TEXAS INSTRUMENTS
OPA1655, OPA1656
SBOS901B – MARCH 2019 – REVISED DECEMBER 2021

OPA165x Ultra-Low-Noise, Low-Distortion, FET-Input, Burr-Brown™ Audio Operational Amplifiers

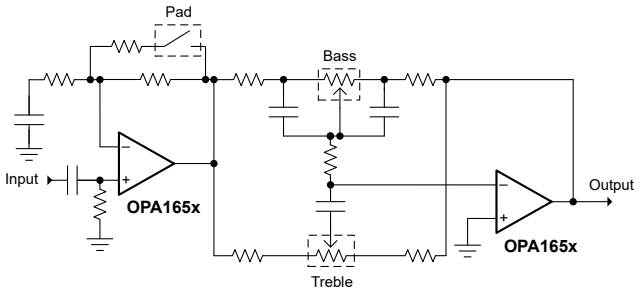
Texas Instruments Burr-Brown Audio

1 Features

- Ultra-low noise:
  - Voltage noise: 2.9 nV/√Hz at 10 kHz
  - Current noise: 6 fA/√Hz at 1 kHz
- Low distortion:
  - 0.000029% (–131 dB) at 1 kHz
  - 0.000035% (–129 dB) at 20 kHz
- High open-loop gain: 150 dB
- High output current: 100 mA
- Low input bias current: 10 pA
- Slew rate: 24 V/µs
- Gain bandwidth product: 53 MHz
- Rail-to-rail output
- Wide supply range:
  ±2.25 V to ±18 V or 4.5 V to 36 V
- Quiescent current: 3.9 mA per channel

2 Applications

- Professional microphones and wireless systems
- Professional audio mixer/control surface
- Guitar amplifier and other music instrument amplifier
- A/V receiver
- Bookshelf stereo system
- Professional audio amplifier
- DJ equipment
- Turntable
- Special function module



Active Baxandall Tone Control

3 Description

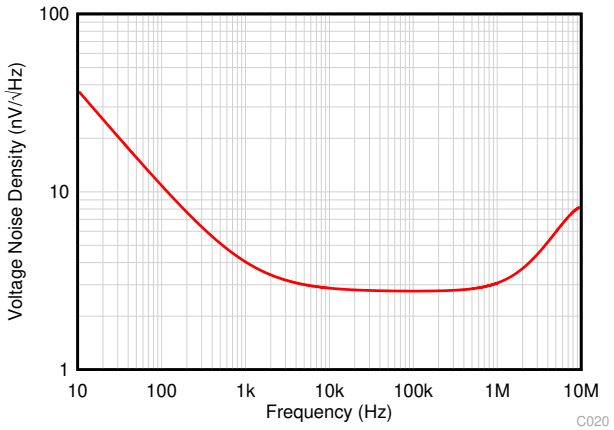
The OPA1655 and OPA1656 (OPA165x) are Burr-Brown™ op amps designed specifically for audio and industrial applications, where maintaining signal fidelity is crucial. The FET-input architecture achieves a low 2.9-nV/√Hz voltage noise density and 6-fA/√Hz current noise density, allowing for very-low noise performance in a wide variety of circuits. The high bandwidth and high open-loop-gain design of the OPA165x delivers a low distortion of 0.000035% (–129 dB) at 20 kHz, and improves audio signal fidelity across the full audio bandwidth. These devices also feature excellent output current drive capability, offering rail-to-rail output swing to within 250 mV of the power supplies with a 2-kΩ load, and can deliver 100 mA of output current.

The OPA165x operate over a very wide supply range of ±2.25 V to ±18 V or (4.5 V to 36 V) on 3.9 mA of supply current to accommodate the power-supply constraints of many types of audio products. The temperature range is specified from –40°C to +125°C.

Device Information

PART NUMBER	PACKAGE(1)	BODY SIZE (NOM)
OPA1655	SOIC (8)	4.90 mm × 3.91 mm
	SOT23 (5) - Preview	2.90 mm × 1.60 mm
OPA1656	SOIC (8)	4.90 mm × 3.91 mm

(1) For all available packages, see the package option addendum at the end of the data sheet.



Ultra-Low Input Voltage Noise

An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

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4 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (July 2019) to Revision B (December 2021)	Page
• Added OPA1655 production data (active) device and associated content	1

Changes from Revision * (March 2019) to Revision A (July 2019)	Page
• Changed device status from advanced information (preview) to production data (active)	1

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5 Pin Configuration and Functions

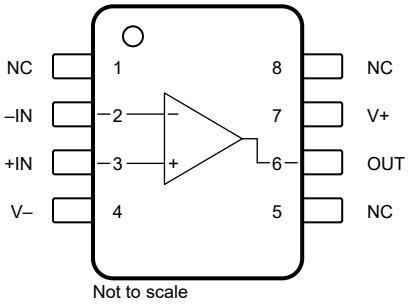

Figure 5-1. OPA1655 D (8-Pin SOIC) Package, Top View

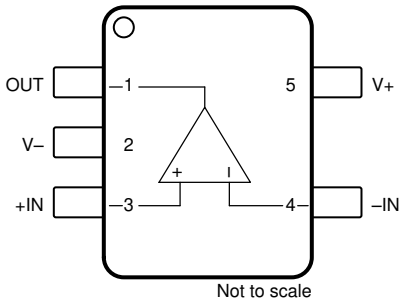

Figure 5-2. OPA1655 DBV (5-Pin SOT-23) Preview Package, Top View

Pin Functions: OPA1655

PIN			TYPE	DESCRIPTION
NAME	NO.			
	D (SOIC)	DBV (SOT-23)		
–IN	2	4	Input	Inverting input
+IN	3	3	Input	Noninverting input
OUT	6	1	Output	Output
V–	4	2	Power	Negative (lowest) power supply
V+	7	5	Power	Positive (highest) power supply

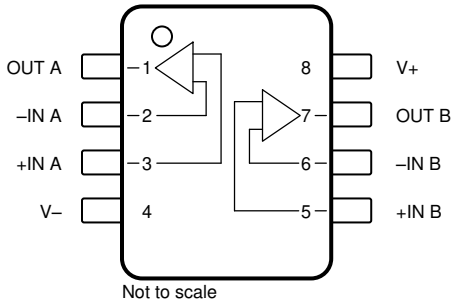

Figure 5-3. OPA1656 D (8-Pin SOIC) Package, Top View

Pin Functions: OPA1656

PIN		TYPE	DESCRIPTION
NAME	NO.		
–IN A	2	Input	Inverting input, channel A
+IN A	3	Input	Noninverting input, channel A
–IN B	6	Input	Inverting input, channel B
+IN B	5	Input	Noninverting input, channel B
OUT A	1	Output	Output, channel A
OUT B	7	Output	Output, channel B
V–	4	Power	Negative (lowest) power supply
V+	8	Power	Positive (highest) power supply

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6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

		MIN	MAX	UNIT
Voltage	Supply voltage, V_S = (V+) – (V–)		40	V
	Input	(V–) – 0.5	(V+) + 0.5	V
Current	Input (all pins except power-supply pins)	–10	10	mA
	Output short-circuit(2)	Continuous		
Temperature	Operating, T_A	–55	125	°C
	Junction, T_J		150	°C
	Storage, T_{stg}	–65	150	°C

(1) Operation outside the Absolute Maximum Ratings may cause permanent device damage. Absolute Maximum Ratings do not imply functional operation of the device at these or any other conditions beyond those listed under Recommended Operating Conditions. If used outside the Recommended Operating Conditions but within the Absolute Maximum Ratings, the device may not be fully functional, and this may affect device reliability, functionality, performance, and shorten the device lifetime.
(2) Short-circuit to V_S / 2 (groundinsymmetrical dual-supply setups), one amplifier per package.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001(1)	±2000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101(2)	±1000	

(1) JEDEC document JEP155 states that 500-V HBM allowssafemanufacturing with a standard ESD control process.
(2) JEDEC document JEP157 states that 250-V CDM allowssafemanufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

			MIN	NOM	MAX	UNIT
V_S	Supply voltage	Single supply	4.5		36	V
		Dual supply	±2.25		±18	
T_A	Operating temperature		–40		125	°C

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6.4 Thermal Information: OPA1655

THERMAL METRIC(1)		OPA1655 D (SOIC) 8 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance	120.9	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	58.9	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	65.1	°C/W
ψ_{JT}	Junction-to-top characterization parameter	13.5	°C/W
ψ_{JB}	Junction-to-board characterization parameter	64.2	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

6.5 Thermal Information: OPA1656

THERMAL METRIC(1)		OPA1656 D (SOIC) 8 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance	119.9	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	51.8	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	65.4	°C/W
ψ_{JT}	Junction-to-top characterization parameter	10.0	°C/W
ψ_{JB}	Junction-to-board characterization parameter	64.2	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

