Low Distortion Design – 1

TIPL 1321
TI Precision Labs – Op Amps

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Prerequisites: Noise 1 – 3
(TIPL1311 – TIPL1313)

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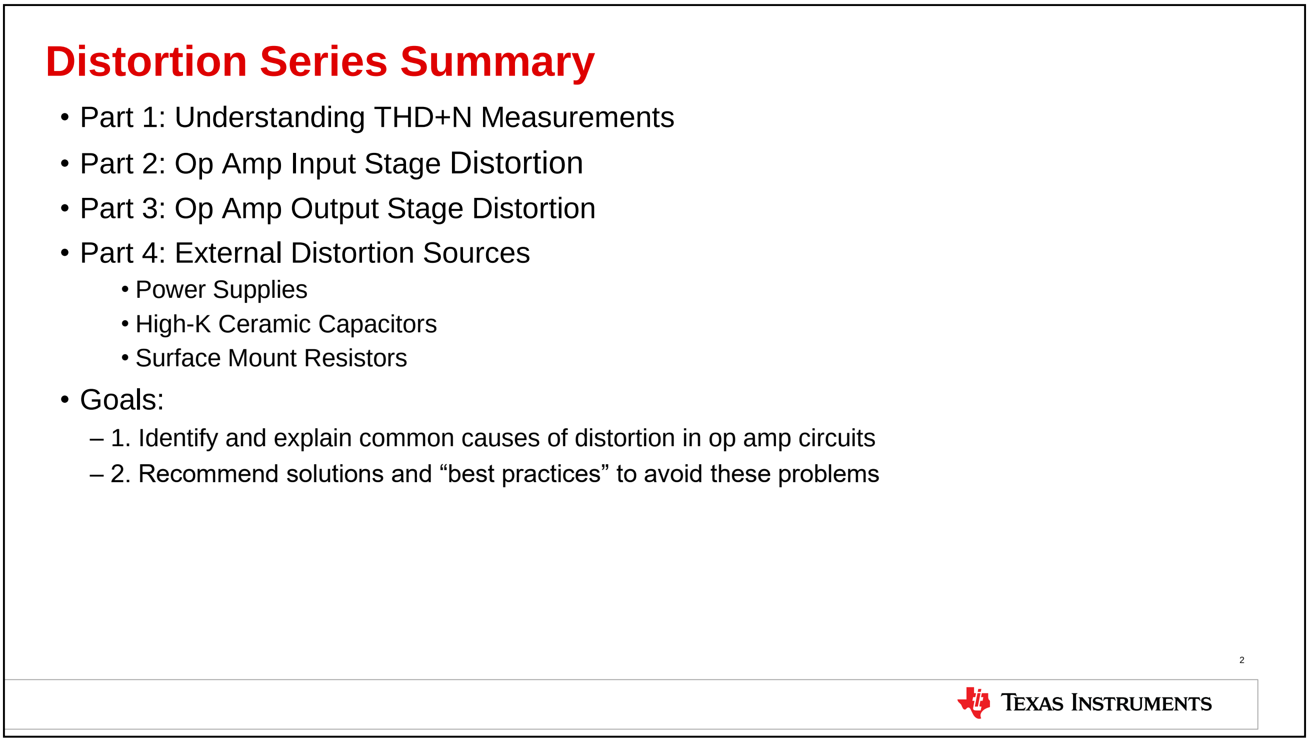
Hello, and welcome to the TI Precision Labs series on low distortion design with op amps. This video will provide an overview of the distortion series and also introduce and define the key topics related to op amp distortion. The goal of this series is to understand the distortion sources in op amp circuits and also learn methods to minimize distortion.

