Low Distortion Design – 3

TIPL 1323
TI Precision Labs – Op Amps

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Prerequisites: Noise 1 – 3
(TIPL1311 – TIPL1313)

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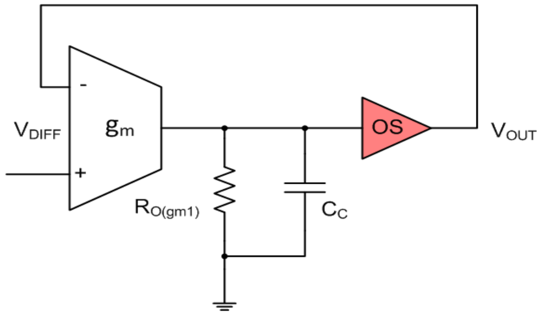
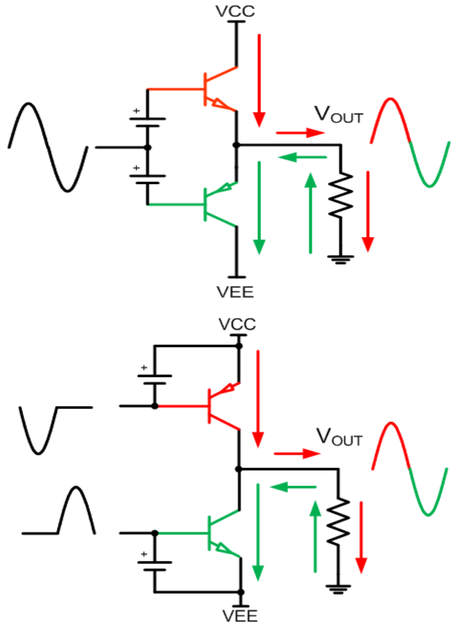
Hello, and welcome to part 3 of the TI Precision Labs series on designing low distortion op amp circuitry. This video will focus on sources of distortion from the op amp's internal output stage. Specifically we will look at how different internal topologies affect distortion, as well as how loading and clipping introduce distortion.

Output Stage Topologies





- Most op amps use a Class-AB output stage configuration
  - Classic emitter follower configuration (top), gain = 1.
  - Rail-to-rail output (bottom), gain depends on load resistor.

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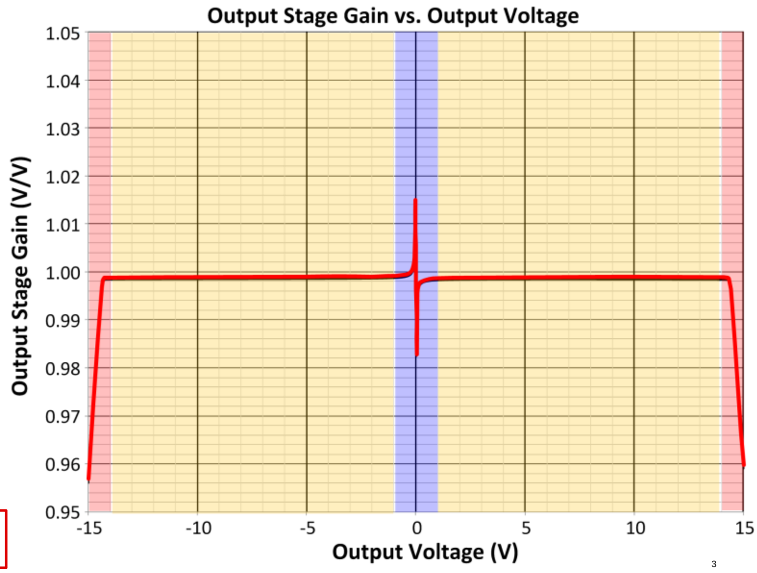
Output stage distortion originates in the final output block of the op amp, highlighted in red in this diagram. Output stages can be categorized into two main configurations. There's the classic class-AB output stage, or emitter follower output stage, shown here in the upper right hand side. There's also the rail-to-rail, or common collector configuration, shown on the lower right hand side.