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6.6 Electrical Characteristics

at T_A = 25°C, V_S = ±18 V, R_L = 2 kΩ, and V_{CM} = V_{OUT} = V_S/2 (unless otherwise noted)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
AUDIO PERFORMANCE							
THD+N	Total harmonic distortion + noise	G = 1, R_L = 600 Ω, V_O = 3.5 V_{RMS}, f = 1 kHz, 80-kHz measurement bandwidth			0.000029%		
					–131		dB
		G = 1, R_L = 600 Ω, V_O = 3.5 V_{RMS}, f = 20 kHz, 80-kHz measurement bandwidth			0.0001%		
					–120		dB
		G = 1, R_L = 2 kΩ, V_O = 3.5 V_{RMS}, f = 1 kHz, 80-kHz measurement bandwidth			0.000029%		
					–131		dB
		G = 1, R_L = 2 kΩ, V_O = 3.5 V_{RMS}, f = 20 kHz, 80-kHz measurement bandwidth			0.000035%		
					–129		dB
IMD	Intermodulation distortion	G = 1 V_O = 3.5 V_{RMS}	SMPTE/DIN two-tone, 4:1 (60 Hz and 7 kHz)		0.000018%		
					–135		dB
			CCIF twin-tone (19 kHz and 20 kHz)		0.000020%		
					–134		dB
FREQUENCY RESPONSE							
GBW	Gain-bandwidth product	G = 100			53		MHz
	Unity gain bandwidth	G = 1			20		MHz
SR	Slew rate	G = –1, 10-V step			24		V/µs
	Full-power bandwidth(1)	V_O = 1 V_P			3.8		MHz
	Overload recovery time	G = –10			100		ns
	Channel separation	f = 1 kHz			–135		dB
	Settling time	0.01%, G = –1, 10-V step			800		ns
NOISE							
	Input voltage noise	f = 20 Hz to 20 kHz			0.53		μV_{RMS}
		f = 0.1 Hz to 10 Hz			1.9		μV_{PP}
e_n	Input voltage noise density	f = 100 Hz			11.8		nV/√Hz
		f = 1 kHz			4.3		nV/√Hz
		f = 10 kHz			2.9		
i_n	Input current noise density	f = 1 kHz			6		fA/√Hz
OFFSET VOLTAGE							
V_{OS}	Input offset voltage	V_S = ±2.25 V to ±18 V			±0.5	±1	mV
dV_{OS}/dT	Input offset voltage drift(2)	V_S = ±2.25 V to ±18 V T_A = –40°C to +125°C			0.3	2	µV/°C
PSRR	Power-supply rejection ratio	V_S = ±2.25 V to ±18 V			0.3	5	µV/V
INPUT BIAS CURRENT							
I_B	Input bias current(3)	V_{CM} = 0 V	OPA1655		±10		pA
			OPA1656		±10	±20	
I_{OS}	Input offset current	V_{CM} = 0 V	OPA1655		±10		pA
			OPA1656		±10	±20	
INPUT VOLTAGE RANGE							
V_{CM}	Common-mode voltage range			(V–)		(V+) – 2.25	V
CMRR	Common-mode rejection ratio	(V–) ≤ V_{CM} ≤ (V+) – 2.25		106	120		dB
INPUT IMPEDANCE							
	Differential				100 || 9.1		MΩ || pF
	Common-mode				6 || 1.9		10^{12}Ω || pF
OPEN-LOOP GAIN							
A_{OL}	Open-loop voltage gain	(V–) + 1.3 V ≤ V_O ≤ (V+) – 1.3 V R_L = 600 Ω		134	150		dB
		(V–) + 0.5 V ≤ V_O ≤ (V+) – 0.5 V R_L = 2 kΩ		134	154		

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6.6 Electrical Characteristics (continued)

at T_A = 25°C, V_S = ±18 V, R_L = 2 kΩ, and V_{CM} = V_{OUT} = V_S/2 (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
OUTPUT						
V_O	Voltage output		(V–) + 0.25		(V+) – 0.25	V
Z_O	Open-loop output impedance	f = 1 MHz		26		Ω
I_{SC}	Short-circuit current(4)			±100		mA
C_L	Capacitive load drive			100		pF
POWER SUPPLY						
I_Q	Quiescent current (per channel)	I_O = 0 A, V_S = ±2.25 V to ±18 V		3.9	4.6	mA
		I_O = 0 A, T_A = –40°C to +125°C(2)			5.0	

(1) Full-power bandwidth = SR / (2π × V_P), where SR = slew rate.
(2) Specified by design and characterization.
(3) Input bias current test conditions can vary from nominal ambient conditions as a result of junction temperature differences.
(4) One channel at a time.

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6.7 Typical Characteristics

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)

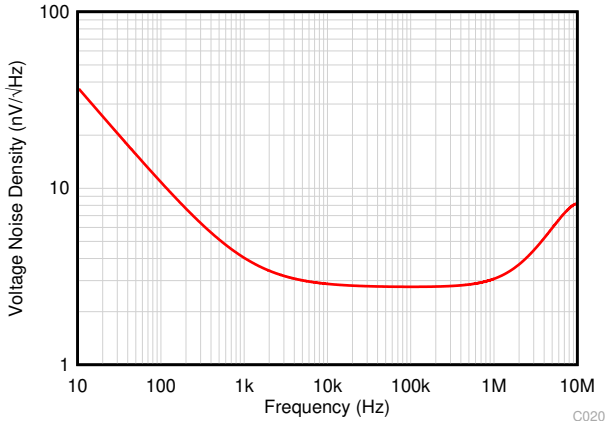


Figure 6-1. Input Voltage Noise Density vs Frequency

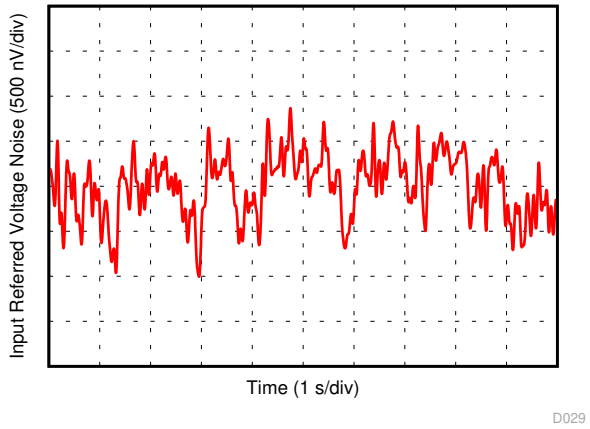


Figure 6-2. 0.1-Hz to 10-Hz Noise

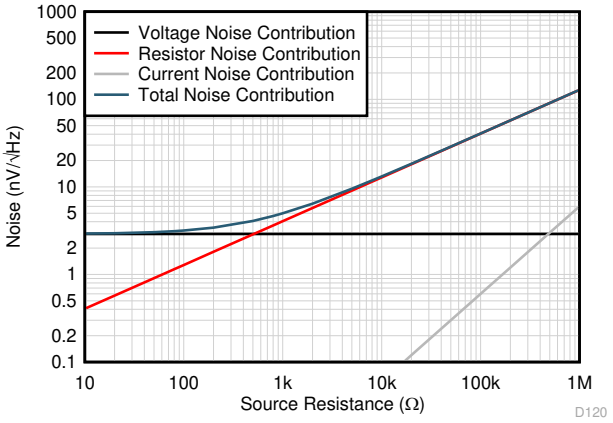


Figure 6-3. Voltage Noise vs Source Resistance

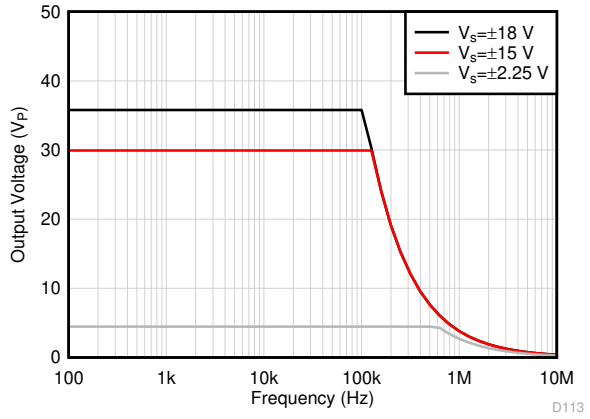
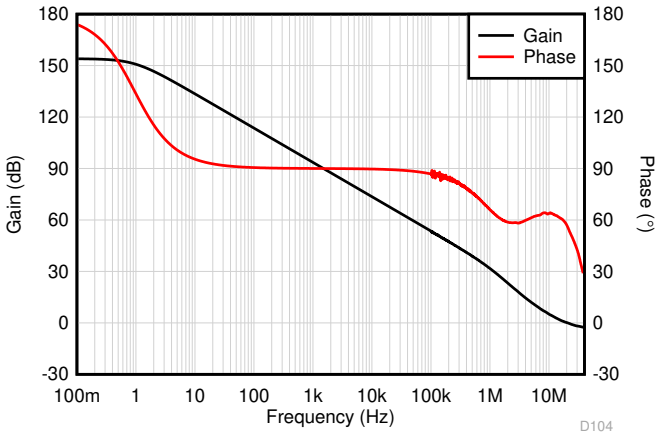
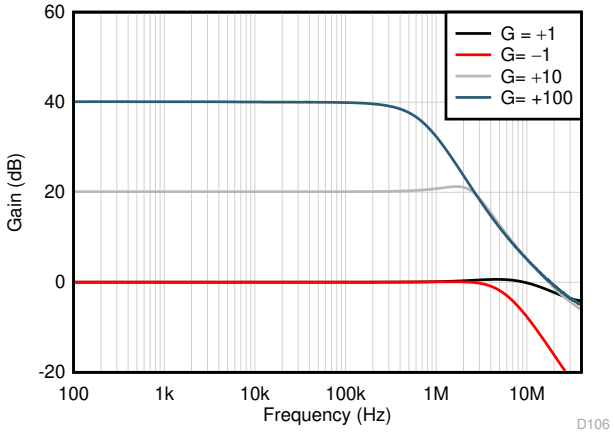


