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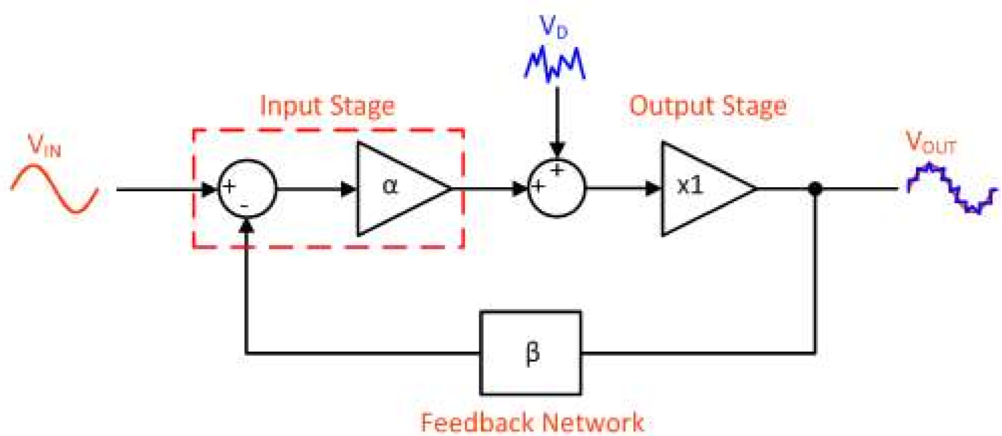
John Caldwell Mar 4, 2016

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.



$$V_{OUT} = \frac{\alpha V_{IN}}{1+\alpha\beta} + \frac{V_D}{1+\alpha\beta}$$

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}).

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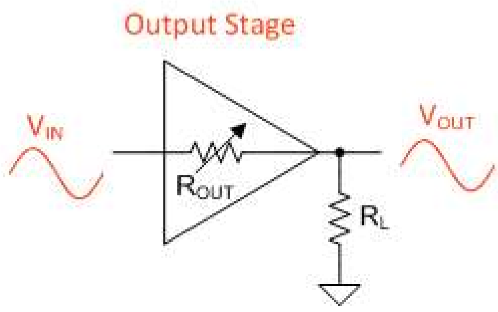

Figure 2: The output stage gain depends on output impedance and load impedance

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.

