Application Note

How to Measure Total Harmonic Distortion of an Op-Amp and THD + N Fundamentals

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ABSTRACT

This application note discusses how to measure total harmonic distortion plus noise or THD + N of an operational amplifier, how to interpret the measurements, and the fundamental principles of THD + N.

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1 Introduction

In an ideal amplifier circuit, the operational amplifier or op amp can perfectly output the signal of interest without modification to the phase or waveform shape.

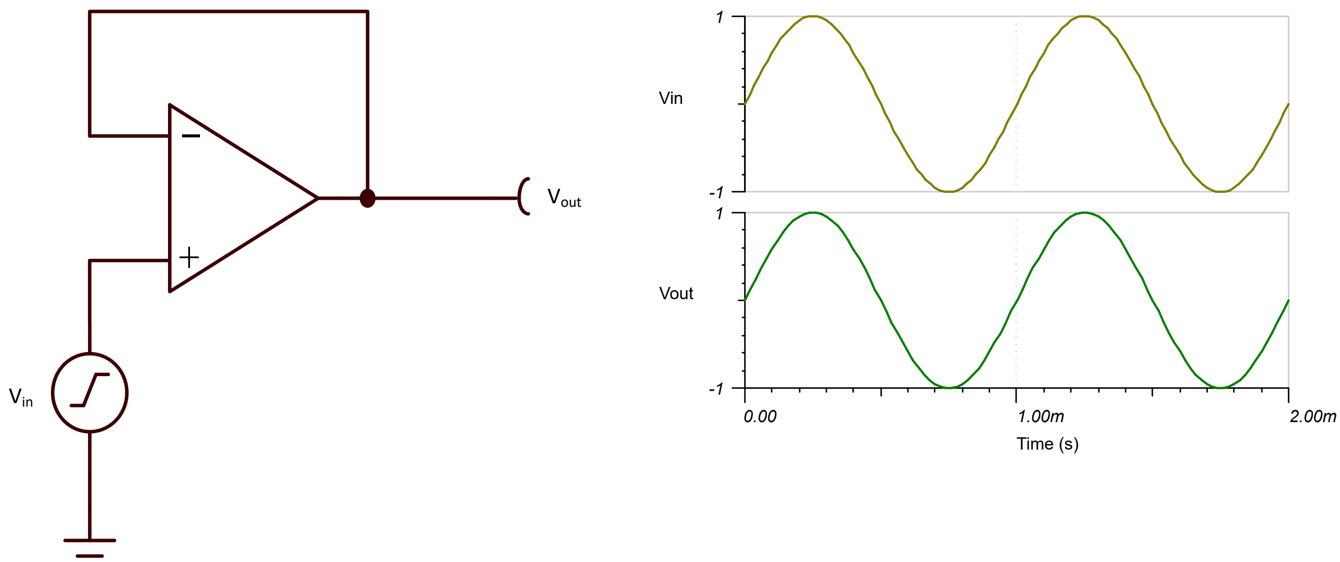


Figure 1-1. Ideal Buffer Amplifier

A Fast Fourier Transform or FFT converts a signal into its spectral components and provides frequency information about the signal. Figure 1-2 shows an FFT for a pure 1 kHz sine wave with an amplitude of 1 V peak seen on the ideal amplifier output. The FFT shows only the fundamental frequency and no noise. This is the ideal case. The FFT shows no other frequency components in addition to the 1 kHz fundamental frequency indicating that the amplifier did not distort the input signal.

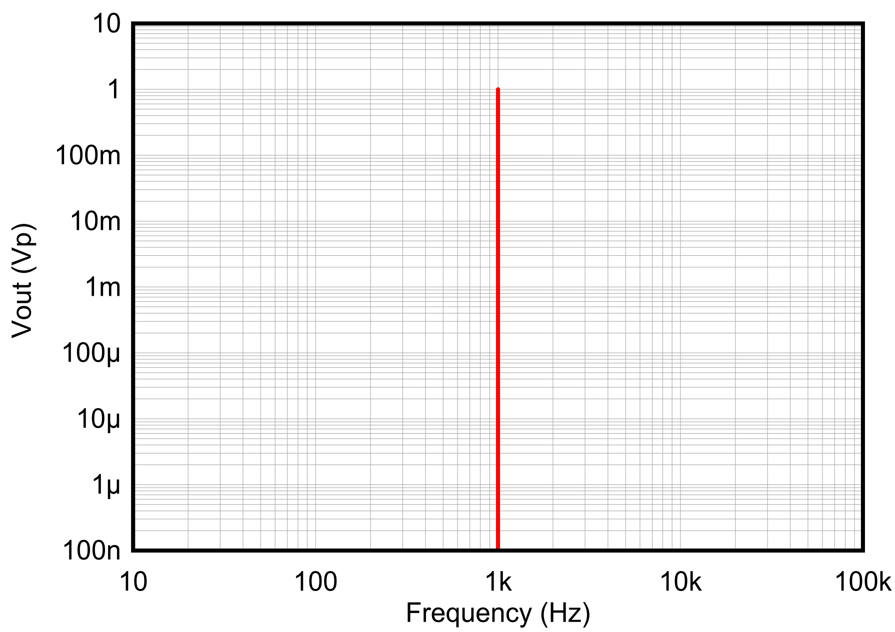


Figure 1-2. Ideal FFT of 1 V Peak Amplitude 1 kHz Sine Wave

Real amplifiers have non-linear characteristics and limitations that distort the input signal adding harmonics and noise that can be seen in an FFT as shown in Figure 1-3. The FFT is a measurement made at the output of the amplifier that is configured in a gain of 1 V/V. The y-axis is in units of volts root mean squared or V_{RMS}. The input signal to the amplifier is a 1 kHz sine wave with a magnitude of 6 V_{RMS}. The signal harmonics are seen in Figure 1-3 and are integer multiples of the 1 kHz fundamental frequency. Signal harmonics are highlighted at 2 kHz, 3 kHz, and 4 kHz, however higher order signal harmonics are also visible up to 10 kHz. The test equipment and circuit power supply are connected to a 120 VAC (volts alternating current) 60 Hz power outlet. The 60 Hz power line cycle and integer multiples of 60 Hz are also present in the FFT. In audio circuits, 60 Hz is often described to sound like a hum when it is coupled into the signal chain.

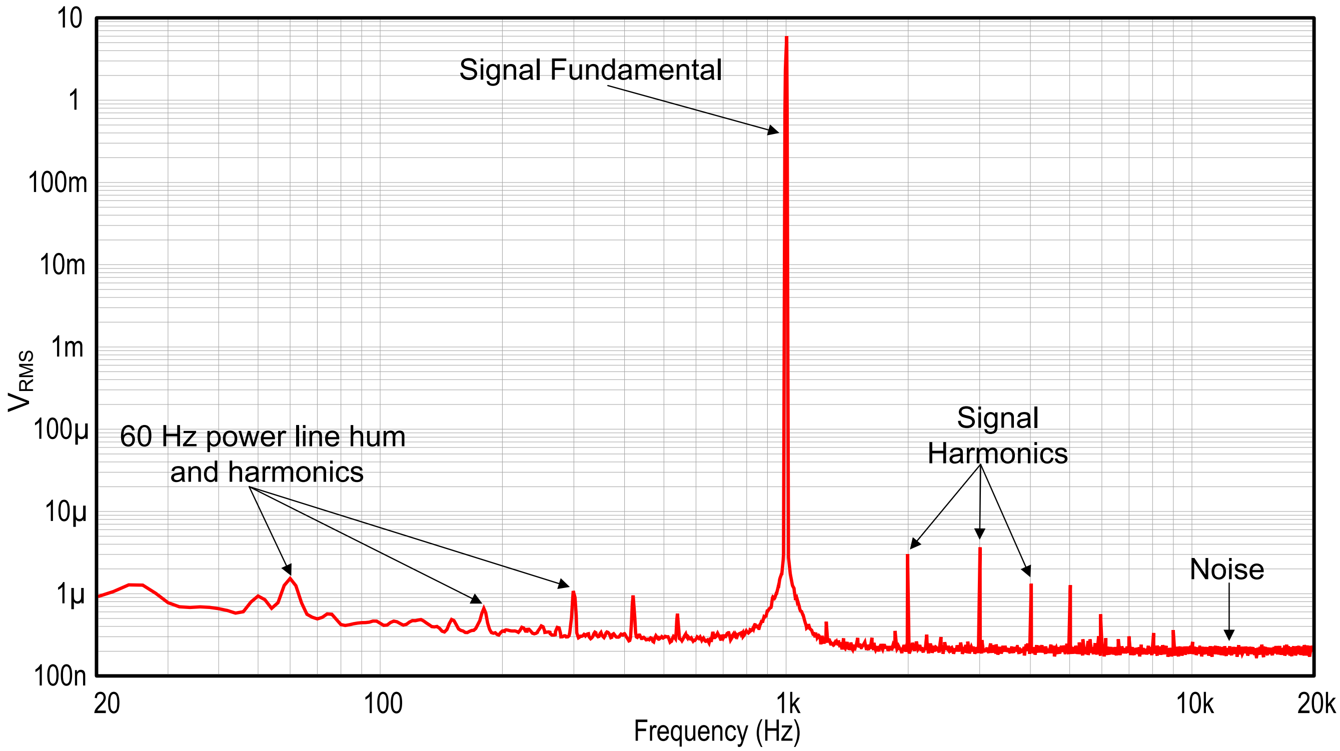


Figure 1-3. Realistic FFT

Total harmonic distortion plus noise is a measurement that provides a figure of merit for a circuits ability to accurately output a signal seen at it's input. THD + N is an important measurement in audio systems. Audio systems with low THD + N provide a more accurate representation of how the audio was intended to sound. Equation 1 mathematically shows that THD + N is defined as the ratio of the harmonic power measurements summed together to the power of the fundamental frequency.