Figure 6-4. Maximum Output Voltage vs Frequency



C_L = 10 pF

Figure 6-5. Open-Loop Gain and Phase vs Frequency



C_L = 10 pF

Figure 6-6. Closed-Loop Gain vs Frequency

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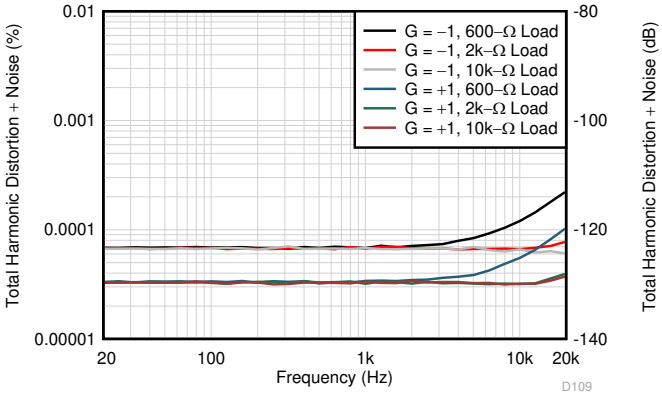
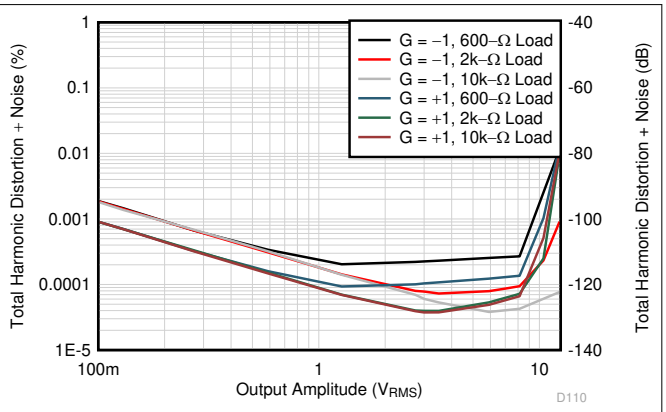
6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)



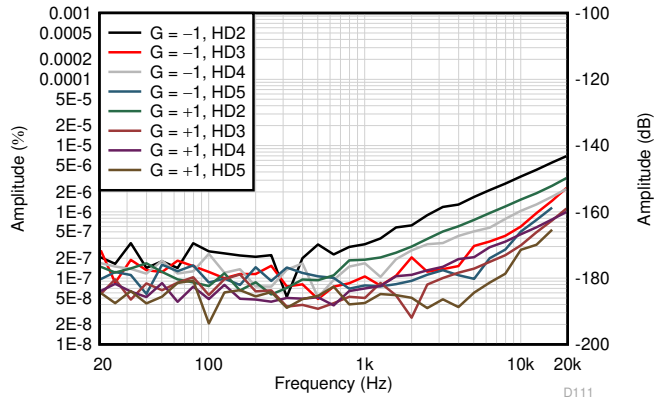
V_{OUT} = 3 V_{RMS} Bandwidth = 80 kHz

Figure 6-7. THD+N Ratio vs Frequency



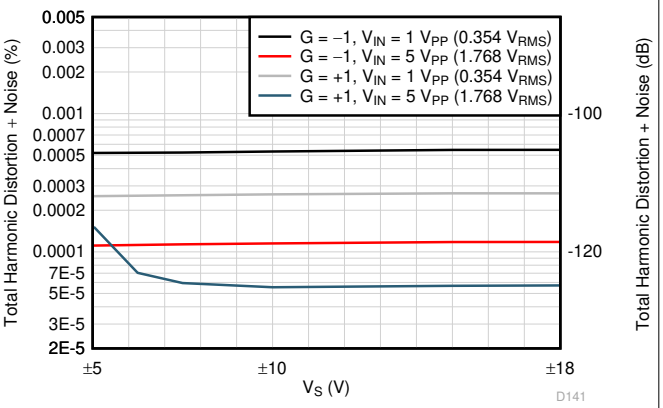
f = 1 kHz Bandwidth = 80 kHz

Figure 6-8. THD+N Ratio vs Output Amplitude



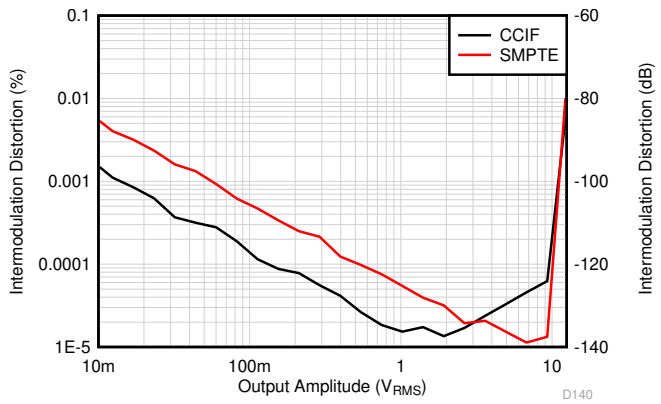
V_{OUT} = 3 V_{RMS} Bandwidth = 80 kHz

Figure 6-9. Individual Harmonic Amplitude vs Frequency



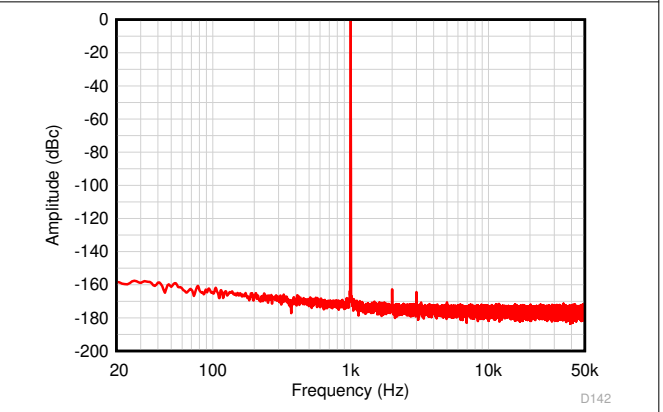
f = 1 kHz R_L = 2 kΩ Bandwidth = 80 kHz

Figure 6-10. THD+N vs Supply Voltage



Bandwidth = 80 kHz

Figure 6-11. Intermodulation Distortion vs Amplitude



G = 1, V_{OUT} = 3 V_{RMS} R_L = 2 kΩ Bandwidth = 80 kHz

Figure 6-12. FFT, 1-kHz Sine Wave

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6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)

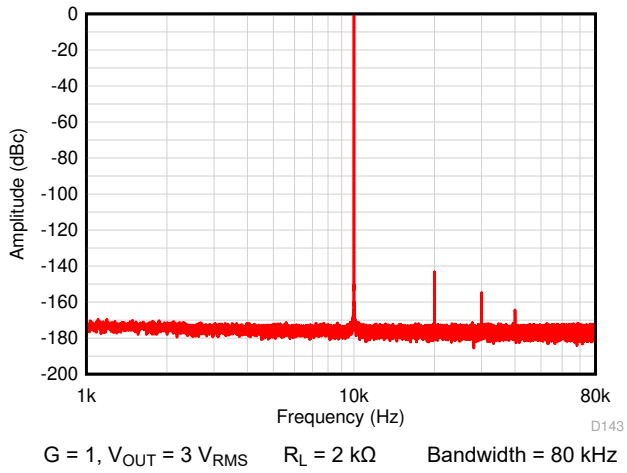

Figure 6-13. FFT, 10-kHz Sine Wave

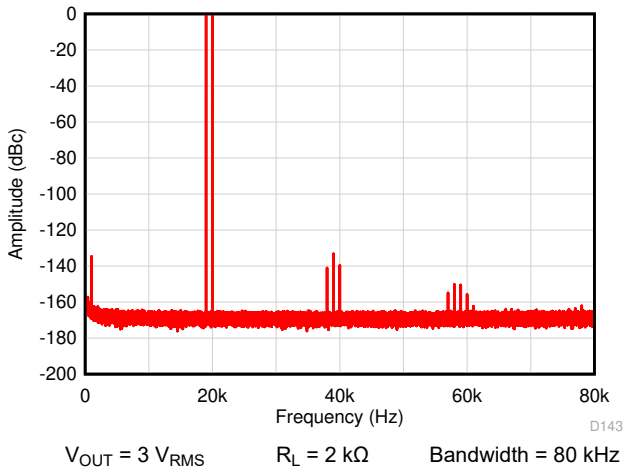

Figure 6-14. FFT, CCIF Input (19 kHz + 20 kHz)

