as my design for a Single-Supply Microphone Preamplifier) I recommend that you start a new thread in the Precision Amplifiers section of the e2e forum. Thank you.

Bharath Vasan *Apr 15, 2016*

Other Parts Discussed in Post: OPA1622

This post was co-authored with John Caldwell.

In the final installment of this five-part blog series, I will discuss pop/click noise in operational amplifiers (op amps) driving headphone loads, and some techniques to minimize them. The previous posts discussed power considerations for headphone loads, impedance of headphones, and sources of headphone amplifier stability and distortion.

Undesirable audible noise resulting from applying power or changing operational modes in an audio system is commonly called a pop or a click. This effect is of extreme concern in high-fidelity headphone systems due to the high efficiency of the headphone drivers. Even relatively small transients in the signal voltages will produce loud and unpleasant sounds from the headphones. In order to improve the user experience and prevent damage to headphones or other sensitive electronics, many systems employ circuitry to suppress transient signals from the amplifier output during power-up.

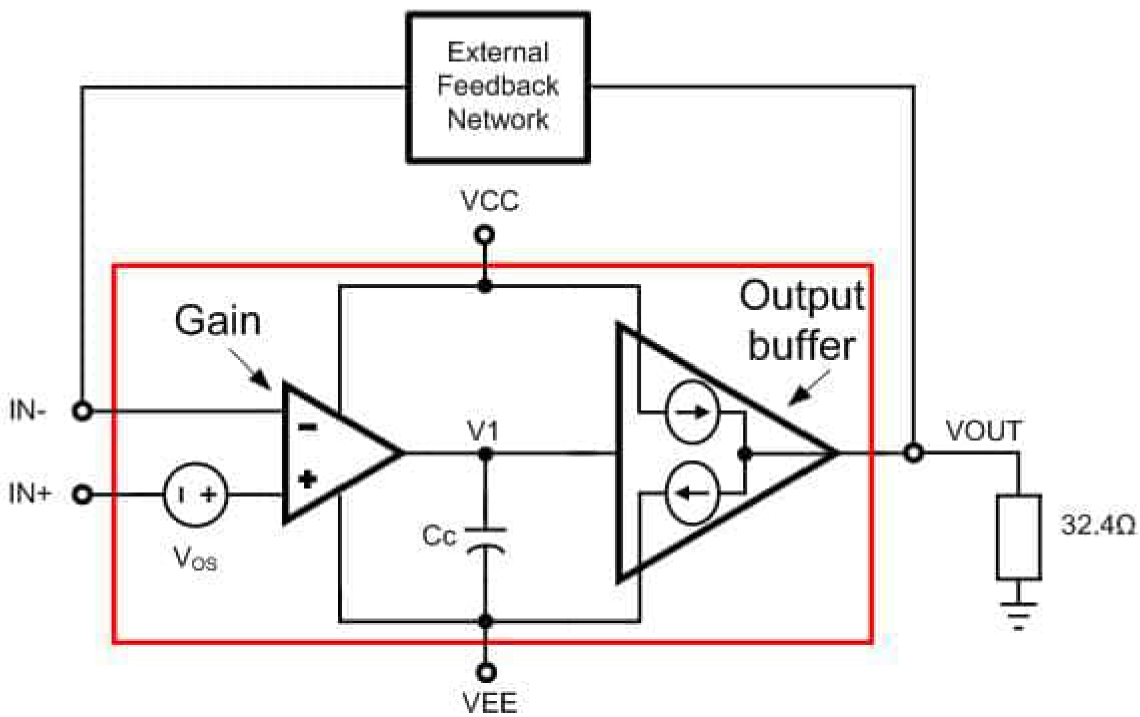


Figure 1: Op amp driving a headphone load

Let's look at some of the common sources of pop/click noise in an op amp.

· Figure 1 is a simplified block diagram of an op amp driving a headphone load. It consists of two stages – a gain stage and an output buffer – as well as a compensation capacitor, Cc, and an offset voltage, Vos. The output buffer is a unity gain stage capable of sinking and sourcing current as shown.

Pop/click noise is typically associated with transients at the output pin of the op amp. The chief sources of pop/click noise are:

- **Power-supply ramp**: During power-on, VCC and VEE gradually ramp up. Until the op amp reaches its minimum supply requirement, it has not yet attained steady-state operation and is not regulating the output. During this period, large transients could result at the output pin. A power-off where VCC and VEE ramp down could be accompanied by similar transients, as could asymmetric ramping of VCC and VEE.
- **Enabling/disabling the amplifier**: Many op amps include options to enable or shut down the device. The enable command turns on the op amp's internal bias circuitry. As the bias currents come up, the gain stage starts charging the compensation capacitor to the appropriate voltage, the sourcing and sinking currents in the output buffer start stabilizing, and the op amp approaches steady state. During this phase, unequal sourcing and sinking currents in the output buffer result in current being injected into the load. This could result in significant pop/click noise. Similar transients can occur after a shutdown command.
- **Offset voltage of the amplifier**: An interesting source of pop/click noise is the offset voltage. Once the amplifier reaches steady state, the output of the amplifier jumps to the offset (or Vos/β, β = feedback factor) of the amplifier. If the offset is large enough, the change in the output is audible.