$$THD + N\left(\%\right) = 100\% \times \sqrt{\frac{\sum_{i=2}^{\infty}\left(V_i^2 + V_n^2\right)}{V_f^2}} \quad (1)$$

Where:

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

2 Violating Linear Operating Ranges

Figure 2-1 shows an application circuit that is in the non-inverting amplifier configuration. The circuit is in a gain of $2\ \frac{V}{V}$. All conditions are within the linear operating regions of the OPA1656. Figure 2-2 shows the FFT that corresponds to the output signal shown in Figure 2-1. The harmonics shown in Figure 2-2 are very low and therefore the harmonic distortion is very low.

OPEN-LOOP GAIN		Test Conditions	Min	Max	Unit
A_{ol}	Open-loop voltage gain	(V–) + 1.3 V ≤ VO ≤ (V+) - 1.3 V R_L = 600 Ω	134	150	dB

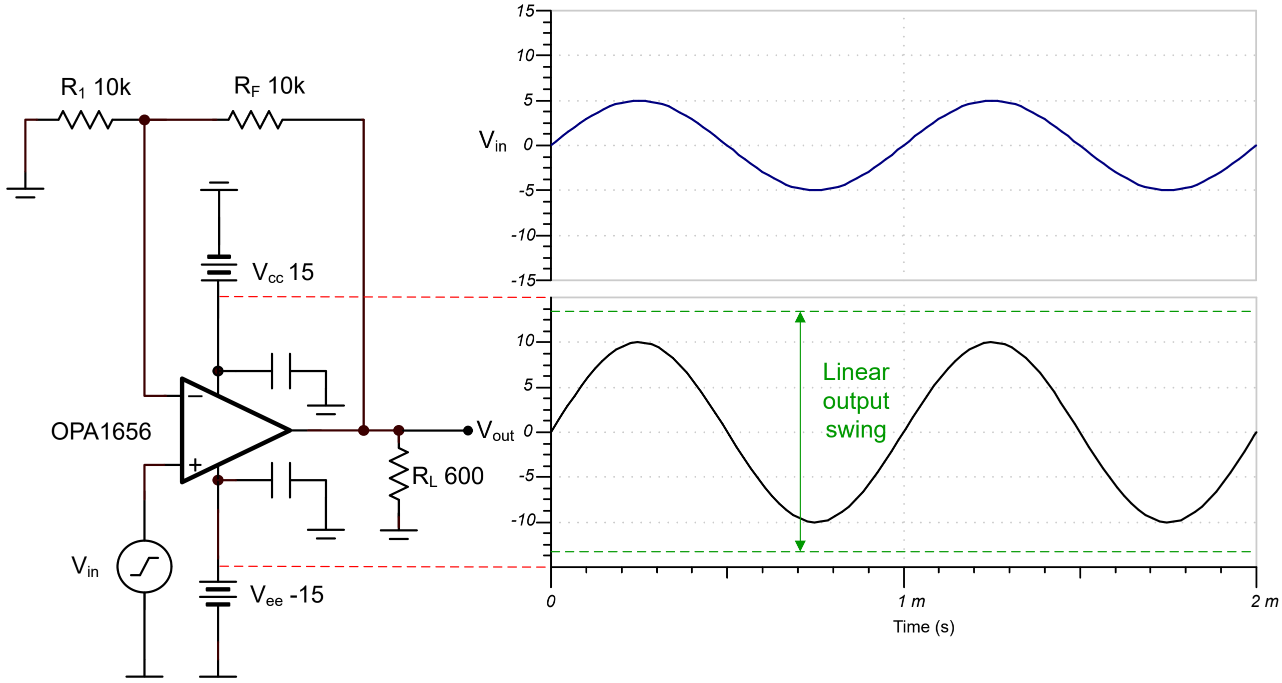


Figure 2-1. Non-Inverting Amplifier

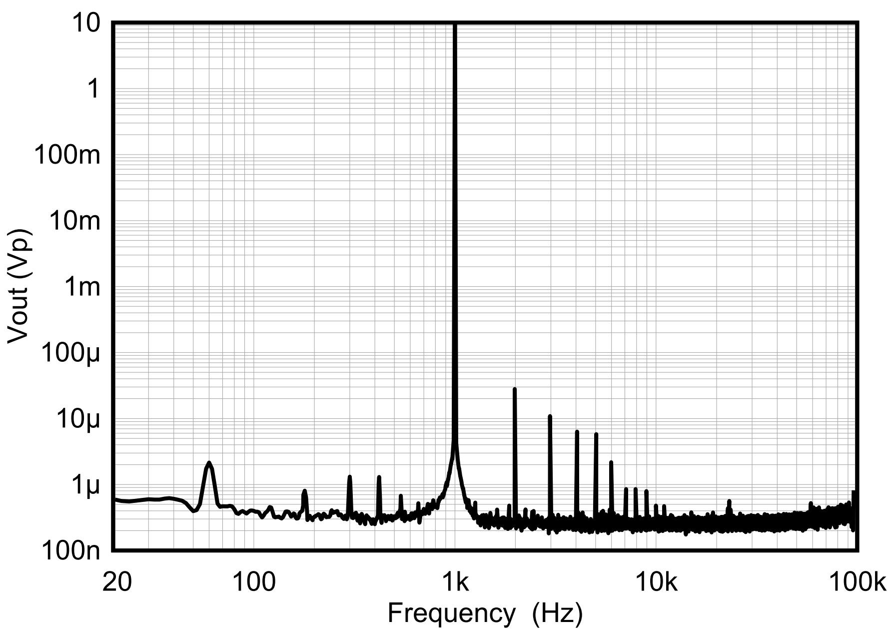


Figure 2-2. Measured Output FFT

Violating the linear output voltage swing of any amplifier is one way distortion greatly increases. Figure 2-3 shows an example where the linear output voltage specification of the OPA1656 is being violated. A signal of 7.5 V peak is applied to the input. The circuit is in a gain of $2\ \frac{V}{V}$. The output is limited by the power supply voltage and therefore clipped below 15 V. Figure 2-4 shows the measured FFT of the output signal and demonstrates how distortion greatly increases when the linear operating conditions are not met.