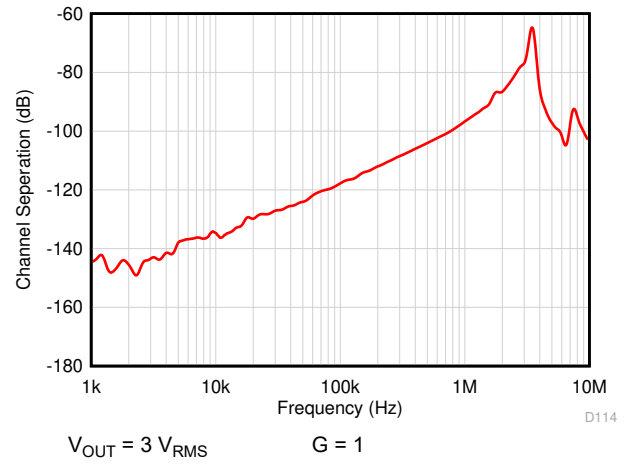

Figure 6-15. Channel Separation vs Frequency

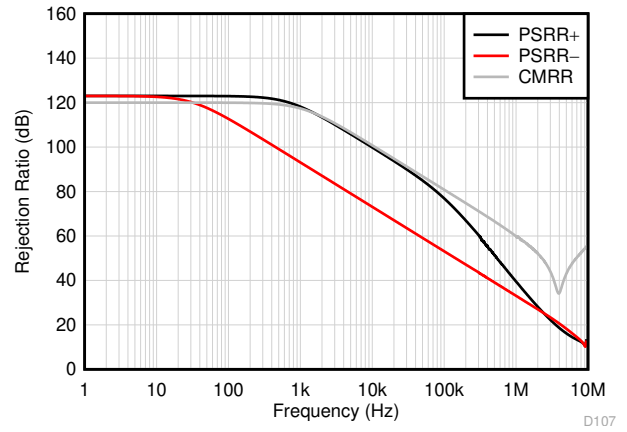

Figure 6-16. CMRR and PSRR vs Frequency (Referred to Input)

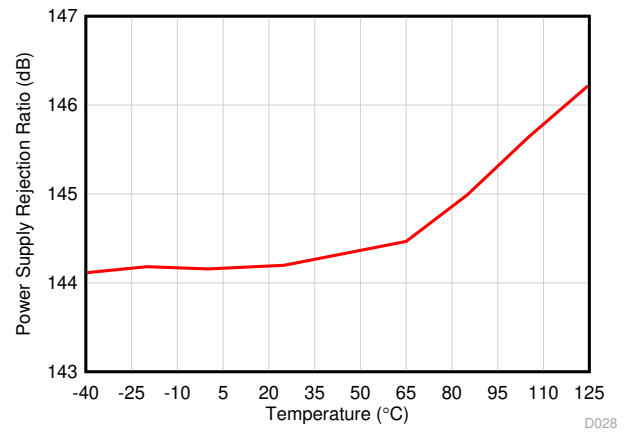

Figure 6-17. Power Supply Rejection Ratio vs Temperature (Referred to Input)

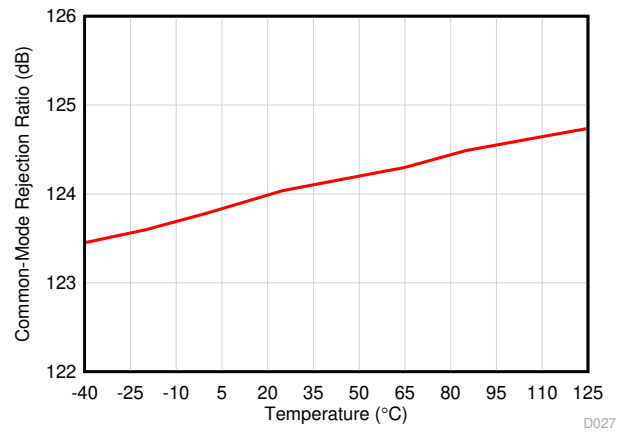

Figure 6-18. Common Mode Rejection Ratio vs Temperature (Referred to Input)

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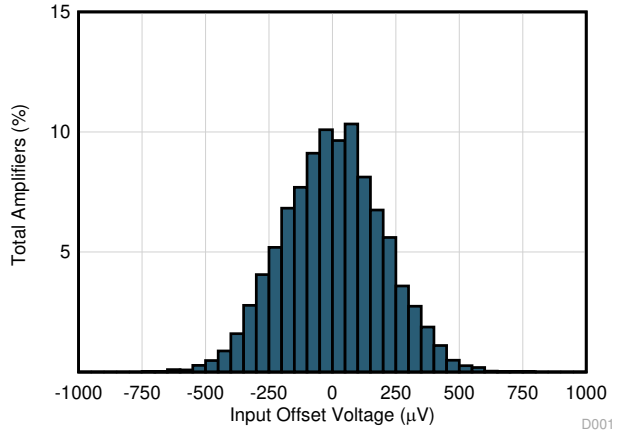
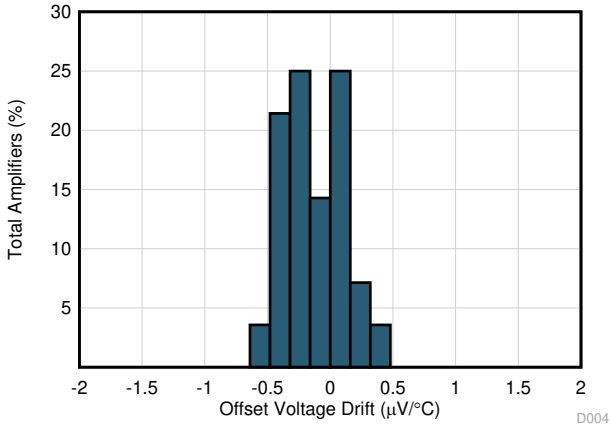
6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)



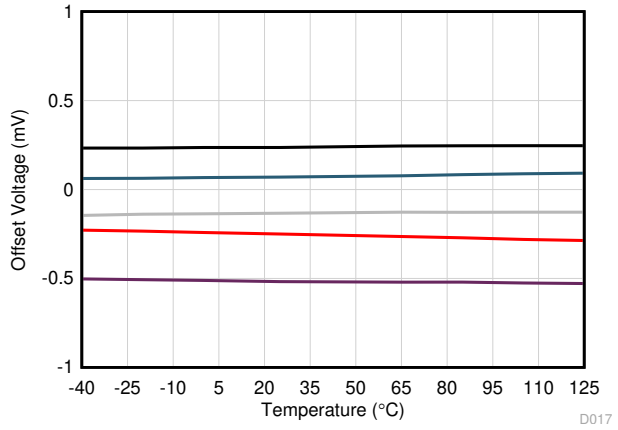
Count = 7955

Figure 6-19. Input Offset Voltage Distribution



Count = 32

Figure 6-20. Input Offset Voltage Drift Distribution



5 typical units shown

Figure 6-21. Input Offset vs Temperature

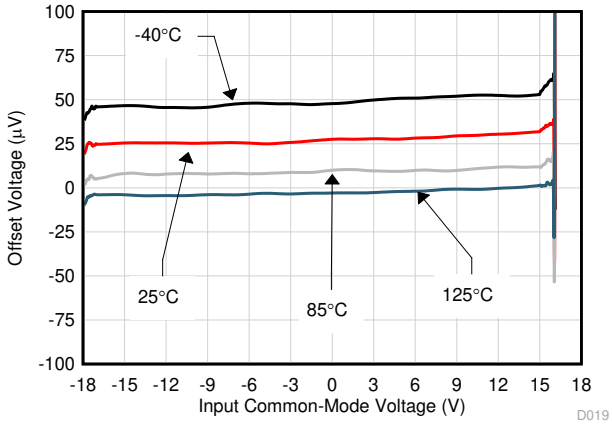
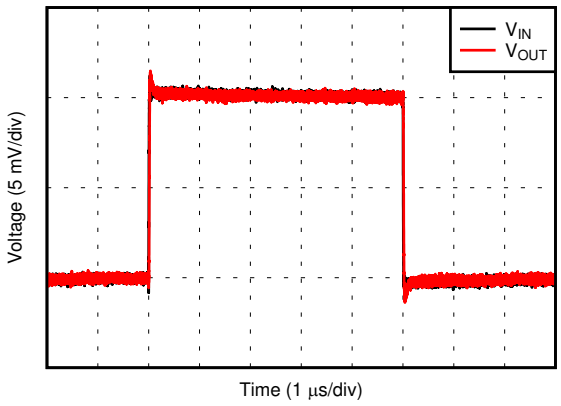
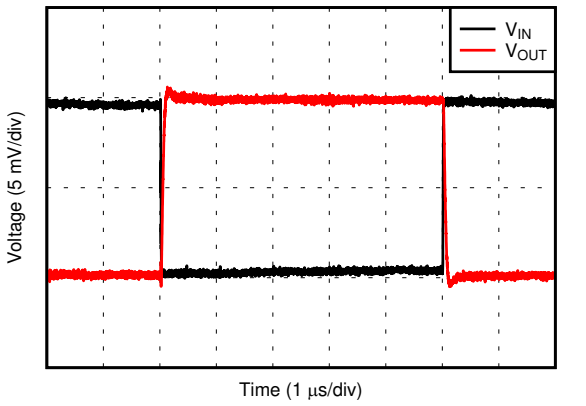