Amplifiers with integrated pop-click suppression can significantly simplify audio systems. The OPA1622 high-performance headphone amplifier includes a solution to suppress pop/click noise when the part is enabled or in shutdown mode. Figure 2 shows a simplified block diagram of the OPA1622.

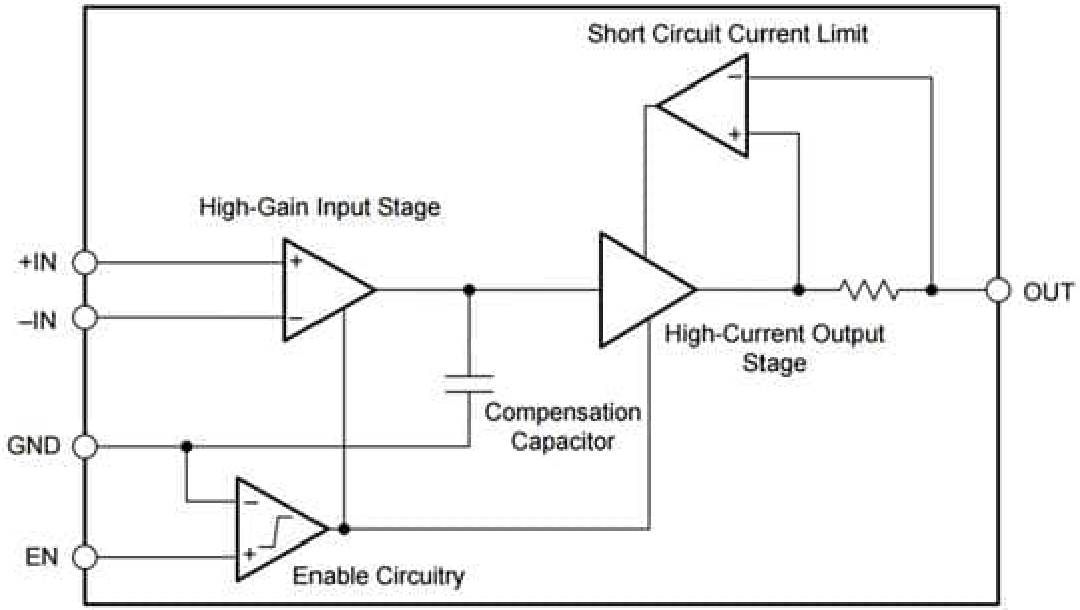


Figure 2: OPA1622 block diagram

The enable circuitry (ENC) maintains control of the input and output stage when the amplifier is enabled or in shutdown mode. When enabled, the ENC steadily transitions to power the gain stage and the output stage. Upon shutdown, the ENC controls the charge on the compensation capacitor and disables the gain stage and the output stage. The carefully optimized transition into and out of shutdown ensures that very small currents are injected into the headphone load, thus minimizing pop/click noise.

During the OPA1622's development, we focused on optimizing the offset voltage and its contribution to pop/click noise. The OPA1622 has an offset voltage of 50μV typical and 500μV max.

Figures 3 and 4 show the performance of the OPA1622 during enable and disable, respectively. Only very small output transients accompany the enable or disable events. The output transients occur over a very short duration and are therefore unlikely to be audible in headphone applications.