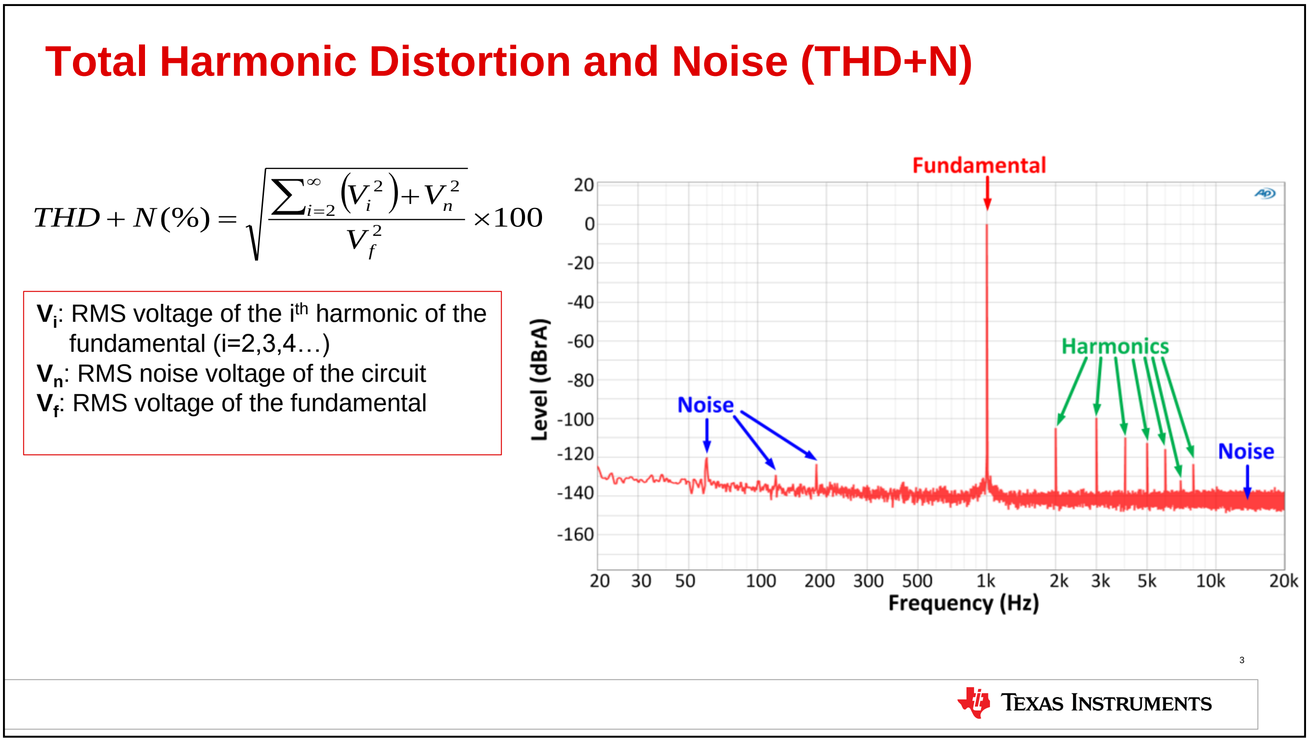
Before proceeding with the distortion series the lectures and problem sections for Op-Amp Noise one through three should be completed.



Distortion Series Summary

- Part 1: Understanding THD+N Measurements
- Part 2: Op Amp Input Stage Distortion
- Part 3: Op Amp Output Stage Distortion
- Part 4: External Distortion Sources
    - Power Supplies
    - High-K Ceramic Capacitors
    - Surface Mount Resistors
- Goals:
    - 1. Identify and explain common causes of distortion in op amp circuits
    - 2. Recommend solutions and “best practices” to avoid these problems

This video series covers the important topics related to distortion in op amp circuits. In this video, we will define and introduce total harmonic distortion plus noise, commonly referred to as THD+N. We will look at the way it is calculated and examine typical data sheet curves for THD+N. In the next video, we will cover distortion caused by the op amp’s input stage. The third video covers distortion from the op amp’s output stage. The fourth video will cover external sources of distortion which can come from the power supplies or external components like resistors and capacitors. The goals for this series are to identify and explain common causes of distortion in op amp circuits, and then to recommend solutions and “best practices” to avoid these problems.