OPEN-LOOP GAIN		Test Conditions	Min	Max	Unit
A_{ol}	Open-loop voltage gain	(V–) + 1.3 V ≤ VO ≤ (V+) - 1.3 V R_L = 600 Ω	134	150	dB

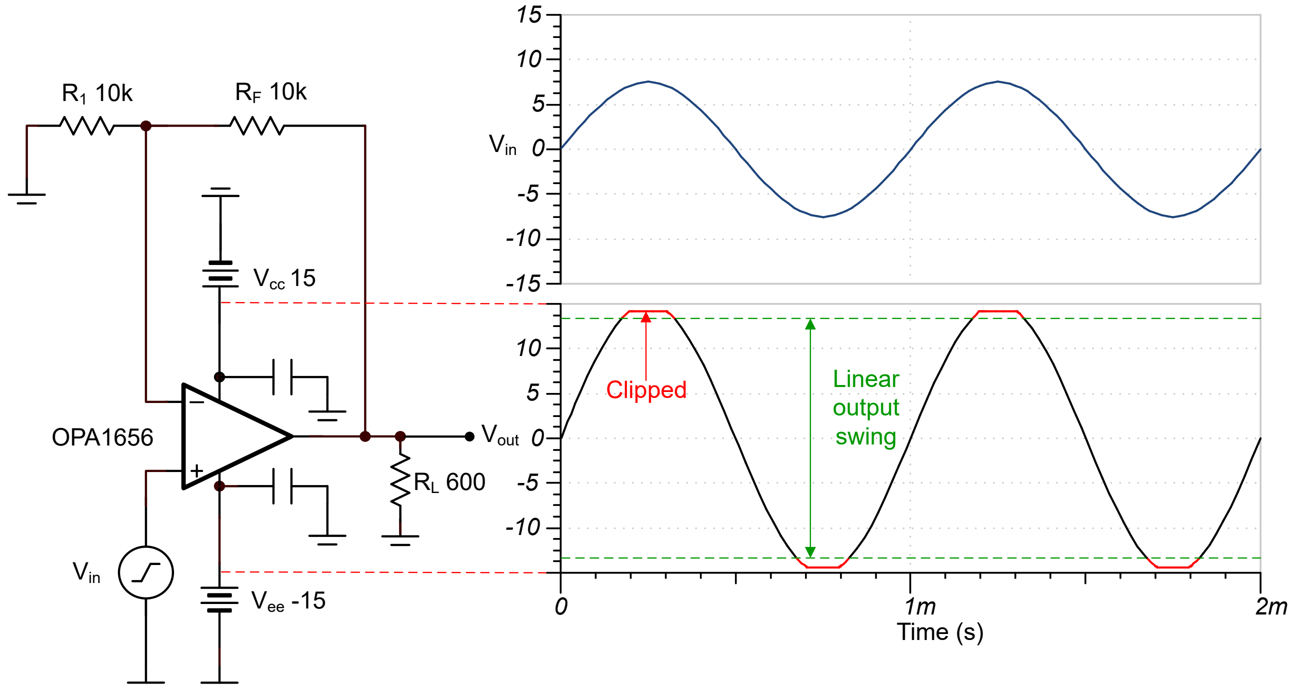


Figure 2-3. Non-Inverting Amplifier With Clipped Output

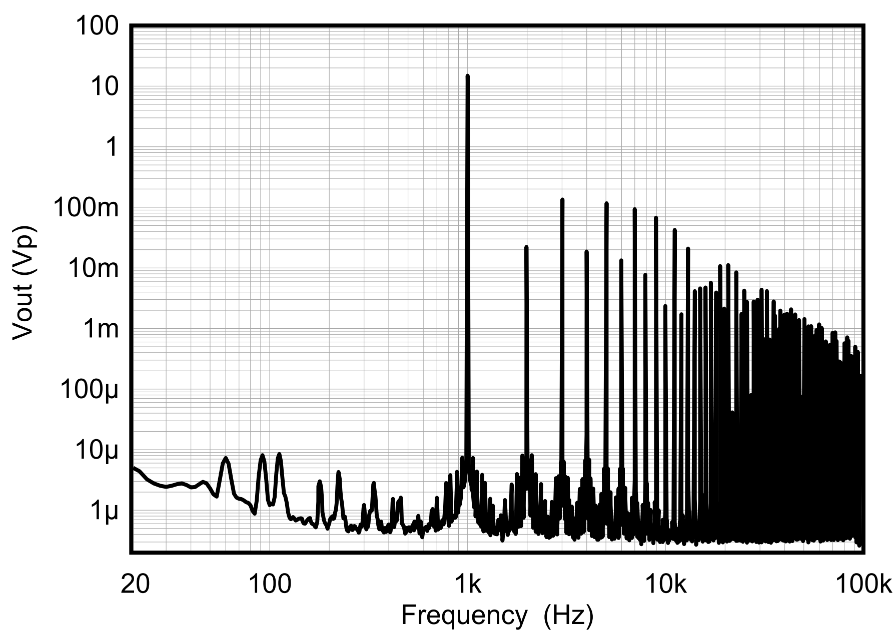


Figure 2-4. Measured Output FFT

3 How to Measure THD+N of an Op Amp

Op amp distortion can be considered an internal error source that can be measured by observing changes of the input offset voltage V_{os} and how these changes in V_{os} alter the signal of interest V_{in}. The V_{os} of an amplifier is the difference between the inverting and non-inverting inputs. Fluctuations in V_{os} are small when operating within the linear region of the amplifier. Examples that can directly or indirectly cause a change between the op amp inputs or V_{os} are but not limited to temperature drift, common mode and power supply voltage fluctuations, slew rate, and reduction in open loop gain or A_{ol}. A_{ol} is dependent on frequency. Ignoring the A_{ol} frequency dependency, Equation 2 shows the relationship between V_{os}, V_{out} and A_{ol}.

$$A_{ol} = \frac{\Delta V_{out}}{\Delta V_{os}} \tag{2}$$

Equation 3 is found by rearranging Equation 2. Two observations are made from Equation 3, $\Delta V_{os} = 0\,V\,|_{A_{ol} \to \infty}$ and $\Delta V_{os} = \infty\,|_{A_{ol} \to 0}$. These observations show that A_{ol} is responsible for correcting amplifier errors. Parts with high open loop gain create less V_{os} errors. In theory a virtual short of an op amp is when the inverting and non-inverting terminals have equal voltage potentials even though there is no connection between them. The assumption $\Delta V_{os} = 0\,V\,|_{A_{ol} \to \infty}$ is used in the following sections when applying the principles of superposition.

$$\Delta V_{os} = \frac{\Delta V_{out}}{A_{ol}} \tag{3}$$

The distortion produced by TI precision op amps is often below the measurement limit of commercially available distortion analyzers. However, a special test circuit can be used to extend the measurement capabilities. Figure 3-1 shows a circuit that amplifies the op amp distortion to be $101\,\frac{V}{V}$ times (or approximately 40 dB) greater than that normally produced by the op amp. Figure 3-2 shows the THD + N of the OPA1656 is below the theoretical noise floor of the distortion analyzer. The purpose of the test circuit is to gain the THD + N of the op amp above the distortion analyzer noise floor to measure the true performance of the op amp. The addition of R_A to the otherwise standard non-inverting buffer amplifier configuration alters the feedback factor or noise gain of the circuit. The closed-loop signal gain A_{CL} is unchanged, but the feedback available for error correction is reduced by a factor of $101\,\frac{V}{V}$, thus extending the resolution by $101\,\frac{V}{V}$ or 40 dB. For further details see Section 6. Note that the input signal and load applied to the op amp are the same as with conventional feedback without R_A. When altering the noise gain, the gain bandwidth product or GBW of the amplifier can be considered. A practical guideline can be used when designing the test circuit noise gain. If the amplifier GBW is 10 MHz or greater a noise gain of $101\,\frac{V}{V}$ can be used. Amplifiers with a GBW less than 10 MHz can use a noise gain of $11\,\frac{V}{V}$. The value of R_A is kept small to minimize the effect on the distortion measurements and extraneous thermal noise.

3.1 Non-Inverting Measurement

Figure 3-1 shows a test circuit used to measure THD + N of the non-inverting buffer amplifier configuration. The input signal V_{in} to the amplifier is provided by the generator output. The input offset voltage V_{os} and the input voltage noise V_n are series error sources internal to the op amp. V_{os} and V_n are always referred to the non-inverting terminal and are amplified by the noise gain of the amplifier configuration. When referring to THD + N measurements, noise gain is sometimes called distortion gain or THD + N gain, and is not equal to the signal gain.