The classic emitter follower configuration is not a rail-to-rail output stage. The output stage gain in the signal path for this topology is one. There will be a circuit that biases the transistors into class-AB. The top transistor, shown in red, sources current into the load on the positive half cycle, and the bottom transistor, shown in green, sinks current during the negative half cycle.

The function is similar for the rail to rail, common collector, output stage. Although now instead of the emitters being connected to the load, the transistors are flipped and the collectors are connected to the load. The result is that the rail-to-rail output has gain that depends on the load impedance.

Output Stage Transfer Function

- The transfer function of the output stage shows 3 distinct regions:
  - Large Signal Regions (Orange)
    - A single device conducts current from the power supply to the load.
  - Clipping Region (Red)
    - Insufficent V_{CE} (V_{DS}) drop on output devices to sustain load current
  - Crossover Region (Blue)
    - Both or neither output device conducting current to the load
- All 3 regions will produce some type of distortion



Self, D., Audio Power Amplifier Design, 6th Edition, Focal Press, 2013, ISBN-13: 978-0240526133

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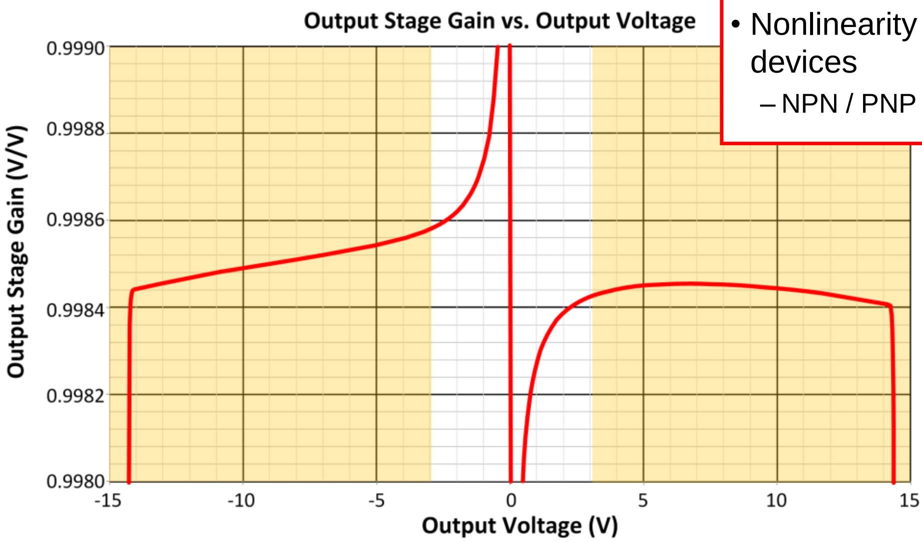
Since the output stage has its own gain, we can plot the gain versus output voltage. We can use this to understand the different regions of output stage operation and how they each produce their own unique type of distortion. The plot shown at right is typically call a wing spread plot. These plots were popularized by the author Douglas Self, see the reference for more information.

The plot shown in this example is a classic emitter follower output. The gain is plotted versus the output voltage of an amplifier on +/-15V supplies. We have three different regions denoted by different colors. First are the large signal regions shown in orange. In each of the orange regions, only a single device, either the top transistor or the bottom transistor is conducting current to the load. The next region is the region near either supply and is shown in red. This is the clipping region. In this region there is insufficient collector to emitter voltage to sustain the load current. We can see that the output stage gain starts to decrease in the clipping region.

The last region is called the crossover region and is shown in blue. In this region, either both, or temporarily neither, of the output transistors are conducting current to the load. We can see that this creates a discontinuity in the gain of the output stage near the zero crossing point. So, all three of these regions can create some form of distortion. In the next slide we will zoom in on the large signal region, so that we can see the nonlinearity of this part of the curve. The new y-axis range will go from 0.998 to 0.999 instead of 0.95 to 1.05 as is shown here.