Figure 6-22. Input Offset vs Common Mode Voltage



G = 1 C_L = 20 pF

Figure 6-23. Small-Signal Step Response (100 mV)



G = –1 C_L = 100 pF

Figure 6-24. Small-Signal Step Response (100 mV)

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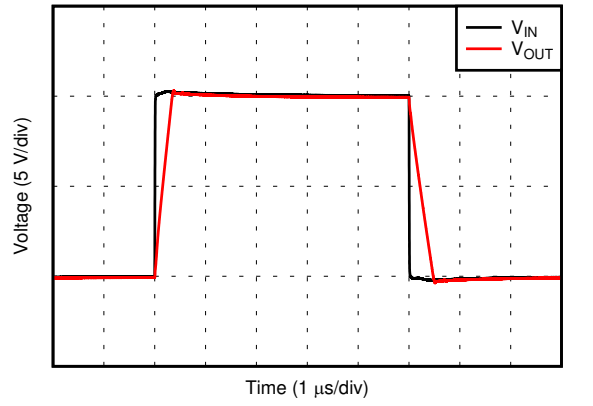
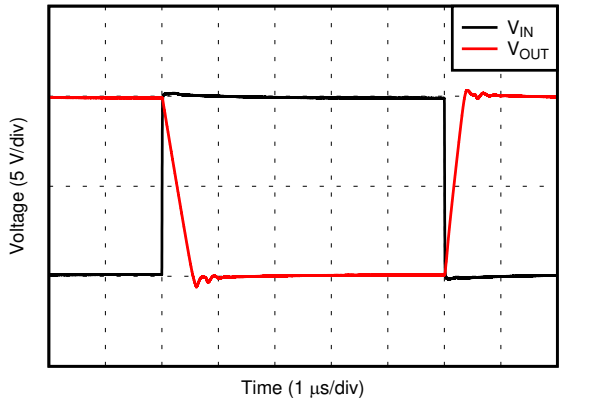
6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)



G = 1 R_L = 2 kΩ C_L = 100 pF

Figure 6-25. Large-Signal Step Response



G = –1 C_L = 100 pF

Figure 6-26. Large-Signal Step Response

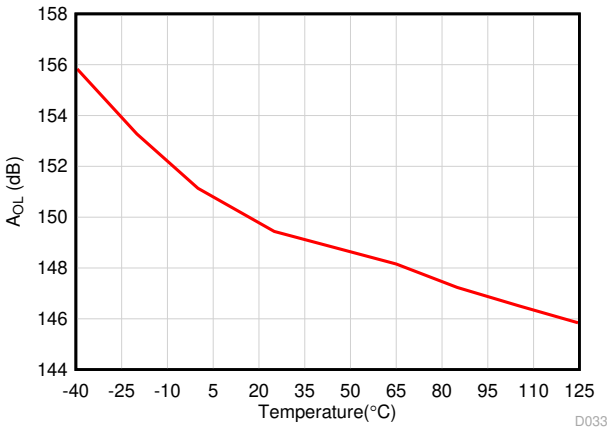


Figure 6-27. Open-Loop Gain vs Temperature

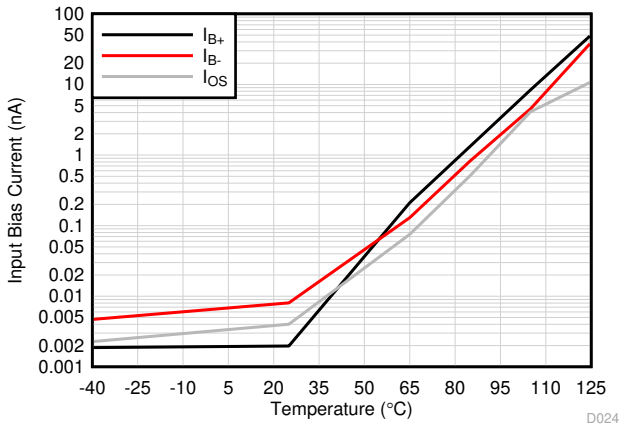


Figure 6-28. I_B and I_{OS} vs Temperature

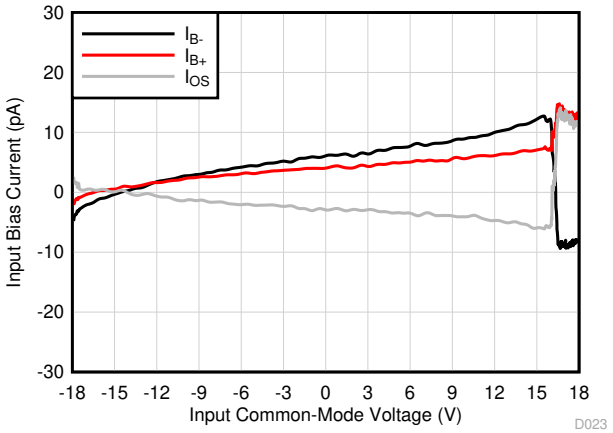


Figure 6-29. I_B and I_{OS} vs Common-Mode Voltage

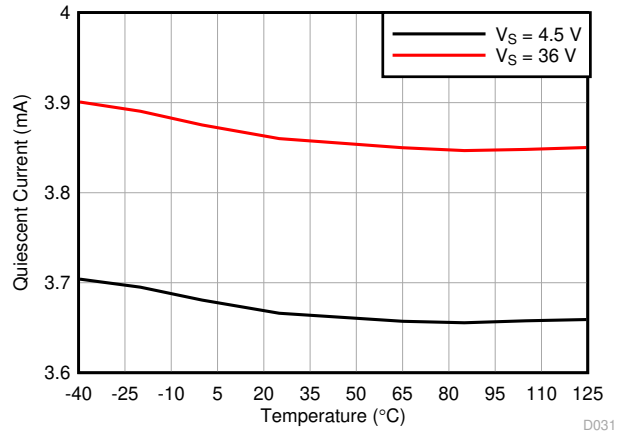


Figure 6-30. Supply Current vs Temperature

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6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)

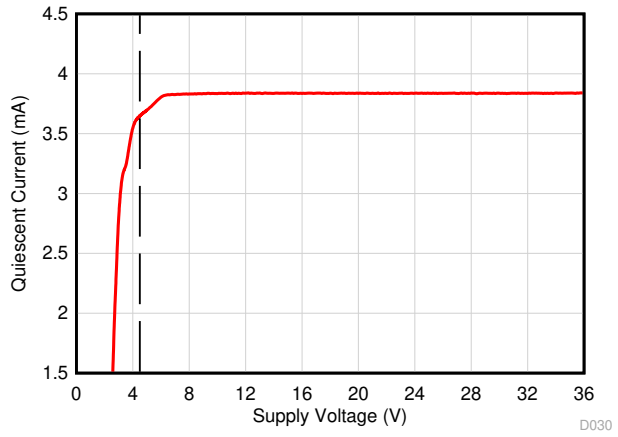


Figure 6-31. Supply Current vs Supply Voltage

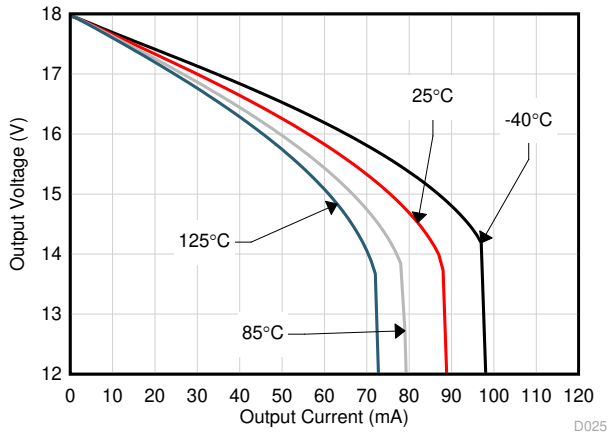


Figure 6-32. Output Voltage vs Output Current (Sourcing)