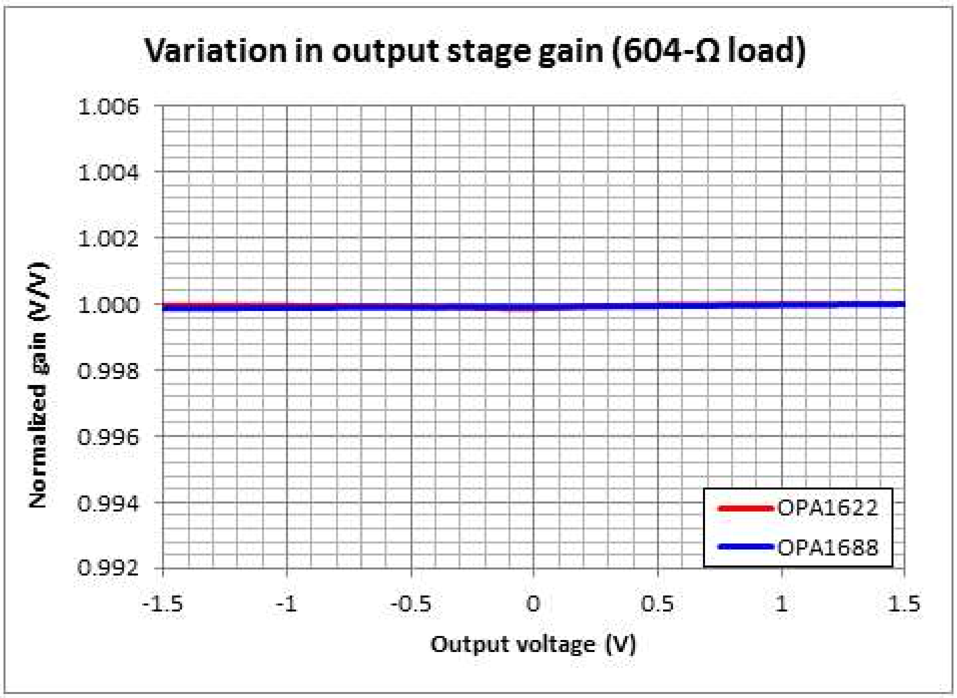

Figure 3: Output stage gain vs. output voltage for a 604-Ω load

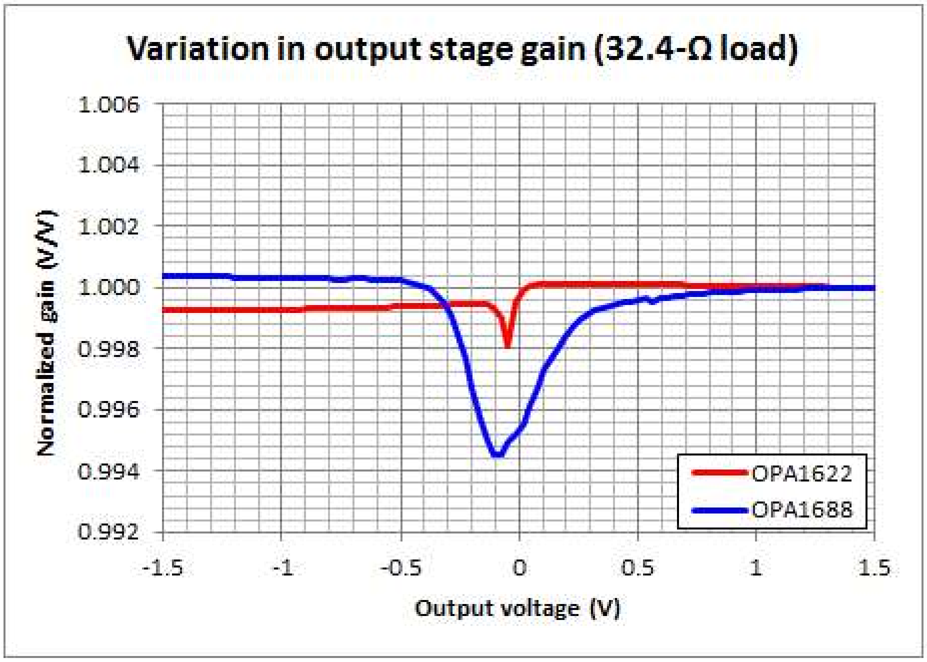

Figure 4: Output stage gain vs. output voltage for a 32.4-Ω load

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.

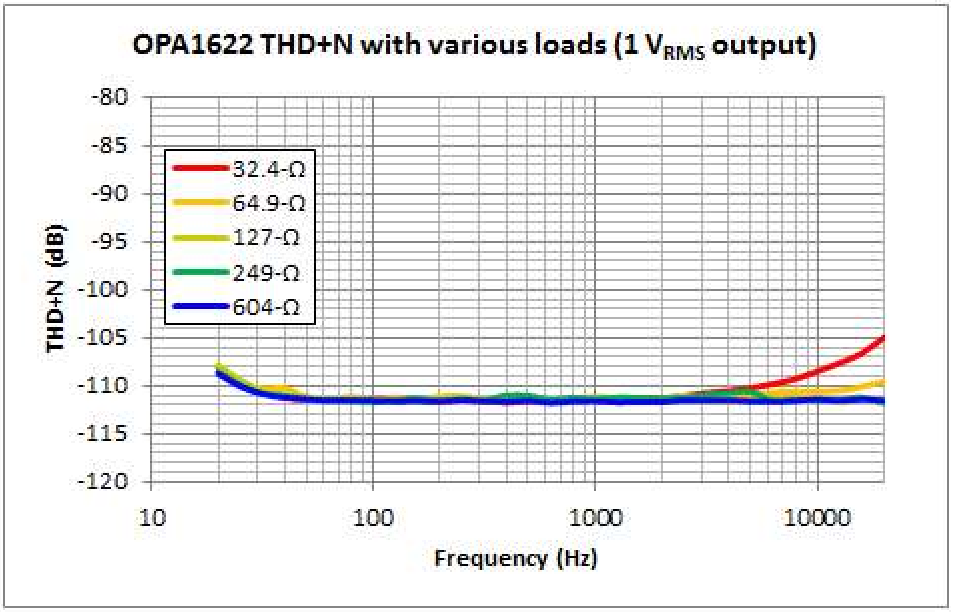

Figure 5: THD+N vs. frequency curve for an OPA1622 with various loads

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.