Large Signal Non-Linearity



- Magnified Transfer Function
- Nonlinearity from dissimilar output devices
  - NPN / PNP different transfer functions

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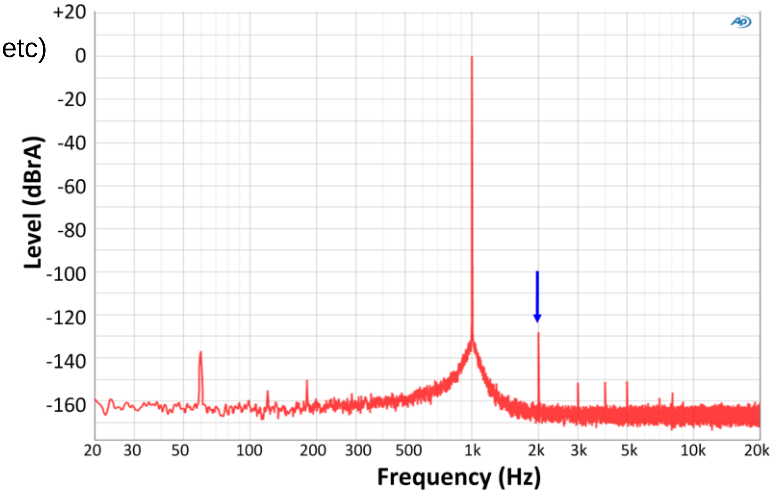
Let's first start with what is commonly called "large signal nonlinearity". Here we've zoomed in on the previous plot to take a closer look at the gain characteristic in the orange colored large signal region. Now we can see that the two different large signal regions are actually quite different and are not symmetrical. This is because the NPN and PNP devices are not matched and each device will have it's own transfer function. This will cause the positive half cycle and negative half cycle to be non-symmetrical. This type of distortion will show up as an even harmonic. Consequently, large signal nonlinearity from the output stage of an op amp typically generates even harmonics.

Identifying Large Signal Non-Linearity

- Large signal non-linearity dominates at large output voltages
  - Even-order distortion (2nd, 4th, 6th, etc)
  - 2nd Harmonic is largest
- FFT
  - OPA1652
  - Gain: +1
  - +/-15V Supplies
  - V_{OUT}: 8.1V_{RMS}
  - 2nd Harmonic: -128dB



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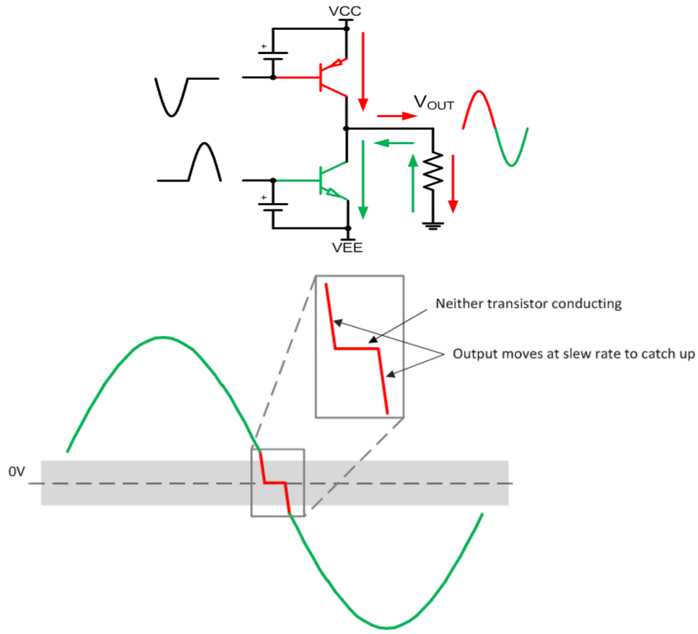
This plot shows a measured FFT plot for an OPA1652 with +/-15V supplies in a gain of +1. The output signal is fairly large at 8.1Vrms, or 11.5Vpk. Examining the FFT of the output, you can see that the second harmonic is by far the largest. This type of result is indicative of large signal output stage distortion. In general, the second harmonic will be the largest, although you may see other even order harmonics.