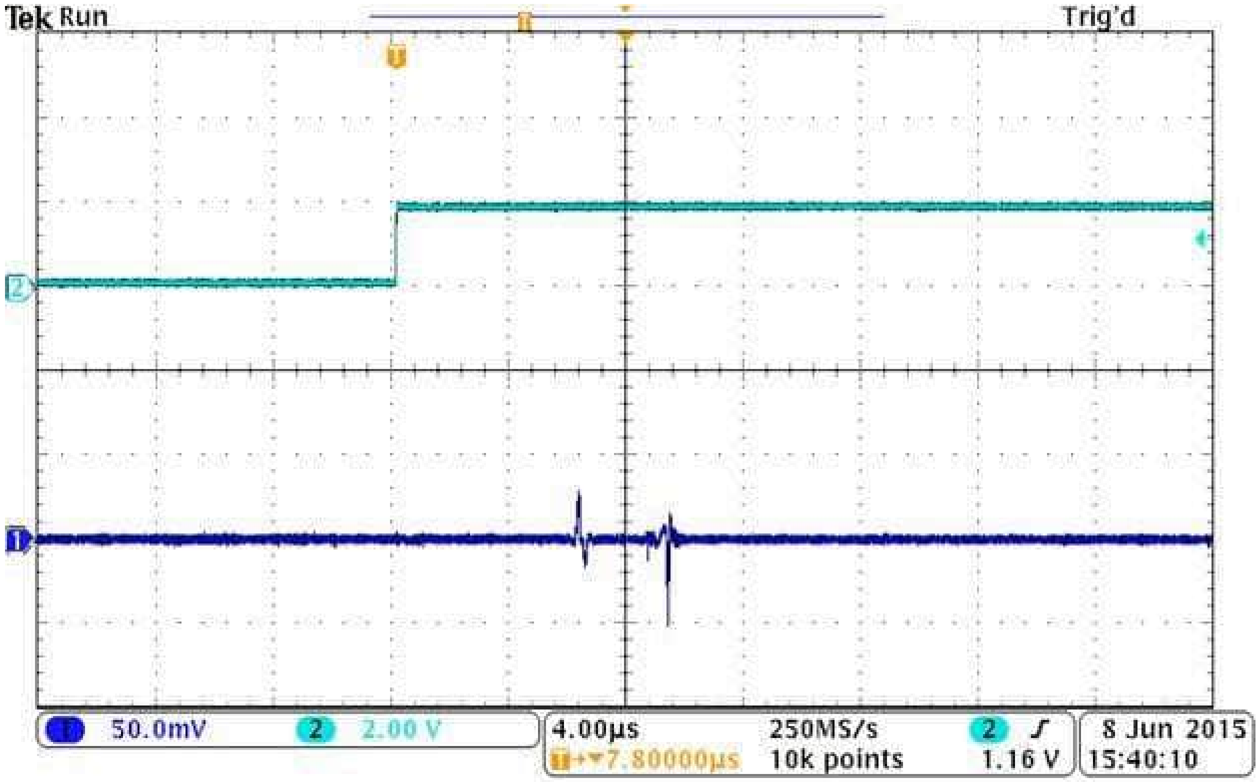


Figure 3: Output voltage when enable transitions high (32Ω)

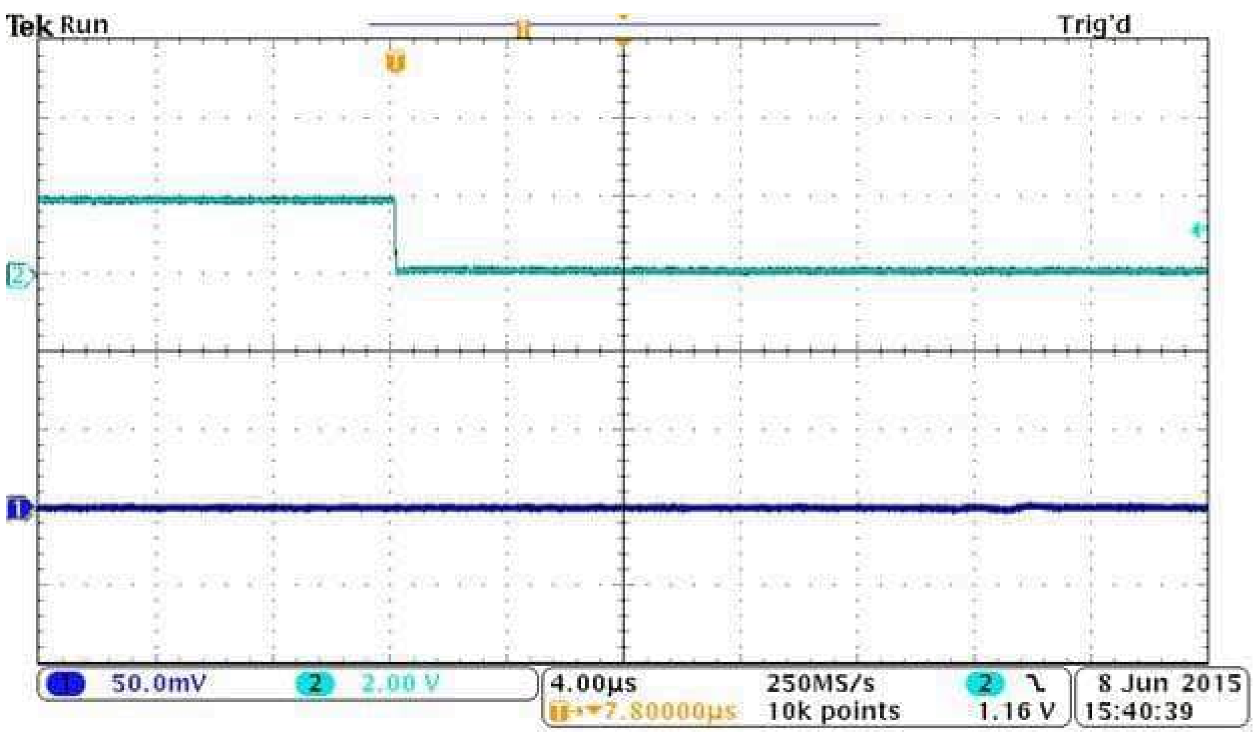


Figure 4: Output voltage when enable transitions low (32Ω)

Several factors can affect pop/click noise performance in op amps driving headphones. By including a pop/click noise-suppression circuit, the OPA1622 can improve the overall user experience in audio

- applications.

Do you have experience with pops and clicks in your system? Log in, leave a comment and let us know about your system design.

Additional resources

- Watch a four-part TI Precision Labs – Op Amps training course on low-distortion design.
- Search TI Designs – Precision reference designs to help get your next design started.
- Download the OPA1622 TINA-TI™ SPICE macromodel.
- Learn about TI's entire portfolio of amplifier ICs and find technical resources.