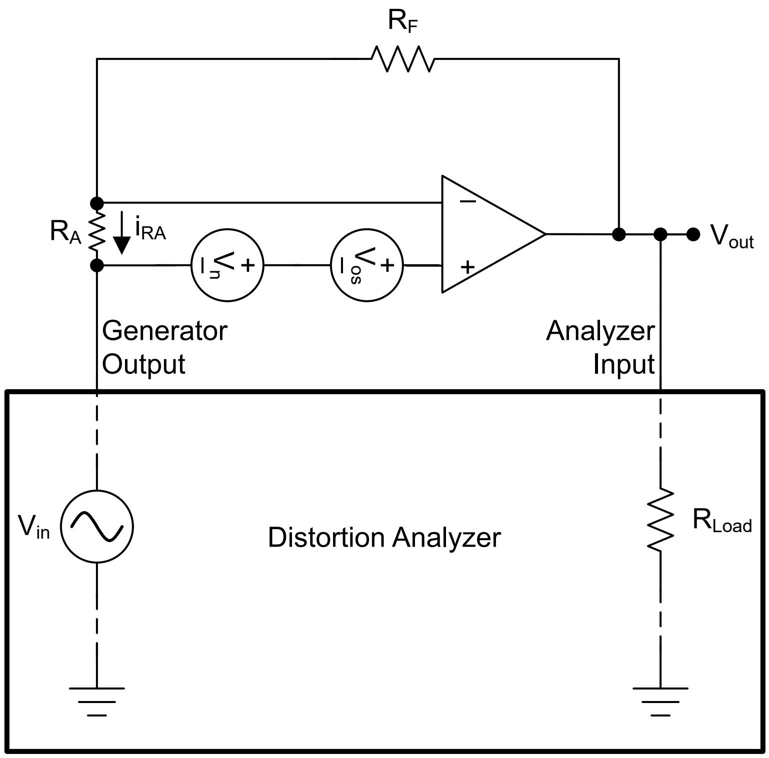


Figure 3-1. Non-Inverting Buffer Distortion Test Circuit

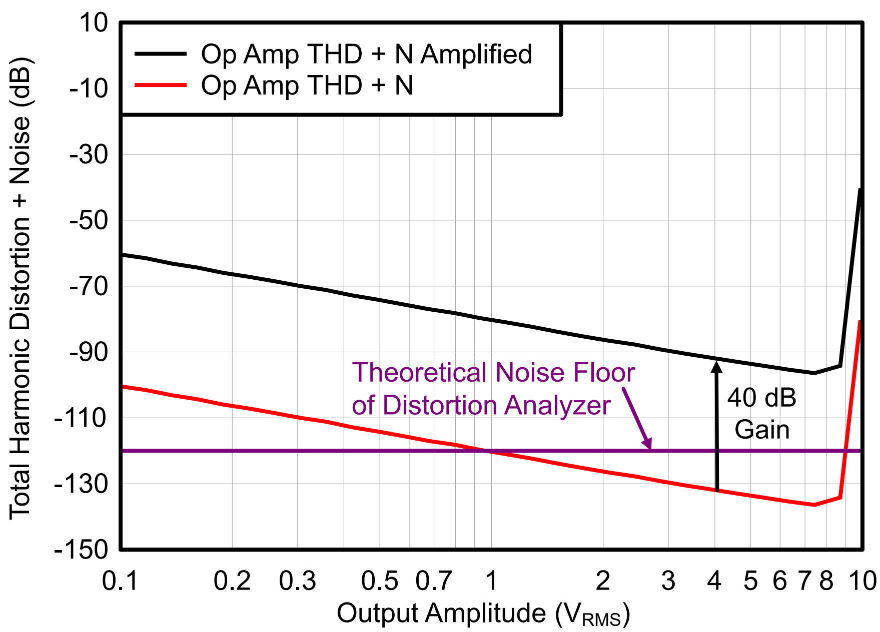


Figure 3-2. Gaining Op Amp THD + N Above Distortion Analyzer Noise Floor

Superposition is used to derive separate equations for the signal gain and the distortion gain. Assuming the input offset voltage V_{os} = 0 V, the noise voltage V_n = 0 V, and the current i_{RA} = 0 A the amplifier configuration shown in Figure 3-1 can be observed as a buffer as shown in Figure 3-3. Therefore the signal gain is $1\ \frac{V}{V}$ and the output voltage is equal to the input voltage, as described by Equation 4. The concept of a virtual short is assumed when removing resistor R_A. The voltage potential across resistor R_A on the inverting and non-inverting terminals are equal when applying the concept of a virtual short and therefore i_{RA} = 0 A and R_A is viewed as an open.

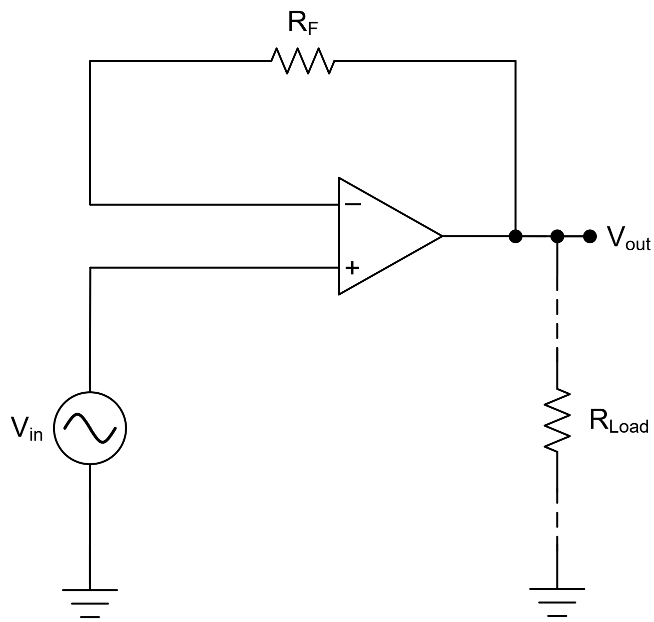


Figure 3-3. Signal Gain

$$V_{out} = V_{in} \tag{4}$$

Assuming the input signal to the amplifier V_{in} = 0 V, the amplifier can be observed as a standard non-inverting amplifier with voltages V_{os} + V_n applied at the non-inverting terminal as shown in Figure 3-4. Therefore V_{os} + V_n appear on the output amplified by the familiar non-inverting gain equation of one plus the ratio of resistor R_F to resistor R_A. Equation 5 describes the THD + N gain.

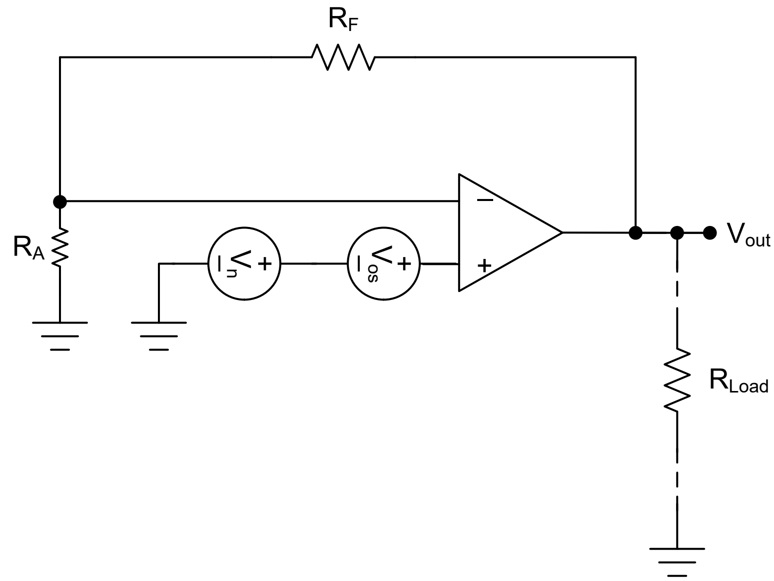


Figure 3-4. THD + N Gain

$$V_{out} = (V_{os} + V_n)\left(\frac{R_F}{R_A} + 1\right) \quad (5)$$

The signal observed at the output of the test circuit shown in Figure 3-1 is the amplified combination of V_{in}, V_n and V_{os}. Combining Equation 4 with Equation 5 results in Equation 6, the final gain equation of the test circuit shown in Figure 3-1.

$$V_{out} = V_{in} + (V_{os} + V_n)\left(\frac{R_F}{R_A} + 1\right) \quad (6)$$

A typical non-inverting buffer application circuit does not include the additional resistor R_A. Resistor R_A was added to the test circuit to provide additional gain for the purpose of overcoming the signal analyzer measurement limitation. Table 3-1 assigns values to resistors R_F and R_A resulting in gain values for both the test circuit and application circuit . With the assigned resistor values in Table 3-1 the THD + N gain is $101\ \frac{V}{V}$ with the additional R_A resistor. In the typical non-inverting buffer circuit R_A = ∞, or in other words doesn't exist and the THD + N gain is $1\ \frac{V}{V}$. Therefore R_A added an additional $101\ \frac{V}{V}$ or approximately 40 dB of distortion gain.

Table 3-1. Test Circuit and Application Circuit Gain Values

Condition	Signal Gain	THD + N Gain	R_F	R_A
Signal and THD + N Gain with R_A	$1\ \frac{V}{V}$	$101\ \frac{V}{V}$	10 kΩ	100 Ω
Signal and THD + N Gain without R_A	$1\ \frac{V}{V}$	$1\ \frac{V}{V}$	10 kΩ	∞

Figure 3-5 shows the measured THD + N ratio of the OPA1656 in units of decibels. 40 dB is subtracted from the test circuit measurement and represents the actual op amp THD + N for a non-inverting buffer circuit. The measurement bandwidth of the distortion analyzer is 80 kHz for the measurements made in this application note.