Crossover Distortion

- At 0V load current switches from one device to the other
  - Small discontinuity at 0V crossing
  - Produces high-order harmonics
- Worst THD at low output amplitudes and high output currents
  - Load current degrades biasing
  - Low output voltages means crossover region makes up more of the total amplitude



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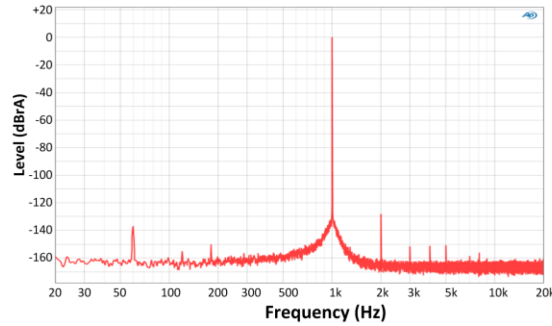
Now let’s switch to another region of operation, the crossover region. In this region, temporarily either both or neither transistor might be conducting current to the load. We can consider that for outputs near zero volts, the load current will switch from one device to the other. So we switch from sourcing current into the load, to sinking current out of the load. There will always be a small discontinuity in the output near zero volts because we can’t get that handoff of current perfect. After the output moves out of the condition where neither transistor is conducting the amplifier will move at the slew rate to try to catch up. The bias circuitry is designed to make this handoff region as small as possible, but there always some region where either neither transistor is conducting, or a worst case scenario is where the output stage is over-biased and temporarily both devices are turned on. When both transistors are on this is referred to as a shoot through or cross conduction condition.

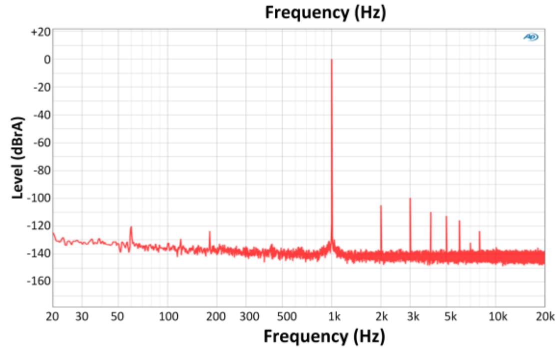
Crossover distortion is a little counterintuitive when compared to other types of distortion, and that is because crossover distortion is worse at low output amplitudes. For example, if the output signal is small enough, it might reside entirely in the output crossover region. Also lower load impedances result in greater current draw from the output BJTs. This causes output transistor Beta to droop which steals current from the class-AB bias and results in a wider crossover region. This is why low distortion headphone applications are so challenging because these applications have very small output amplitudes and very low load impedances.

Output Crossover Distortion

- Test #1
  - OPA1652
  - Gain: +1
  - +/-15V Supplies
  - 2.5mA$_{RMS}$ output current
  - Rload: 3240 Ohms, Vout: 8.1 Vrms
  - THD: -128dB

- Test #2
  - OPA1652
  - Gain: +1
  - +/-15V Supplies
  - 2.5mA$_{RMS}$ output current
  - Rload: 32.4 Ohms, Vout: 81 mVrms
  - THD: -100dB





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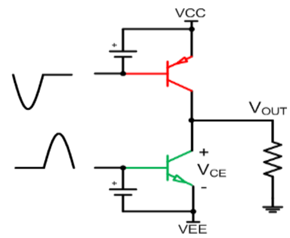
To illustrate this point we again return to the OPA1652. The top plot is the one we showed previously. The op amp is in a gain of +1 with +/-15V supplies. The output is providing 2.5mArms into a load impedance of 3.24k with an output voltage of 8.1Vrms. As we mentioned previously, the distortion is dominated by a second harmonic, and THD in this case is -128dB. However, if we lower both the output voltage amplitude and the load impedance, keeping the same output current we get significantly more distortion. Specifically, in this case we reduced the load resistance to 32.4 ohms and reduced the output signal to 81mV. Note that the load current in both test 1 and test 2 was intentionally kept equivalent to show that these effects are not from the output current. The reason for the significant increase in distortion is because the low level output signal is staying almost entirely in the crossover region.