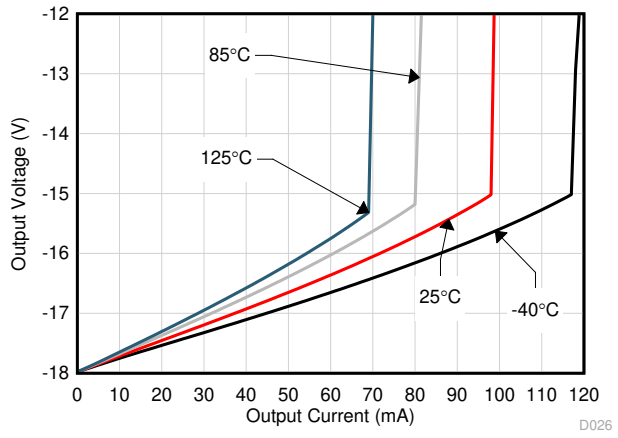


Figure 6-33. Output Voltage vs Output Current (Sinking)

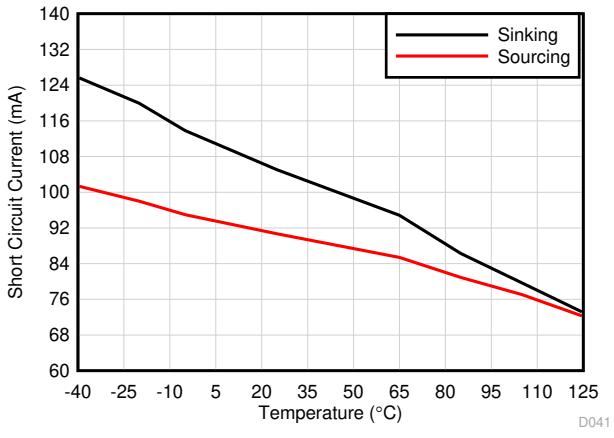


Figure 6-34. Short-Circuit Current vs Temperature

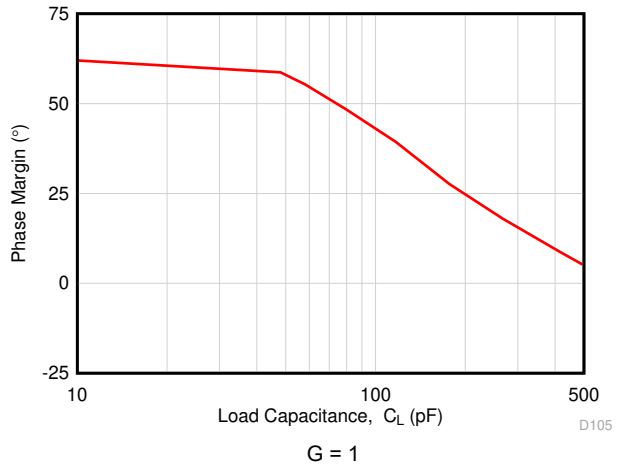


Figure 6-35. Phase Margin vs Capacitive Load

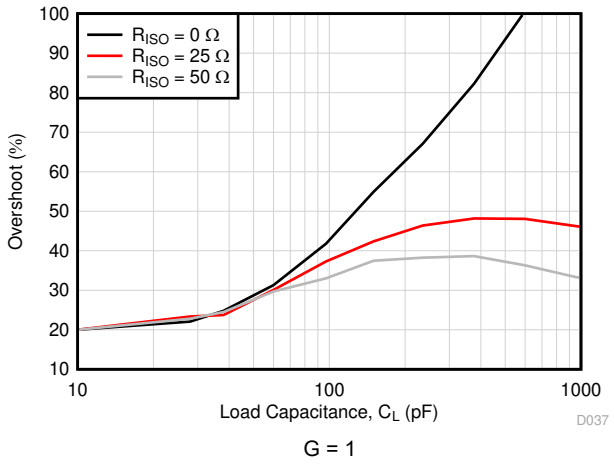
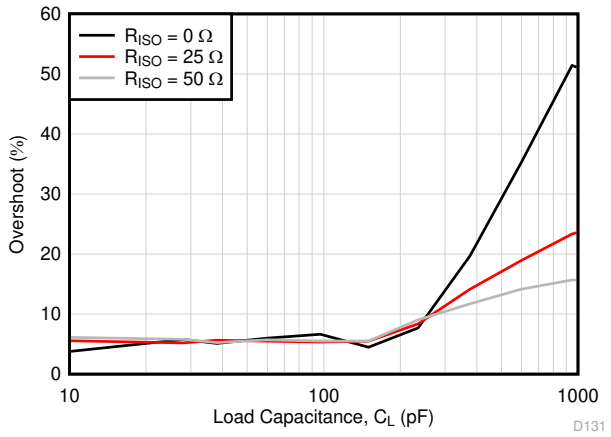


Figure 6-36. Percent Overshoot vs Capacitive Load

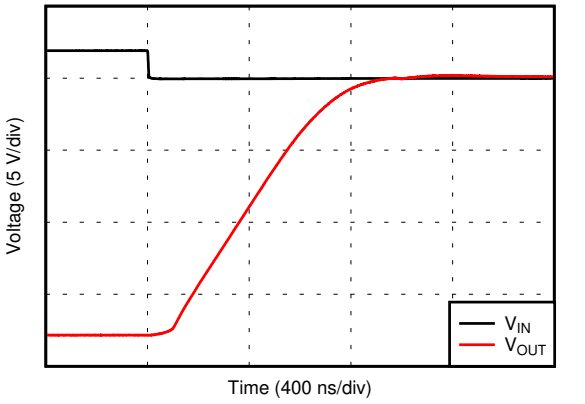
6.7 Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, R_L = 2 kΩ, and V_{CM} = V_S/2 (unless otherwise noted)



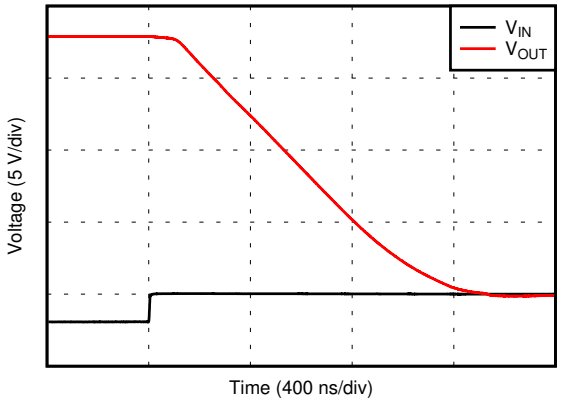
G = –1

Figure 6-37. Percent Overshoot vs Capacitive Load



G = –10

Figure 6-38. Negative Overload Recovery



G = –10

Figure 6-39. Positive Overload Recovery

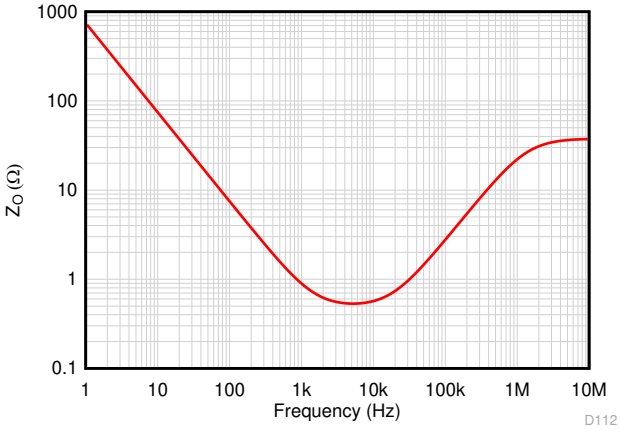
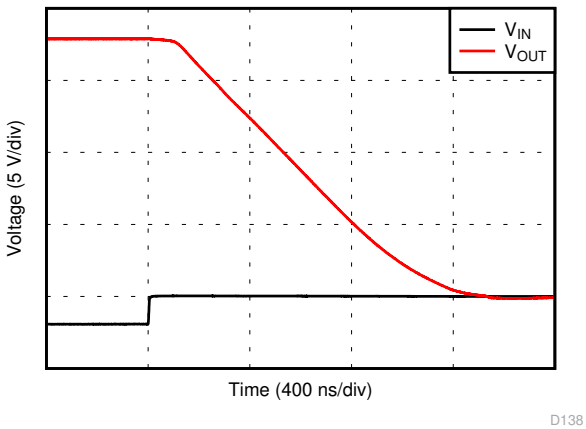