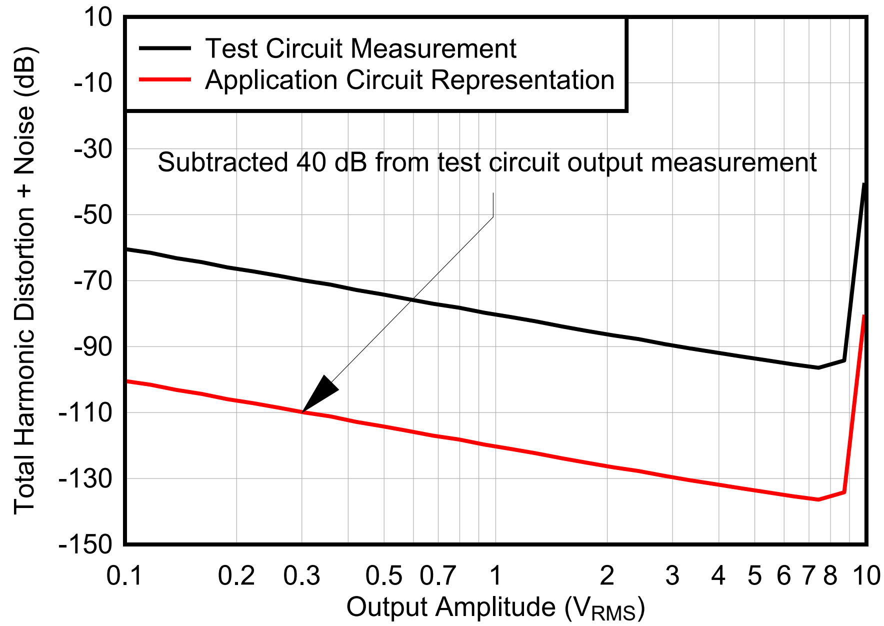


Figure 3-5. Non-Inverting Buffer Distortion Measurement: Output Referred

Amplifier data sheets often represent the THD + N ratio in terms of percentage. Equation 7 is used to convert the measured THD + N ratio from dB to percentage.

$$THD + N\left(\%\right) = 100 \times 10^{\frac{THD + N\,(dB)}{20}} \tag{7}$$

Figure 3-6 shows the THD + N (%) Ratio vs Output Amplitude (V_{RMS}) for the non-inverting buffer configuration. Two independent measurements were made for 1 kHz and 20 kHz frequencies as the output amplitude was swept from 0.1 V_{RMS} to 10 V_{RMS}.

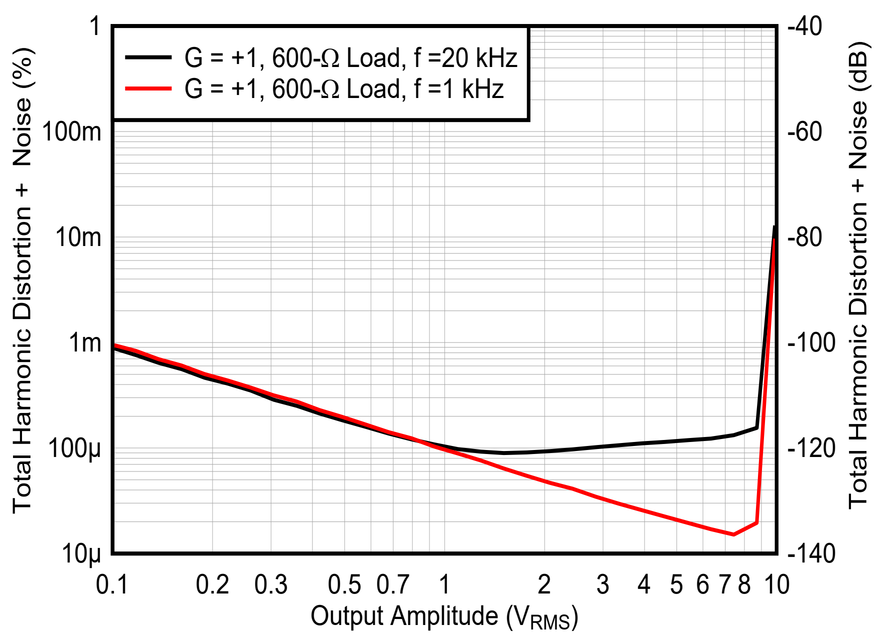


Figure 3-6. Non-Inverting Buffer THD + N (%) Ratio vs Output Amplitude

3.2 Inverting Measurement

Figure 3-7 shows a test circuit used to measure THD + N of the inverting amplifier configuration. The input signal V_{in} to the amplifier is provided by the generator output. The input offset voltage V_{os} and the input voltage noise V_n are series error sources internal to the op-amp. V_{os} and V_n are always referred to the non-inverting terminal and both are amplified by the noise gain of the amplifier configuration.

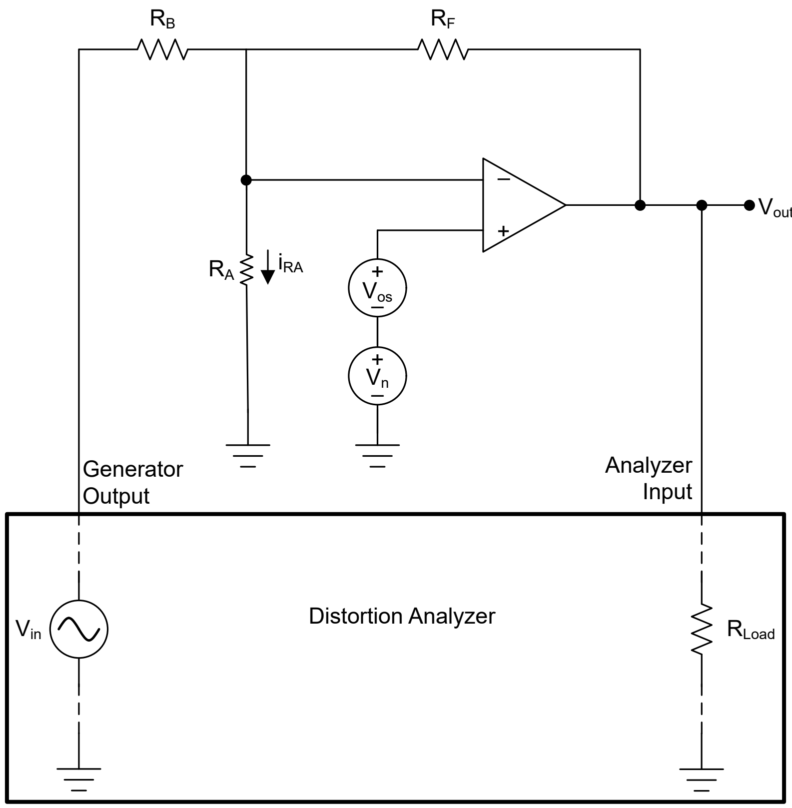


Figure 3-7. Inverting Distortion Test Circuit

Superposition is used to derive separate equations for the signal gain and the distortion gain of the inverting distortion test circuit shown in Figure 3-7. Assuming the input offset voltage V_{os} = 0 V, the noise voltage V_n = 0 V, and the current i_{RA} = 0 A the amplifier configuration shown in Figure 3-7 can be viewed as the standard inverting amplifier configuration as shown in Figure 3-8. The signal gain magnitude is determined by the ratio of resistor R_F to resistor R_B. Equation 8 represents the signal gain of the inverting distortion test circuit. The concept of a virtual short is assumed when removing resistor R_A. The voltage potential across resistor R_A on the inverting and non-inverting terminals are equal when applying the concept of a virtual short and therefore i_{RA} = 0 A and R_A is viewed as an open.