Total Harmonic Distortion and Noise (THD+N)

$$THD+N(\%)=\sqrt{\frac{\sum_{i=2}^{\infty}\left(V_i^2\right)+V_n^2}{V_f^2}}\times 100$$

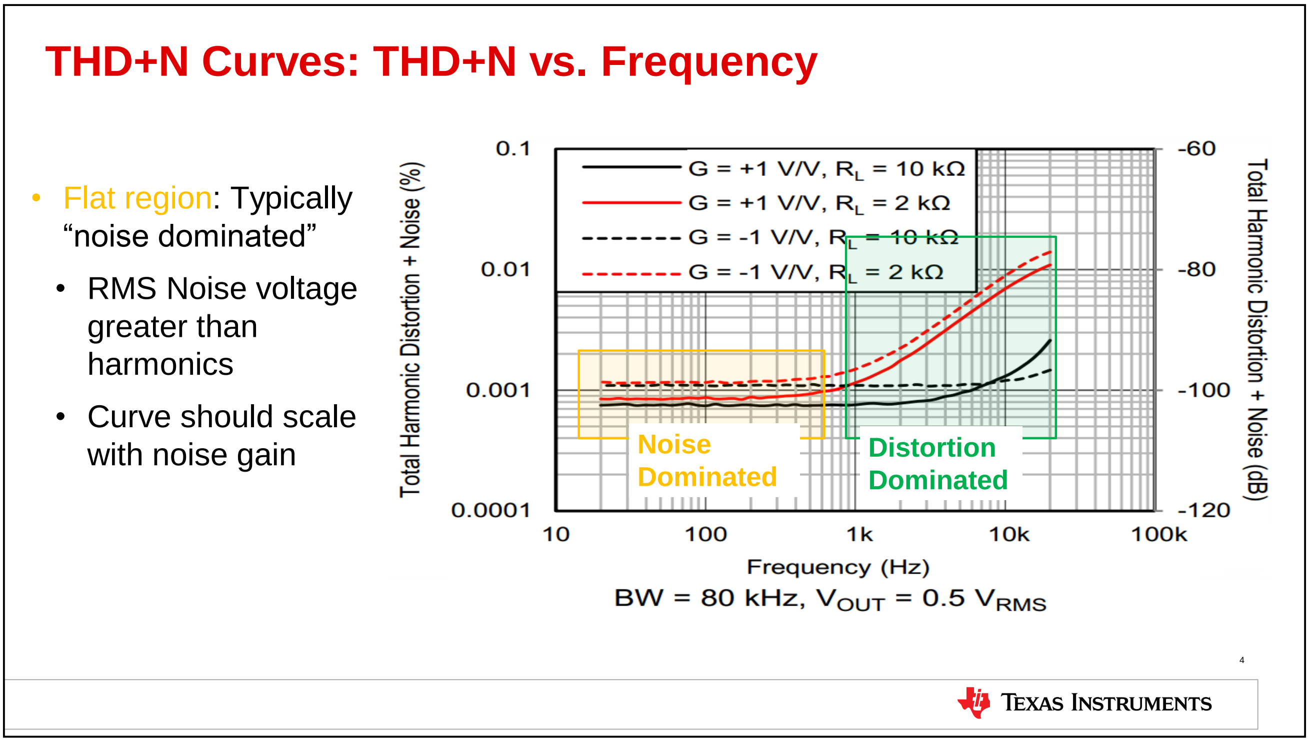
V_i: RMS voltage of the ith harmonic of the fundamental (i=2,3,4…)
V_n: RMS noise voltage of the circuit
V_f: RMS voltage of the fundamental

Total harmonic distortion and noise (THD+N) is a figure of merit that seeks to quantify the amount of unwanted content added to a signal by a circuit's noise and non-linearity. This can be important in audio systems, vibration analysis systems, data acquisition systems, and many other applications.

THD+N is defined as the ratio of the sum of the fundamental signal harmonics and system RMS noise voltage to the RMS voltage of the fundamental signal (equation shown). Harmonics, or signals at frequencies that are integer multiples of the input signal, arise from non-linear behavior of passive components and integrated circuits. Noise is produced by the intrinsic noise of integrated circuits and passive components, or may be coupled into a circuit by extrinsic sources.

This example shows the output of an amplifier circuit in the frequency domain. A 1kHz fundamental frequency is applied to the circuit, and the output contains the fundamental and harmonics. Notice that the harmonics of the fundamental happen at integer multiples of the fundamental. For example, 2kHz, 3kHz, 4kHz, and so on. The noise floor of the circuit, can be seen at the bottom of the curve as a fuzzy line. The noise is from the intrinsic noise of the amplifier and thermal noise of the resistors. Noise can also come from extrinsic noise sources that show up as spurs that are not related to the fundamental. Examples of noise spurs are 50Hz or 60Hz power line noise, pick-up from switching power supplies, and other extrinsic noise sources. The important thing to note here is that all noise within the measurement bandwidth is include in the THD+N calculation. This includes both intrinsic and extrinsic noise sources.