Clipping

- Collector to emitter drop across output devices:
  - $V_{CE} = V_{OUT} - V_S$
- Insufficient voltage for linear operation.
  - $V_{CE} < V_{CE(SAT)}$
  - Notice $V_{CE(SAT)}$ depends on I_C
- Outside of active region:
  - Output stage gain drastically decreases
    - A_{OL} also decreases
  - Output stage distortion increases
    - Typically odd harmonics
- Use the A_{OL} test conditions for linear swing range



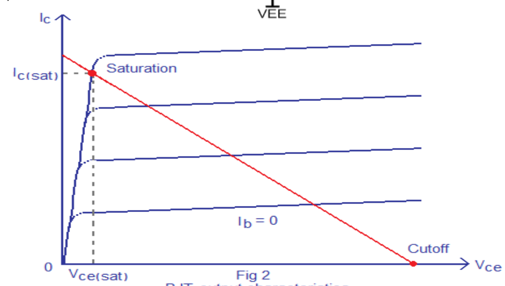


Fig 2
BJT output characteristics

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
OPEN-LOOP GAIN						
A_{OL}	Open-loop voltage gain	(V–) + 0.2 V ≤ V_O ≤ (V+) – 0.2 V, R_L = 10 kΩ	114	130		dB
		(V–) + 0.6 V ≤ V_O ≤ (V+) – 0.6 V, R_L = 2 kΩ	110	114		dB

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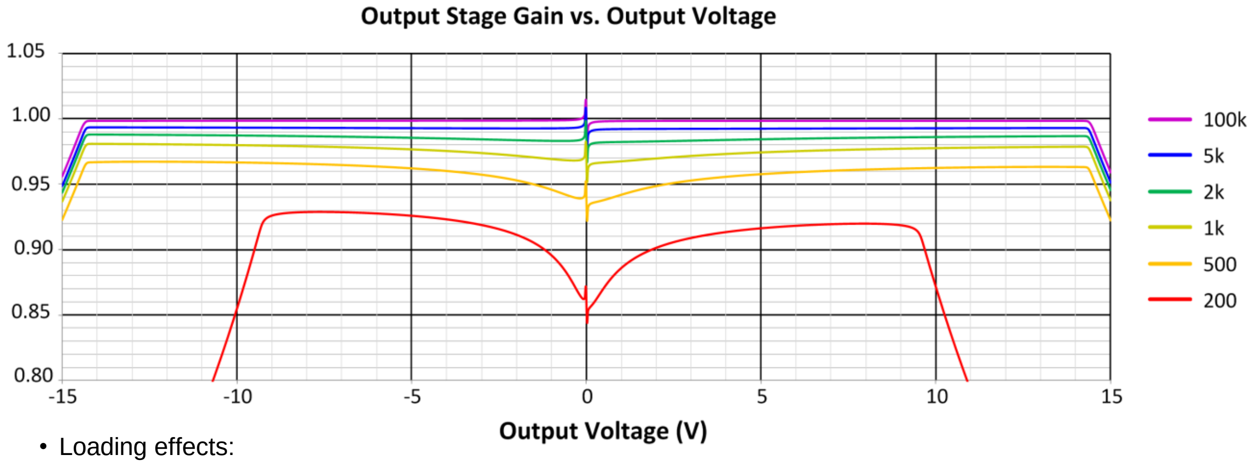
What about clipping? We all know that if the output amplitude gets close to either power supply rail, the sine wave is squared off. This type of distortion will generate a lot of odd order harmonics.