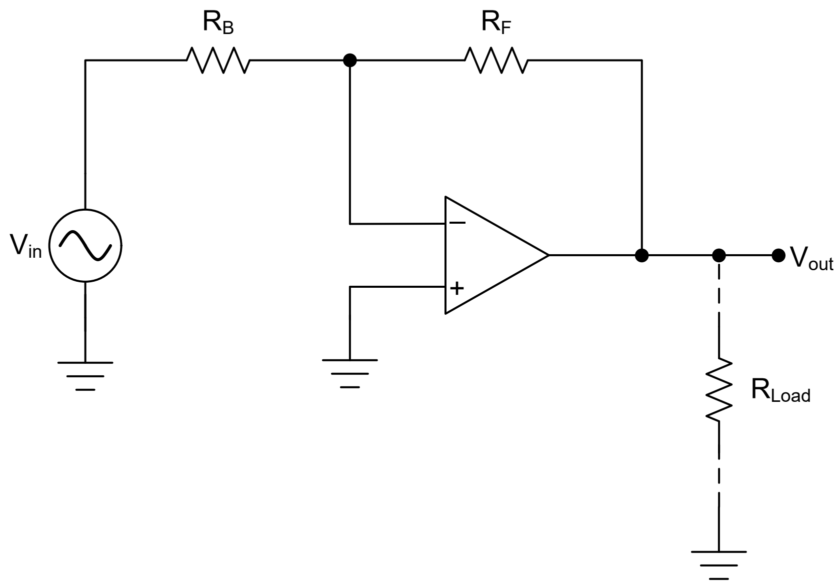


Figure 3-8. Inverting Signal Gain

$$V_{out} = -V_{in} \times \frac{R_F}{R_B} \quad (8)$$

Figure 3-9 represents the THD + N gain circuit. Assuming V_{in} = 0 V, resistors R_A and R_B are in parallel. The amplifier can be observed as a standard non-inverting amplifier with the addition of resistor R_A. The voltages V_{os} + V_n are applied at the non-inverting terminal. V_{os} + V_n appear at the output gained up by the familiar non-inverting gain equation of one plus the ratio of resistor R_F to $R_A || R_B$. Equation 9 represents the THD + N gain of the inverting distortion test circuit.

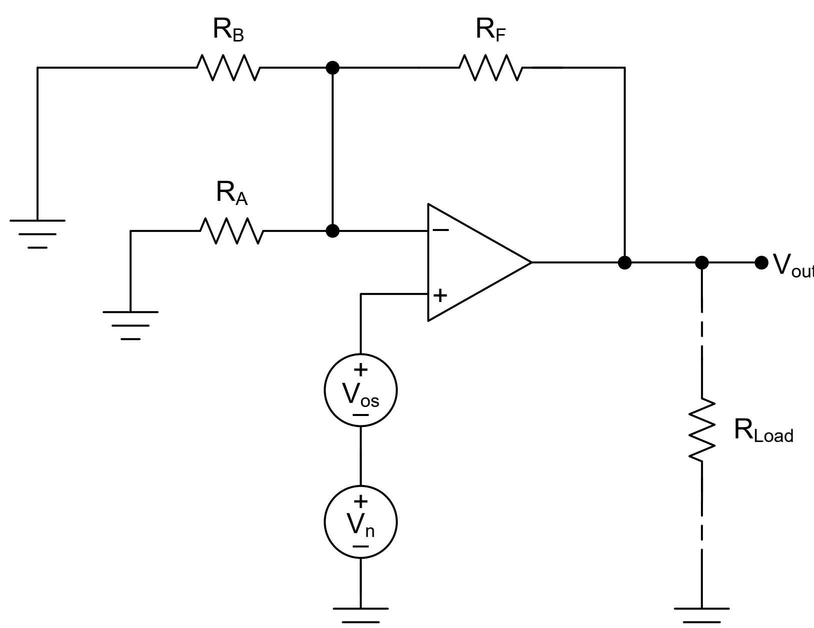


Figure 3-9. Inverting THD+N Gain

$$V_{out} = (V_{os} + V_n)\left(\frac{R_F}{R_A||R_B} + 1\right) \quad (9)$$

Equation 10 is found by expanding Equation 9.

$$V_{out} = (V_{os} + V_n)\left(\frac{R_F}{R_A} + \frac{R_F}{R_B} + 1\right) \quad (10)$$

The signal observed on the output of the test circuit shown in Figure 3-7 is the amplified combination of V_{in}, V_n and V_{os} and is represented by Equation 11. Equation 11 represents the final gain equation of the inverting distortion test circuit shown in Figure 3-7.

$$V_{out} = -V_{in} \times \frac{R_F}{R_B} + (V_{os} + V_n)\left(\frac{R_F}{R_A} + \frac{R_F}{R_B} + 1\right) \quad (11)$$

The typical inverting circuit does not include the additional resistor R_A. Resistor R_A was added to the test circuit to provide additional gain for the purpose of overcoming the signal analyzer measurement limitation. Table 3-2 assigns values to resistors R_F, R_A and R_B and the associated gain values for both the test circuit and application circuit are calculated. With the assigned resistor values in Table 3-2 the THD + N gain is $102\ \frac{V}{V}$ with the addition of resistor R_A. In the common inverting application circuit $R_A = \infty$, or in other words doesn't exist and the THD + N gain is $2\ \frac{V}{V}$. Therefore R_A added an additional $51\ \frac{V}{V}$ or approximately 34 dB of distortion gain.

Table 3-2. Test Circuit and Application Circuit Gain Values

Condition	Signal Gain	THD + N Gain	R_F	R_A	R_B
Signal & THD + N Gain with R_A	$-1\ \frac{V}{V}$	$102\ \frac{V}{V}$	10 kΩ	100 Ω	10 kΩ
Signal & THD + N Gain without R_A	$-1\ \frac{V}{V}$	$2\ \frac{V}{V}$	10 kΩ	∞	10 kΩ

Figure 3-10 shows the measured THD + N ratio of the OPA1656 in units of decibels. 34 dB is subtracted from the test circuit measurement and represents the actual op amp THD + N that is seen in the typical inverting circuit. The measurement bandwidth of the distortion analyzer is 80 kHz.

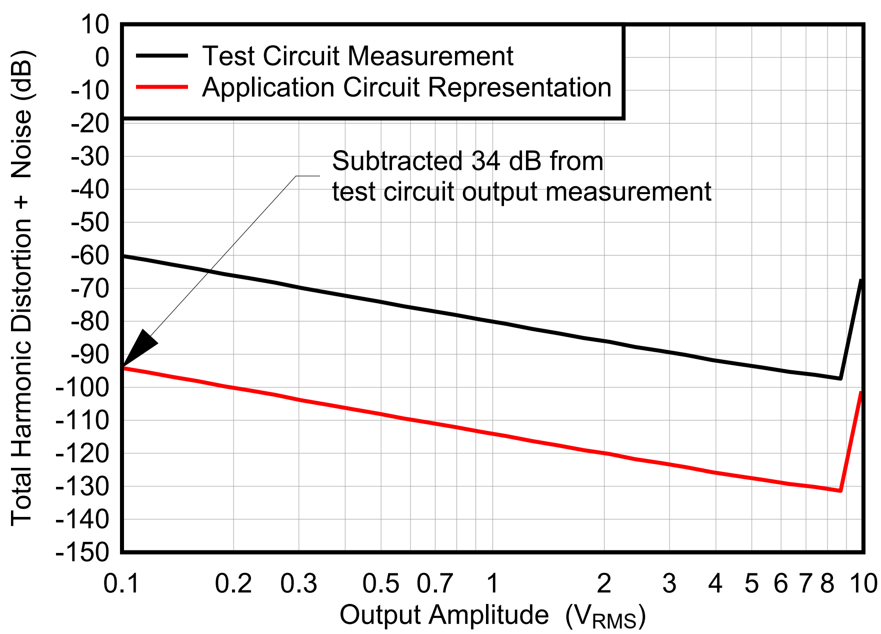


Figure 3-10. Inverting Distortion Measurement: Output Referred

Figure 3-11 shows the THD + N (%) ratio vs Output Amplitude (V_{RMS}) for the common inverting application circuit. Two independent measurements were made for 1 kHz and 20 kHz frequencies as the output amplitude was swept from 0.1 V_{RMS} to 10 V_{RMS}.