The equation for THD+N is given on here on the left hand side of the slide. It is calculated by taking the sum of all the harmonics squared added to the rms noise voltage squared and divided by the fundamental rms voltage squared. We then take the square root of this quantity. For a percentage format we multiply by 100. If this were in dB, we would take 20 times the log base 10 of this.   What we are seeking to describe, is the purity of the output signal. Harmonics and noise are all corruptions of the output signal which we would like to minimize to reduce the total harmonic distortion and noise.

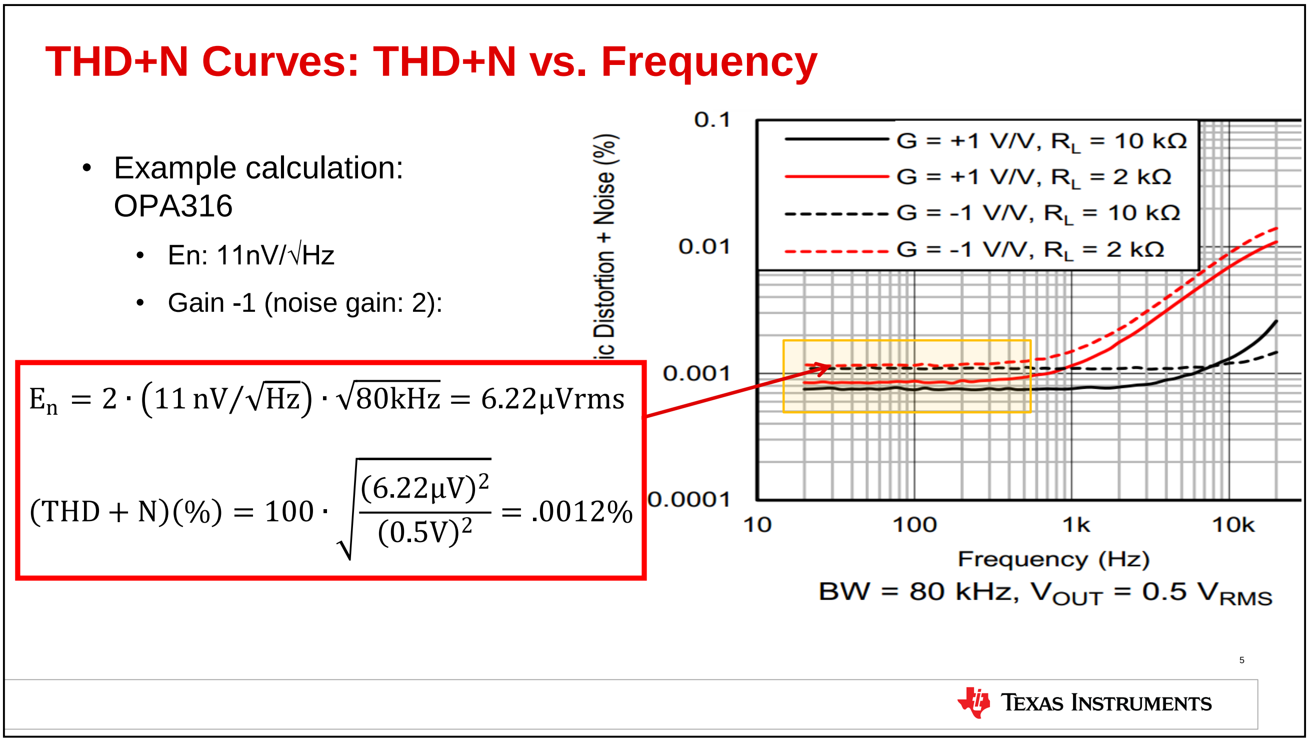


THD+N Curves: THD+N vs. Frequency

- Flat region: Typically "noise dominated"
  - RMS Noise voltage greater than harmonics
  - Curve should scale with noise gain