To understand what is happening when the amplifier clips, you must understand that the Vce voltage across the output transistor is the difference between the supply voltage and the output voltage. If we remember back to the characteristic curves for transistors, they have an active region where the transistor operates as a current source, but this requires a minimum voltage across the transistor, called V_{CE_SAT}. Below this saturation voltage the transistor no longer acts like a current source, but rather acts more like a resistor. As the load voltage increases, the Vce of the transistor is decreasing, and eventually the V_{CE} will drop below the V_{CE_SAT} of the output transistor, and they will no longer act like current sources as desired.

The typical result of this is that the output stage gain decreases which decreases the open loop gain of the amplifier. This behavior is highlighted in the open loop gain test conditions. If you need a good indication of the linear output range of an amplifier, the best place to look is at the data sheet open loop gain test conditions. Typically open loop gain is specified with an output voltage range and a loading condition. This example was taken from the OPA1612 data sheet. We see that with a 10kΩ output load the output can swing within 200mV from either supply rail while maintaining a typical open loop gain of 130dB down to 114 dB. When the output load is decreased to 2kΩ the output swing must stay at least 600mV from either supply rail to maintain a typical open loop gain of 114dB down to the minimum of 110dB. Once the output voltage extends outside of these ranges, the open loop gain will decline. This effect may show up as clipping on an oscilloscope, but will generally show up as distortion harmonics in the frequency domain long before you see it on a scope.

Loading Effects on Transfer Function



- Loading effects:
  - Decreased output stage gain, magnifies dissimilarities in output devices
  - Worsens crossover region
  - Reduced output swing (increased clipping region)

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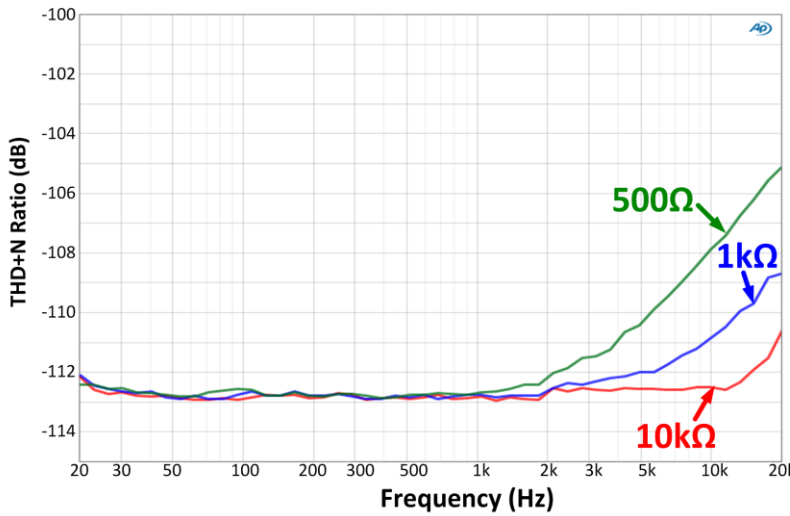
Loading the output an op amp makes all three of these effects worse. The lower the load impedance on the output of an op amp, the worse the distortion in all three of the regions. So, the crossover distortion gets worse, the large signal nonlinearity gets worse, and the clipping regions will extend inward. Looking at this wingspread plot for a high impedance loads, such as 100k ohms, you can see that the gain of the output stage is essentially one. But as the load impedance is decreased, a few things happen. First, in the large signal region, the gain of the output stage is decreasing. Also, you will notice the crossover region gets worse and we can see that on either side of the discontinuity the slope increasing. Finally, the clipping region can drastically changes as seen with the 200 ohm load.