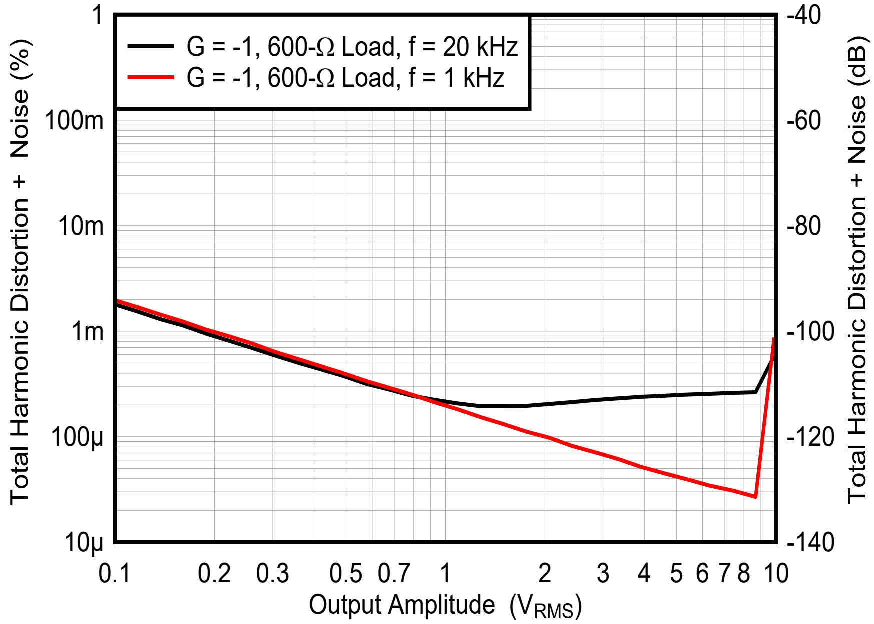


Figure 3-11. Inverting THD + N (%) Ratio vs Output Amplitude

3.3 Observations

Important observations can be made between the inverting and non-inverting application circuits. In the non-inverting configuration V_{in} , V_n, and V_{os} are all applied to the non-inverting terminal and the signal gain is equal to the noise gain. In the inverting configuration the signal is applied to the inverting terminal while V_n and V_{os} are applied to the non-inverting terminal. The signal gain is not equal to the noise gain in the inverting configuration. With the assigned resistor values in Table 3-1 and Table 3-2 the THD + N gain differs by a factor of $2\,\frac{V}{V}$ or 6 dB between the inverting and non-inverting configurations. The difference of 6 dB between these two measurements is shown in Figure 3-12. The output referred THD + N measurement is always worse for the inverting configuration when configured in the same signal gain as the non-inverting configuration. Although the THD + N is worse, the benefit of the inverting configuration is that non-inverting terminal is fixed to a DC potential as seen in Figure 3-8 and provides a fixed common mode voltage. This results in a CMRR benefit for the inverting configuration when the op amp has low CMRR.

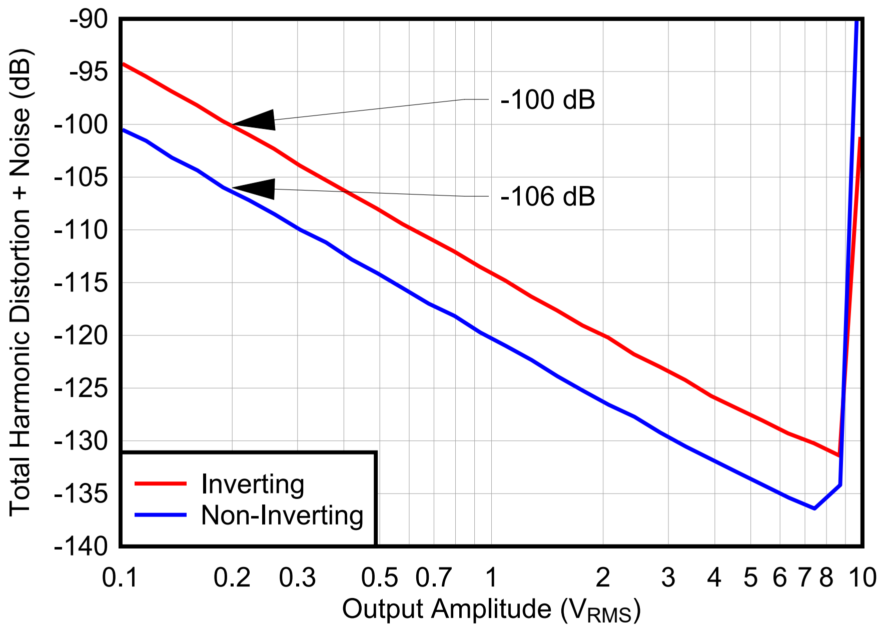
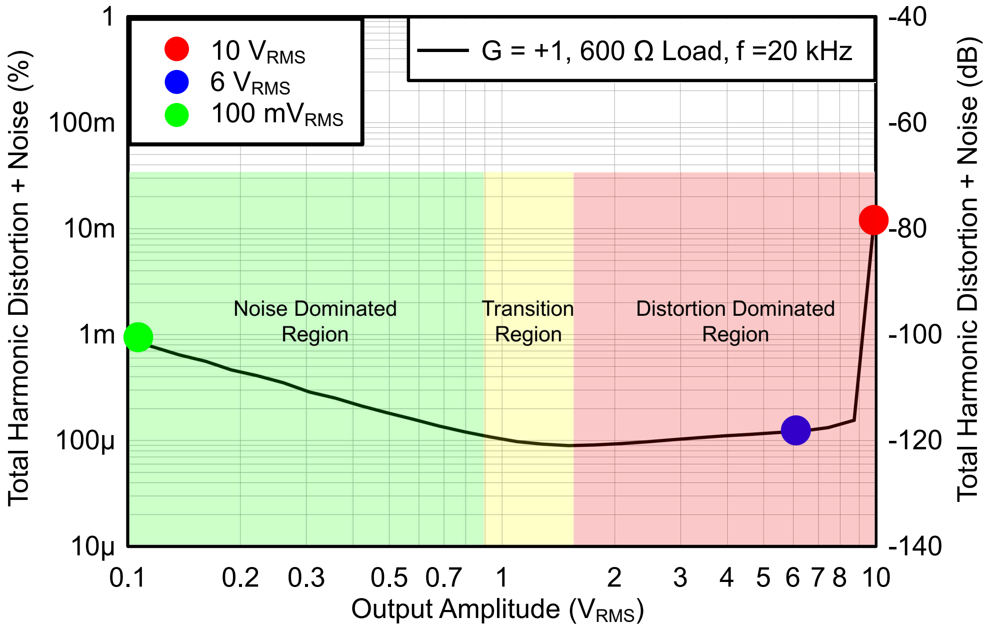


Figure 3-12. THD + N (dB) Inverting and Non-Inverting

3.4 Interpreting THD + N Curves

Figure 3-13 shows the three components that make up the THD + N ratio vs output amplitude curve. There is a noise dominated region, a distortion dominated region and the transition region between the two. Three FFT measurements are shown that correspond to three points along the THD + N vs Output Amplitude curve. When the output amplitude is 100 mV_{RMS}, the FFT shows the fundamental tone at 20 kHz and the harmonics are in the noise floor of the op amp and not visibly apparent. This represents the noise dominated region of the curve. The harmonics increase as the output amplitude increases and become greater than the noise floor of the op amp. The FFT for both 6 V_{RMS} and 10 V_{RMS} output amplitude show these harmonics visually.



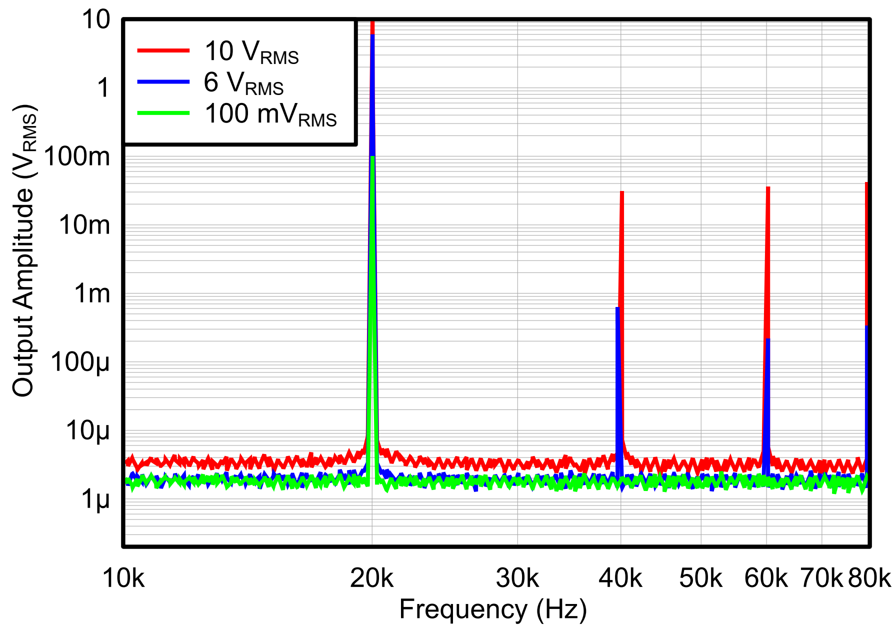


Figure 3-13. Interpreting THD + N Ratio vs Output Amplitude Curves

4 Summary

Total harmonic distortion plus noise or THD + N is a vast subject that presents challenges in applications such as power, audio, instrumentation amplification and many others. Op amps are often one component of a much larger system that contribute to the overall THD + N. Texas Instruments audio op amps such as the OPA1656 provide phenomenally low THD + N and are great choices when designing a signal chain that requires ultra low total harmonic distortion plus noise.

5 References

- Texas Instruments, *OPA165x Ultra-Low-Noise, Low-Distortion, FET-Input, Burr-Brown™ Audio Operational Amplifiers*, data sheet.