Generally, THD+N is presented in data sheets using two different curves. The first curve that is common to see is THD+N as a function of frequency. This graph describes how the THD+N of an op amp changes over a range of frequencies. The example curve shown here is taken from the OPA316 data sheet. On the x-axis we have frequency, and on the y-axis we have THD+N given in both percentage, and in decibels. It is important to understand that this curve was measured under specific test conditions. In this case, the measurement bandwidth is 80kHz. The "measurement bandwidth" is the frequency range of the noise and harmonics used for the THD+N calculation. Theoretically, to get a perfect THD+N measurement, you would need infinite measurement bandwidth that would include all possible harmonics, which is obviously not practical. The curve should also list the amplitude of the output signal, in this case 0.5V rms, as well as information regarding the gain configuration, and the loading for the op amp.

Looking at this curve, you can see two distinct regions. On the left hand side is a flat low frequency region that is noise dominated. In this region, the rms noise voltage of the circuit is greater than the rms voltage of all the harmonics summed together. The reason it is flat is that noise doesn't change with an input fundamental. For example, the rms noise of the circuit at 20Hz is the same as the rms nose at 100Hz, and at 500Hz and so on. This is why if noise is dominating the measurement, the THD+N stays flat as frequency increases.



THD+N Curves: THD+N vs. Frequency

- Example calculation: OPA316
  - En: 11nV/√Hz
  - Gain -1 (noise gain: 2):

$$E_n = 2 \cdot \left(11\,\mathrm{nV}/\sqrt{\mathrm{Hz}}\right) \cdot \sqrt{80\mathrm{kHz}} = 6.22\mu\mathrm{Vrms}$$

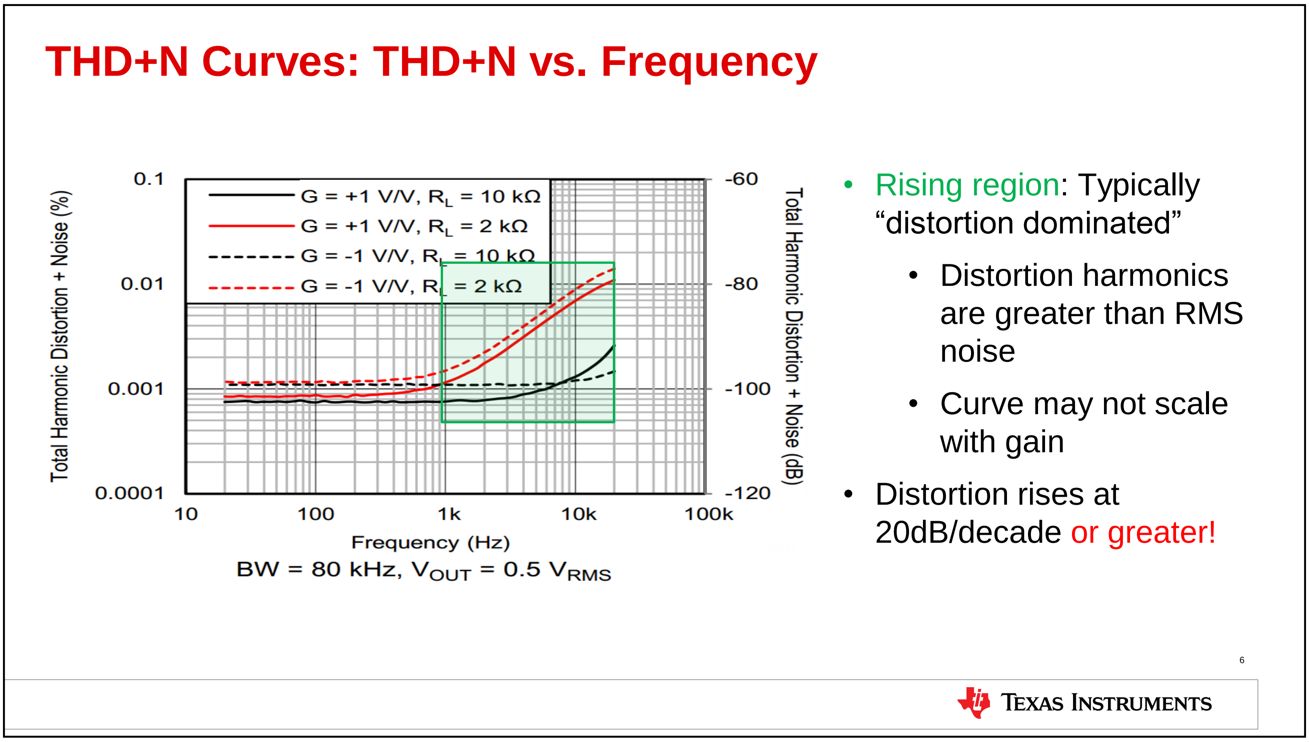
$$(\mathrm{THD}+\mathrm{N})(\%) = 100 \cdot \sqrt{\frac{(6.22\mu\mathrm{V})^2}{(0.5\mathrm{V})^2}} = .0012\%$$