Figure 6-40. Open-Loop Output Impedance vs Frequency



G = 1

Figure 6-41. No Phase Reversal

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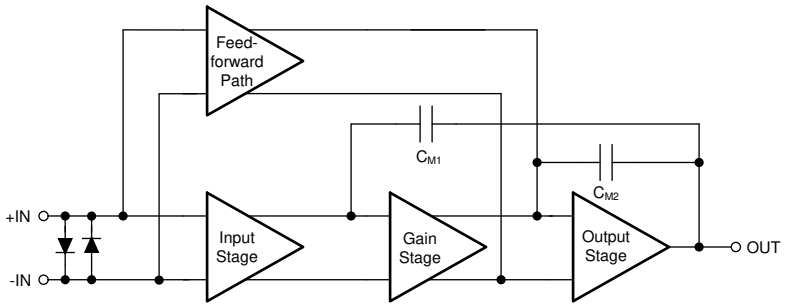
7 Detailed Description

7.1 Overview

The OPA1655 and OPA1656 (OPA165x) use a three-gain-stage architecture to achieve very low noise and distortion. The *Functional Block Diagram* shows a simplified schematic of the OPA165x (one channel shown). The devices consist of a low-noise input stage and feedforward pathway coupled to a high-current output stage. This topology exhibits superior distortion performance under a wide range of loading conditions compared to other operational amplifiers.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Phase Reversal Protection

The OPA165x have internal phase-reversal protection. Many op amps exhibit phase reversal when the input is driven beyond the linear common-mode range. This condition is most often encountered in noninverting circuits when the input is driven beyond the specified common-mode voltage range, causing the output to reverse into the opposite rail. The input of the OPA165x prevents phase reversal with excessive common-mode voltage. Instead, the appropriate rail limits the output voltage. This performance is shown in Figure 7-1.

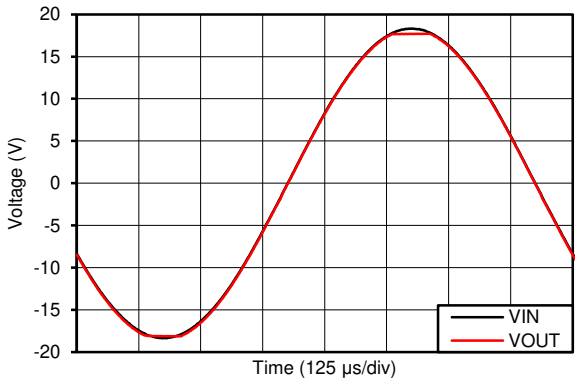


Figure 7-1. Output Waveform Devoid of Phase Reversal During an Input Overdrive Condition

7.3.2 Electrical Overstress

Designers often ask questions about the capability of an operational amplifier to withstand electrical overstress. These questions tend to focus on the device inputs, but can involve the supply voltage pins or even the output pin. Each of these different pin functions have electrical stress limits determined by the voltage breakdown characteristics of the particular semiconductor fabrication process and specific circuits connected to the pin. Additionally, internal electrostatic discharge (ESD) protection is built into these circuits to protect them from accidental ESD events both before and during product assembly.

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A good understanding of this basic ESD circuitry and the relevance to an electrical overstress event is helpful. Figure 7-2 illustrates the ESD circuits contained in the OPA165x (indicated by the dashed line area). The ESD protection circuitry involves several current-steering diodes connected from the input and output pins and routed back to the internal power-supply lines, where the diodes meet at an absorption device internal to the operational amplifier. This protection circuitry is intended to remain inactive during normal circuit operation.

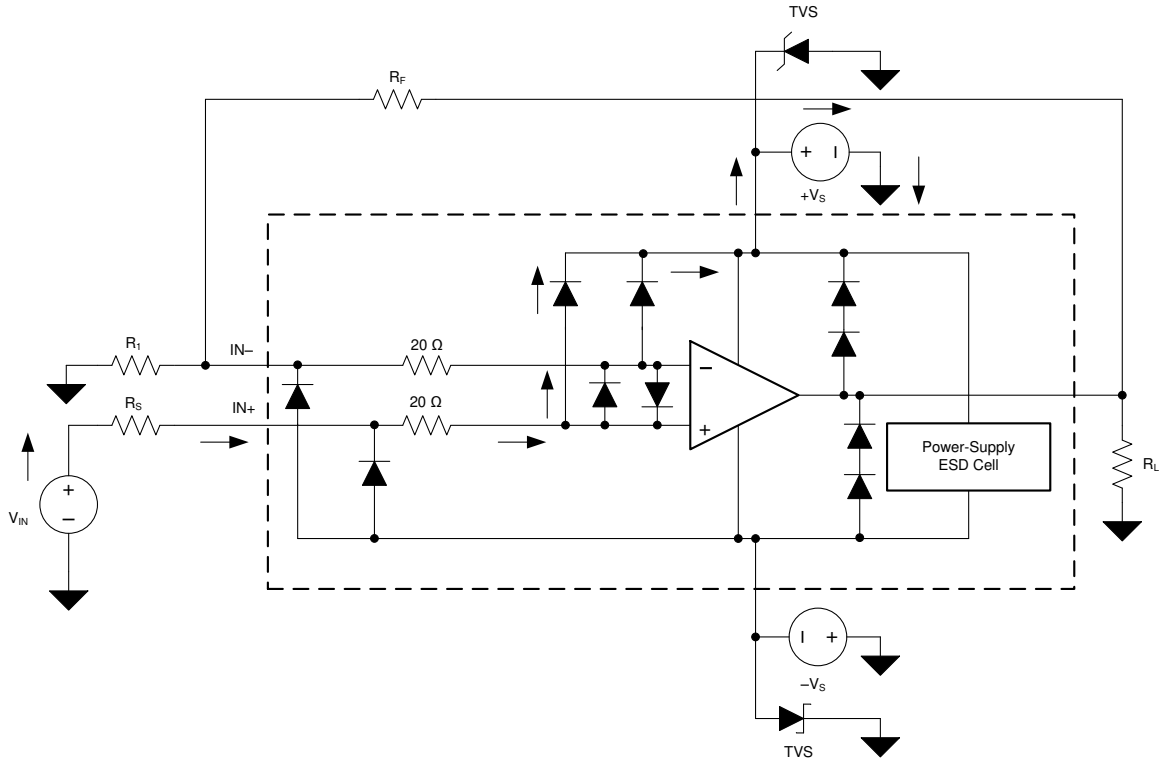

Figure 7-2. Equivalent Internal ESD Circuitry Relative to a Typical Circuit Application

An ESD event produces a short-duration, high-voltage pulse that is transformed into a short-duration, high-current pulse when discharging through a semiconductor device. The ESD protection circuits are designed to provide a current path around the operational amplifier core to prevent damage. The energy absorbed by the protection circuitry is then dissipated as heat.

When an ESD voltage develops across two or more amplifier device pins, current flows through one or more steering diodes. Depending on the path that the current takes, the absorption device can activate. The absorption device has a trigger, or threshold voltage, that is above the normal operating voltage of the OPA165x but below the device breakdown voltage level. When this threshold is exceeded, the absorption device quickly activates and clamps the voltage across the supply rails to a safe level.

When the operational amplifier connects into a circuit, as shown in Figure 7-2, the ESD protection components are intended to remain inactive and do not become involved in the application circuit operation. However, circumstances may arise where an applied voltage exceeds the operating voltage range of a given pin. If this condition occurs, there is a risk that some internal ESD protection circuits can turn on and conduct current. Any such current flow occurs through steering-diode paths and rarely involves the absorption device.

Figure 7-2 shows a specific example where the input voltage (V_{IN}) exceeds the positive supply voltage (V+) by 500 mV or more. Much of what happens in the circuit depends on the supply characteristics. If V+ can sink the current, one of the upper input steering diodes conducts and directs current to V+. Excessively high current levels can flow with increasingly higher V_{IN}. As a result, the data sheet specifications recommend that applications limit the input current to 10 mA.

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If the supply is not capable of sinking the current, V_{IN} can begin sourcing current to the operational amplifier and then take over as the source of positive supply voltage. The danger in this case is that the voltage can rise to levels that exceed the operational amplifier absolute maximum ratings.

Another common question involves what happens to the amplifier if an input signal is applied to the input when the power supplies (V+ or V–) are at 0 V. Again, this question depends on the supply characteristic when at 0 V, or at a level below the input signal amplitude. If the supplies appear as high impedance, then the input source supplies the operational amplifier current through the current-steering diodes. This state is not a normal bias condition; most likely, the amplifier does not operate normally. If the supplies are low impedance, then the current through the steering diodes can become quite high. The current level depends on the ability of the input source to deliver current, and any resistance in the input path.

If there is any uncertainty about the ability of the supply to absorb this current, add external Zener diodes to the supply pins; see Figure 7-2. Select the Zener voltage so that the diode does not turn on during normal operation. However, the Zener voltage must be low enough so that the Zener diode conducts if the supply pin begins to rise above the safe-operating, supply-voltage level.