Loading Effects for Output Distortion

- Output stage distortion appears at high frequency in THD+N curves
  - Mirrors the decline of A_{OL}
- OPA1642 output THD+N
  - Gain: 1
  - $3.5V_{RMS}$
  - Different load resistors:
    - 10kΩ (red)
    - 1kΩ (blue)
    - 500 (green)
- Output loading includes the feedback resistors!
  - Low value feedback resistors increase output distortion



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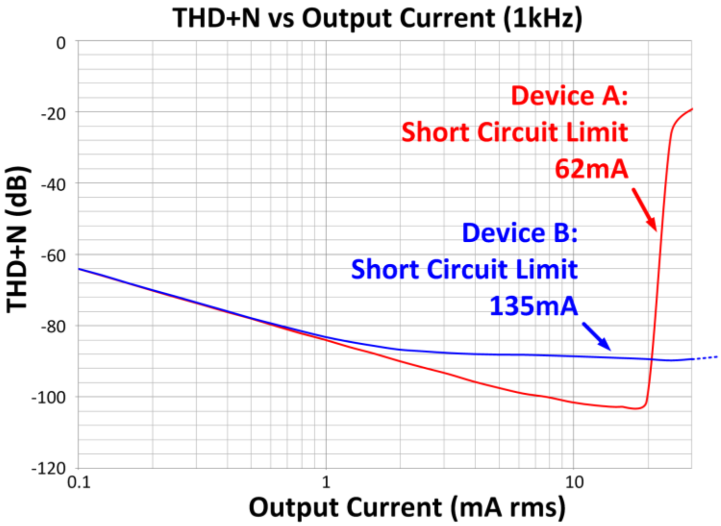
This slide shows OPA1642's measured THD+N versus frequency results for three different loads. As you would expect the THD+N is degraded as the load increases. These types of curves will normally be given in the data sheet, so you can use this as a guideline to understand the effects of loading on your distortion. Don't forget, however, that the feedback resistor also constitutes a load.

Short Circuit Current?



- Short circuit current only defines the output current with 0V output swing.
- It does not indicate linear output current!
- Example:
  - Device A: 80MHz, 1nV/√Hz, **Short circuit current: +55/-62mA**
  - Device B: 230MHz, 1nV/√Hz, **Short circuit current: 135mA**
- Device B shows additional distortion above $1mA_{RMS}$

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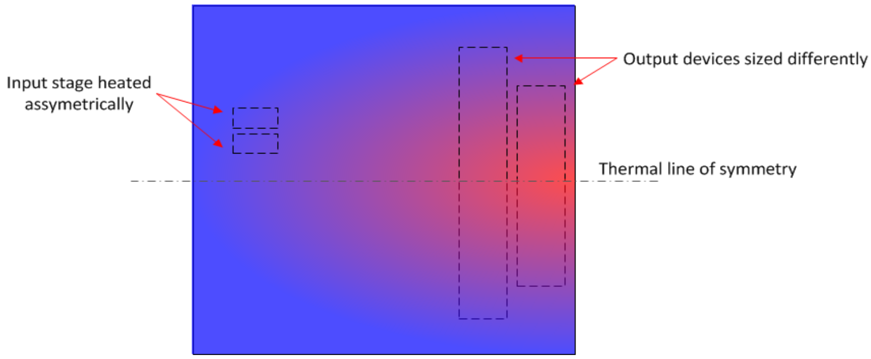
The short circuit limit is a in internal op amp protection mechanism that prevents damage to the device when low resistance loads are connected to the output. Often times, engineers mistakenly believe that the short circuit limit gives a linear current output range. This is not the case. This plot compares the distortion for two different devices versus output current. You can see that device B has a much greater short circuit limit, but it begins to show additional distortion at about 1mA of output current. Device A has a much lower short circuit limit, but it can deliver more linear output current before the THD+N curve becomes distortion dominated. For example, at 10mA rms device A has almost 16dB better THD+N than Device B. The main point here is that you cannot equate the short circuit current to a linear output current range.