BW = 80 kHz, V_{OUT} = 0.5 V_{RMS}

If you know the broadband noise spectral density of an op-amp you can do a simple calculation for the THD+N value in the noise dominated region. For the OPA316 example, the broadband noise spectral density is 11nV/rtHz from the data sheet. If we examine the gain equal to minus one case, then the noise gain of is 2V/V.

The rms noise voltage can be calculated by multiplying the 2V/V noise gain with the noise spectral density of 11nV/rtHz and the the square root of the measurement bandwidth. This yields a total rms noise of 6.22µVrms. To calculate the THD+N in that region, we need to know the amplitude of the fundamental. This is given in the plot test conditions as 0.5Vrms. Using the equation introduced earlier, we can enter the total rms noise and signal amplitude and calculate the THD+N. In this example, the calculated THD+N is .0012% which lines up well with the data in the curve.

There's an error on this slide!! The output of en should be 6.22uVrms. It shown as this in the 2nd equation. Also we should put 0.5V on the denominator.



THD+N Curves: THD+N vs. Frequency

BW = 80 kHz, V_{OUT} = 0.5 V_{RMS}

- Rising region: Typically "distortion dominated"
  - Distortion harmonics are greater than RMS noise
  - Curve may not scale with gain
- Distortion rises at 20dB/decade or greater!

The second region in the curve to take notice of is the area where THD+N rises with frequency. This region is referred to as distortion dominated, and is highlighted in green on this graph. In this case the distortion harmonics of the fundamental are greater in amplitude than the rms noise. The curve may not scale with gain. This is because there are different phenomena like common mode effects at lower gain that are minimized based on the gain and circuit configuration. Also, note that distortion will increase with increasing load current or lower impedance loads. For example, there is substantially more distortion for the 2k load than the 10k load cases. Finally, the distortion may rise at 20dB/decade or greater.

THD+N Curves: THD+N vs. Amplitude

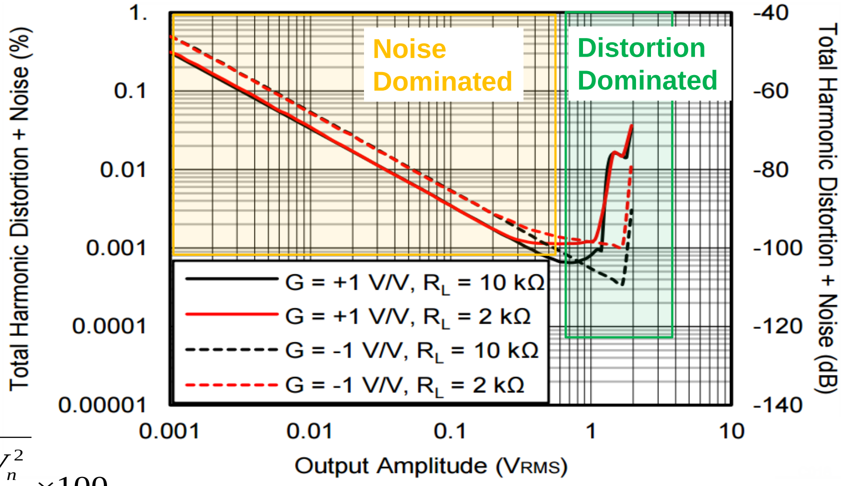
- Small Signal:

Noise dominated

- RMS Noise Constant
- Fundamental amplitude is increasing
- Constant downward slope