6 Appendix

Figure 6-1 shows the loop parameters for the standard non-inverting buffer amplifier from Figure 3-3 without resistor R_A. The feedback factor β and the THD + N gain are 0 dB. The loop gain $A_{OL} + \beta = A_{OL}$

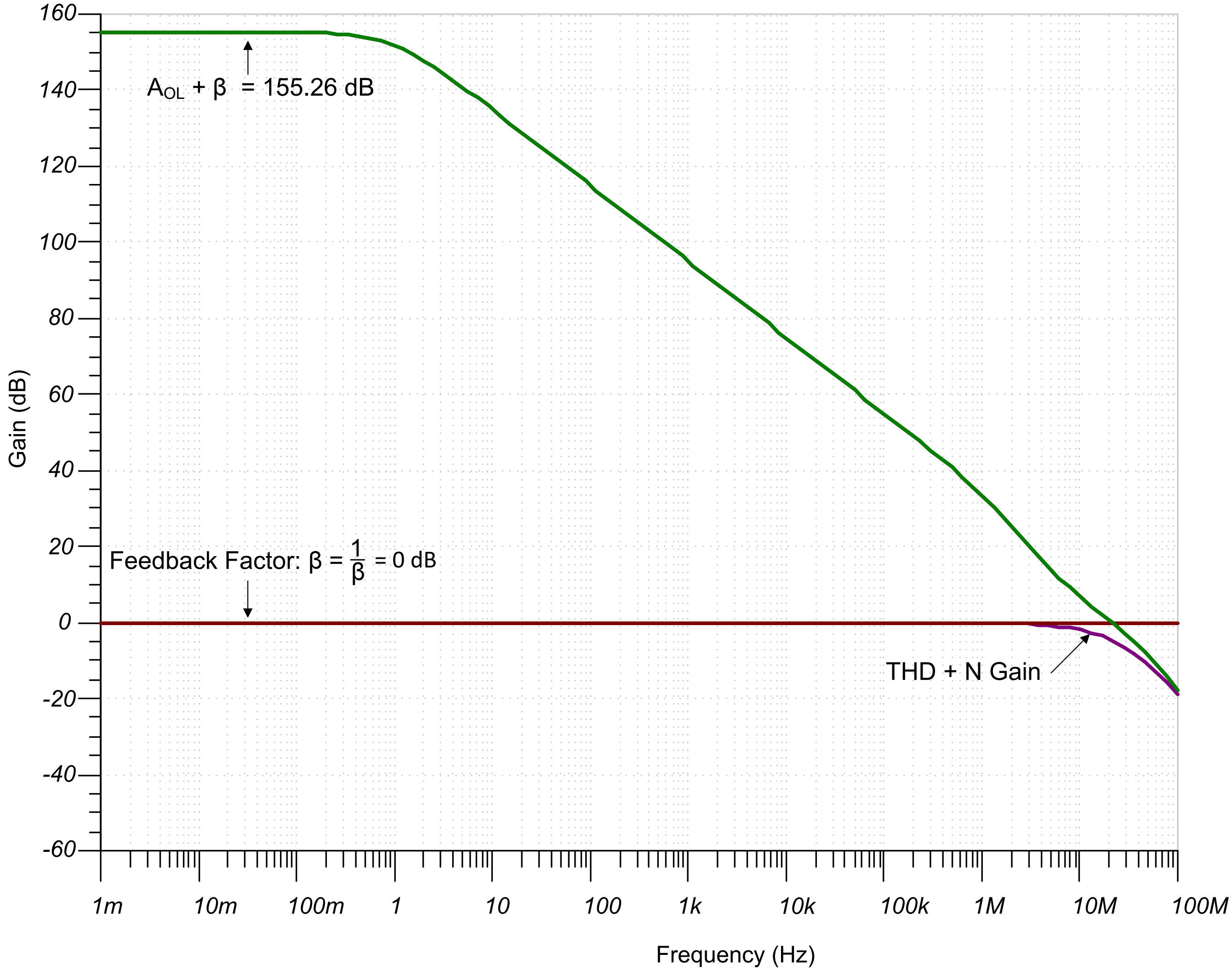


Figure 6-1. Loop Parameters Without R_A

The addition of R_A to the otherwise standard non-inverting buffer amplifier configuration alters the feedback factor or THD + N gain of the circuit. The closed-loop signal gain A_{CL} is unchanged, but the feedback available for error correction is reduced by a factor of $101\,\frac{V}{V}$, thus extending the resolution by $101\,\frac{V}{V}$ or 40 dB. Figure 6-2 shows the loop parameters with the addition of resistor R_A. The feedback factor β is reduced by -40 dB and the THD + N gain is increased by +40 dB. The loop gain $A_{OL}\,+\,\beta$ is reduced by -40 dB.

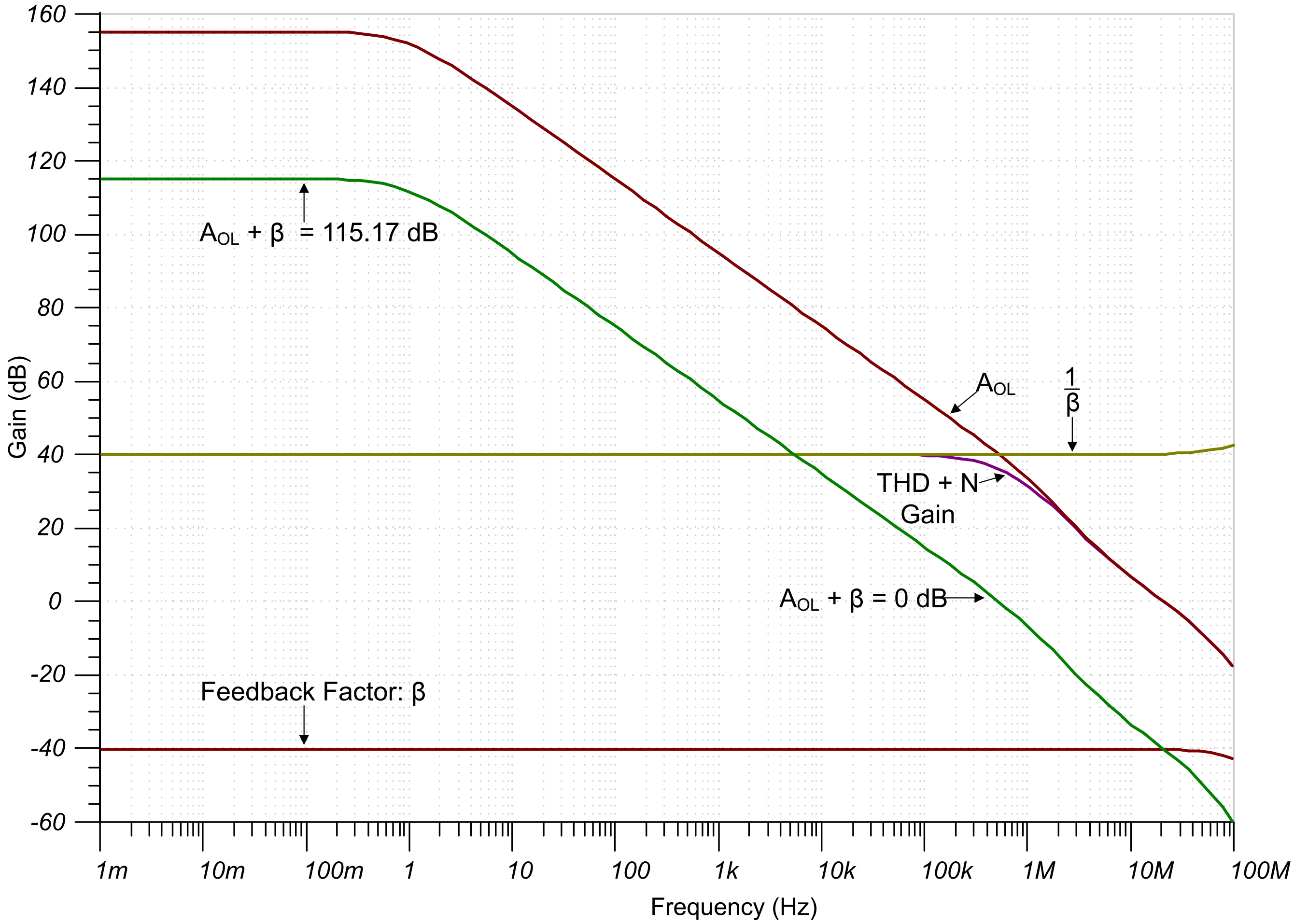


Figure 6-2. Loop Parameters With R_A

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