Thermal Distortion



- Possible causes of thermal distortion in IC amplifiers:
  - Dissimilar output device sizes
    - One transistor heats up significantly more during sourcing/sinking
      - Transistor parameters change over temperature
  - Thermal feedback to input stage
    - Input stage is not placed on thermal line of symmetry
      - One input transistor is heated more than the other

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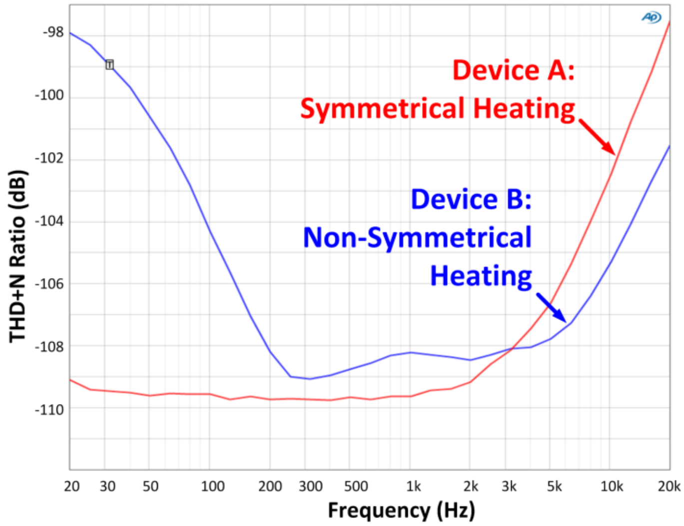
Some distortion factors have to do with the internal layout of the integrated circuit. One of the key considerations in IC design layout is to pay attention to how the heat is distributed across the die. In particular, the majority of the power dissipated in the device is in the output stage of the amplifier. It is important to make sure that heat from the output stage is distributed symmetrically across the input transistor pair so that both input devices are affected equally by the temperature shift. This figure shows the heat map of an IC with the input stage at the left and the output stage on the right. In this case, the input pair is not placed along the line of thermal symmetry, so they will be heated asymmetrically. That is, the transistor at the bottom will be heated more than the transistor at the top. This asymmetrical heating will translate into distortion at low frequency because at low frequency there is enough time for the die to heat up and cool off and create a thermal gradient across the die.

THD+N vs Frequency: 50mW, 32 Ohm Load



Increasing distortion at low frequency indicates thermal effects on die

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This slide shows measured result of a device that has the thermal distortion issue and one that doesn't. Again, notice that this type of distortion happens at low frequency. From a practical point of view, a board and system level designer only needs to be aware of this issue when selecting their amplifier, as they cannot change the internal layout of the amplifier. Nevertheless, it is useful to know that low frequency distortion can be caused by this effect.

Reducing Output Distortion

- Limit output loading
  - Increase feedback resistor values and load resistance
- Improve crossover distortion performance
  - Increase output voltage swing (not usually an option)
  - Bias output stage into class A with a resistor to the supply (increases power consumption)
- Stay away from clipping regions
  - Maximize supply voltage
  - Confirm linear swing range in datasheet (A_{OL} test conditions)
- Composite Amplifiers
  - Place a buffer inside the feedback loop of another amplifier
    - Increases the amount of loop gain around the output stage

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In summary, here are some guidelines for reducing output distortion. First, and perhaps most important, limit the output loading if possible. Remember that the feedback network constitutes a load. Often engineers will choose low value resistors to minimize noise, but may inadvertently degrade the THD. This shows that there is a trade off between noise and distortion in amplifier design. Next if possible you should minimize the crossover distortion. This can be done by increasing the output amplitude, but this is usually not an option as the output range is normally set by the application. One possible solution to this is to bias the output stage into class-A operation using a pull-up to the supply. When you do this only one of the transistors conducts current to the load and you completely avoid the crossover distortion region. Of course, this will dramatically increase the power consumption of the output stange, so this method is typically only used in drastic cases. Next, stay away from clipping regions. This can be done by maximizing the power supplies. Also, make sure you understand the linear output range from the open-loop gain test conditions in the data sheet. Finally, composite amplifiers can be a great way to decrease output stage distortion. When you place a buffer in the feedback loop of another amplifier, this will increase the amount of loop gain around the output stage.

Thanks for your time! Please try the quiz.

In summary, this video explained the sources of output stage distortion and discussed methods for minimizing this distortion.

Stay tuned for the next video which discusses external sources of distortion in op amp circuits.

Thank you for time! Please try the quiz to check your understanding of this video's content.