10x increase fundamental = 10x decrease THD

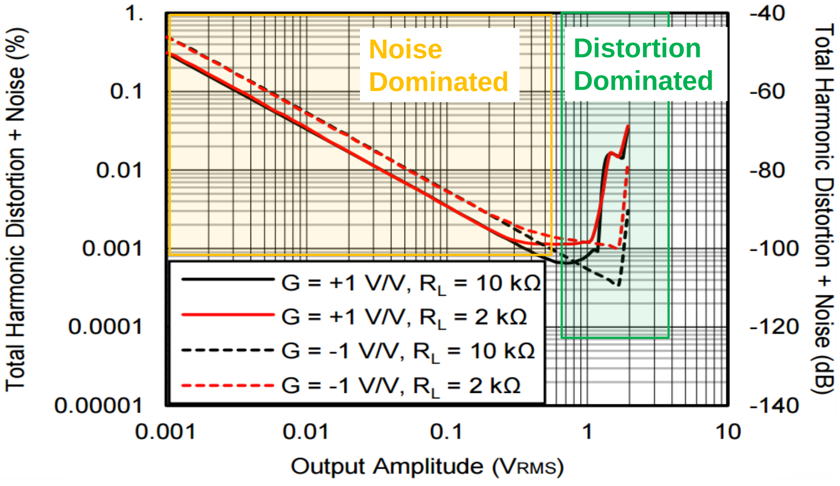
$$THD+N(\%)=\sqrt{\frac{\sum_{i=2}^{\infty}\left(V_i^2\right)+V_n^2}{V_f^2}}\times 100$$



f = 1 kHz, BW = 80 kHz

The second type of curve that is found in data sheets is THD+N versus amplitude. Shown here is an example curve from the OPA316 datasheet. Like the THD+N versus frequency curve, THD+N versus amplitude also has a noise dominated region, indicated by the orange box, and a distortion dominated region, indicated by the green box. The curve inside the orange box can be identified as noise dominated because of the constant downward trend with the increasing output amplitude. Note that region is the small signal region and an increase in the fundamental amplitude results in a corresponding decrease in THD+N. This is because the noise of the circuit is constant and the harmonics of the circuit are not changing. So, increasing the size of the fundamental will decrease the THD+N. Remember from the THD+N equation that the numerator of the equation is the noise and harmonics and the denominator is the fundamental, so in this region the denominator of the THD+N equation is getting larger while the numerator remains constant. This is useful to know this because any deviation from the downward slope means that the harmonics of the circuit are now greater than the noise of the circuit.

THD+N Curves: THD+N vs. Amplitude



f = 1 kHz, BW = 80 kHz

Large signal:

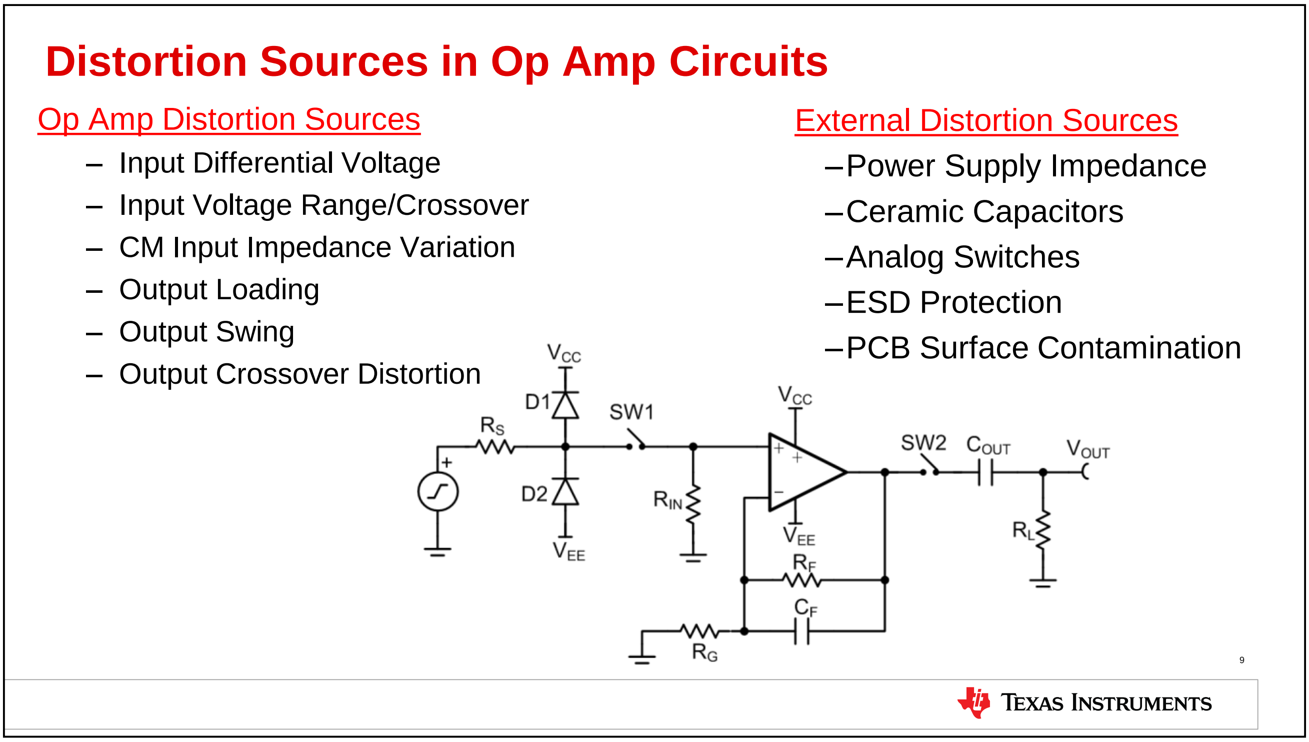
Any deviation from constant downward slope indicates distortion dominates

- Output loading
- Output swing/clipping
- Input CM range

– Some op amps may be noise dominated until clipping

Let's take a close look at the distortion region. In this region, the distortion harmonics are greater than the rms noise voltage. Distortion harmonics can result from output loading, limitations in the output swing, or input common mode range violations. By inspection, we can tell that the slight increase in distortion is likely due to output loading, and we notice that the 2kOhm curves increase before the 10kOhm curves.

Also, in a gain of +1 the op amp might run into an input common mode limitation. This is why the gain of +1 curves show a sharp increase in distortion while the gain of -1 curves do not distort until a higher voltage. All the curves increase sharply at 2V rms which is due to output clipping. Some op amps might be entirely noise dominated until clipping. Their curves would progress downward at a constant slope all the way until the output clips where you would then see a sharp increase in distortion.



Distortion Sources in Op Amp Circuits

Op Amp Distortion Sources

- Input Differential Voltage
- Input Voltage Range/Crossover
- CM Input Impedance Variation
- Output Loading
- Output Swing
- Output Crossover Distortion

External Distortion Sources

- Power Supply Impedance
- Ceramic Capacitors
- Analog Switches
- ESD Protection
- PCB Surface Contamination

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This slide shows a typical op amp circuit. We can identify some distortion sources by inspection. First lets consider the op amp distortion sources. The input differential voltage is a source of distortion. In fact, the larger the input differential signal is the more distortion the op amp will produce.

Also, the input voltage range of an op amp can contribute some distortion due to an effect called input crossover distortion. Also, a somewhat lesser known fact, is that the op amp input impedance may change with common mode voltage which can also contribute distortion depending on the circuit configuration. Output loading and output swing of the amplifier will also contribute distortion. There is a effect called output crossover distortion that needs to be considered.

Outside of the op amp there are other sources of distortion that need to be considered. For example, the impedance of the power supply can contribute distortion. We must emphasize that we are discussing distortion here, not noise. Many engineers immediately think of noise when discussing power supplies, but in this case we are talking about distortion. Ceramic capacitors, specifically Y5V, X7R, or other high K dielectric types will product distortion. Analog switches and multiplexers in the signal path can contribute distortion as will ESD protection diodes. Finally, PCB surface contamination, specifically between the amplifiers inputs can contribute distortion.

Thanks for your time! Please try the quiz.

In summary, we introduced the definition of THD+N. Also, we took a close look at the common THD+N data sheet curves and described how to interpret them. We also learned in a very general sense the distortion sources in op amp circuits.

Stay tuned for the next video which discusses details on input distortion sources.

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