7.3.3 EMI Rejection Ratio (EMIRR)

The electromagnetic interference (EMI) rejection ratio, or EMIRR, describes the EMI immunity of operational amplifiers. An adverse effect that is common to many operational amplifiers is a change in the offset voltage as a result of RF signal rectification. An operational amplifier that is more efficient at rejecting this change in offset as a result of EMI has a higher EMIRR and is quantified by a decibel value. Measuring EMIRR can be performed in many ways, but this document provides the EMIRR IN+, which specifically describes the EMIRR performance when the RF signal is applied to the noninverting input pin of the operational amplifier. In general, only the noninverting input is tested for EMIRR for the following three reasons:

- Operational amplifier input pins are known to be the most sensitive to EMI, and typically rectify RF signals better than the supply or output pins.
- The noninverting and inverting operational amplifier inputs have symmetrical physical layouts and exhibit nearly matching EMIRR performance.
- EMIRR is easier to measure on noninverting pins than on other pins because the noninverting input pin can be isolated on a printed-circuit-board (PCB). This isolation allows the RF signal to be applied directly to the noninverting input pin with no complex interactions from other components or connecting PCB traces.

A more formal discussion of the EMIRR IN+ definition and test method is provided in the *EMI Rejection Ratio of Operational Amplifiers* application report, available for download at www.ti.com.

The EMIRR IN+ of the OPA165x is plotted versus frequency in Figure 7-3. If available, any dual and quad operational amplifier device versions have nearly identical EMIRR IN+ performance. The OPA165x unity-gain bandwidth is 20 MHz. EMIRR performance below this frequency denotes interfering signals that fall within the operational amplifier bandwidth.

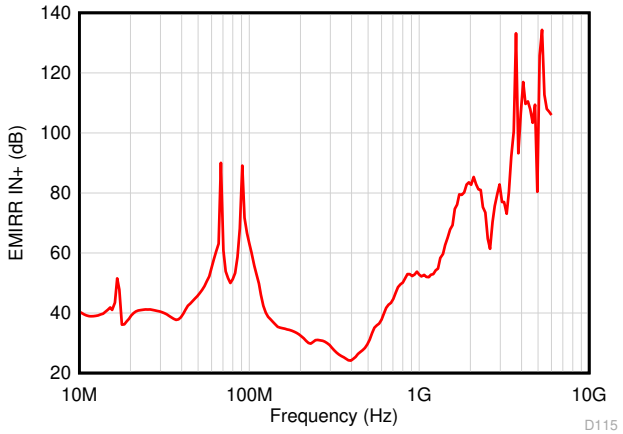

Figure 7-3. OPA165x EMIRR vs Frequency

Table 7-1 lists the EMIRR IN+ values for the OPA165x at particular frequencies commonly encountered in real-world applications. Applications listed in Table 7-1 can be centered on or operated near the particular frequency shown. This information can be of special interest to designers working with these types of applications, or working in other fields likely to encounter RF interference from broad sources, such as the industrial, scientific, and medical (ISM) radio band.

Table 7-1. OPA165x EMIRR IN+ for Frequencies of Interest

FREQUENCY	APPLICATION OR ALLOCATION	EMIRR IN+
400 MHz	Mobile radio, mobile satellite, space operation, weather, radar, UHF	36 dB
900 MHz	GSM, radio communication and navigation, GPS (to 1.6 GHz), ISM, aeronautical mobile, UHF	42 dB
1.8 GHz	GSM, mobile personal comm. broadband, satellite, L-band	52 dB
2.4 GHz	802.11b/g/n, Bluetooth® mobile personal comm., ISM, amateur radio and satellite, S-band	64 dB
3.6 GHz	Radiolocation, aero comm./nav., satellite, mobile, S-band	67 dB
5 GHz	802.11a/n, aero communication and navigation, mobile communication, space and satellite operation, C-band	77 dB

7.3.3.1 EMIRR IN+ Test Configuration

Figure 7-4 shows the circuit configuration for testing the EMIRR IN+. An RF source is connected to the operational amplifier noninverting input pin using a transmission line. The operational amplifier is configured in a unity-gain buffer topology with the output connected to a low-pass filter (LPF) and a digital multimeter (DMM). A large impedance mismatch at the operational amplifier input causes a voltage reflection; however, this effect is characterized and accounted for when determining the EMIRR IN+. The resulting dc offset voltage is sampled and measured by the multimeter. The LPF isolates the multimeter from residual RF signals that can interfere with multimeter accuracy. See the *EMI Rejection Ratio of Operational Amplifiers* application report for more details.

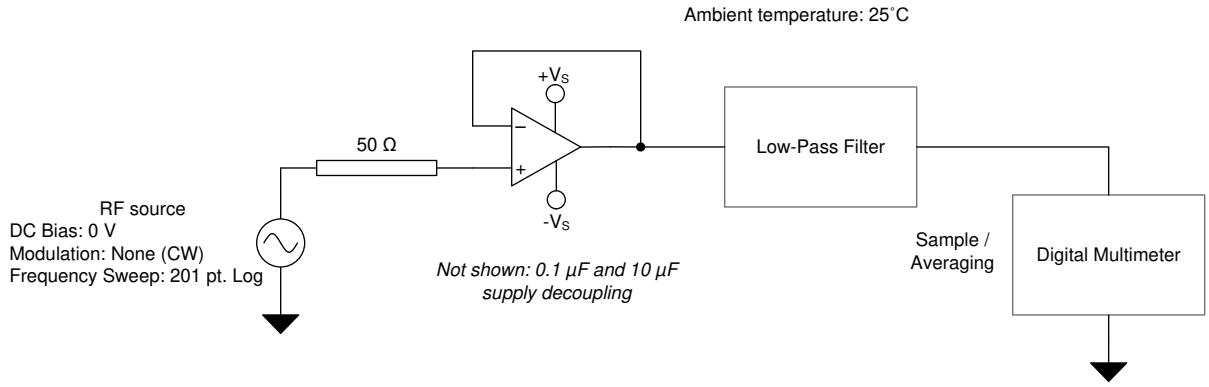

Figure 7-4. EMIRR IN+ Test Configuration Schematic

7.4 Device Functional Modes

The OPA165x have a single functional mode and are operational when the power-supply voltage is greater than 4.5 V. The maximum specified power-supply voltage for the OPA165x is 36 V.

In all cases, the common-mode voltage must be maintained within the specified range. In addition, key parameters are specified over the temperature range of T_A = –40°C to +125°C.

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8 Application and Implementation

Note

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes, as well as validating and testing their design implementation to confirm system functionality.

8.1 Application Information

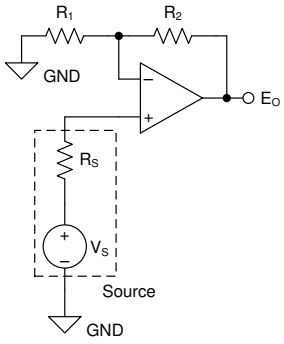
8.1.1 Basic Noise Calculations

Low-noise circuit design requires careful analysis of all noise sources. External noise sources can dominate in many cases; consider the effect of source resistance on overall op amp noise performance. Total noise of the circuit is the root-sum-square combination of all noise components.

Figure 8-1 shows noninverting **(A)** and inverting **(B)** op amp circuit configurations with gain. In circuit configurations with gain, the feedback network resistors contribute noise. In general, the current noise of the op amp reacts with the feedback resistors to create additional noise components.

The selected feedback resistor values make these noise sources negligible. Low impedance feedback resistors load the output of the amplifier. The equations for total noise are shown for both configurations.

(A) Noise in Noninverting Gain Configuration



Noise at the output is given as E_O, where

$$(1)\quad E_O = \left(1+\frac{R_2}{R_1}\right)\cdot\sqrt{(e_S)^2+(e_N)^2+\left(e_{R_1\|R_2}\right)^2+(i_N\cdot R_S)^2+\left(i_N\cdot\left[\frac{R_1\cdot R_2}{R_1+R_2}\right]\right)^2}\quad [\,V_{RMS}\,]$$

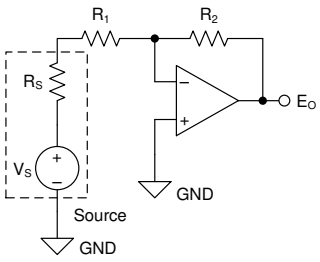
$$(2)\quad e_S = \sqrt{4\cdot k_B\cdot T(K)\cdot R_S}\quad \left[\frac{V}{\sqrt{Hz}}\right]$$ Thermal noise of R_S

$$(3)\quad e_{R_1\|R_2} = \sqrt{4\cdot k_B\cdot T(K)\cdot\left[\frac{R_1\cdot R_2}{R_1+R_2}\right]}\quad \left[\frac{V}{\sqrt{Hz}}\right]$$ Thermal noise of $R_1 \| R_2$

$$(4)\quad k_B = 1.38065\cdot 10^{-23}\quad \left[\frac{J}{K}\right]$$ Boltzmann Constant

$$(5)\quad T(K) = 237.15 + T(°C)\quad [\,K\,]$$ Temperature in kelvins

(B) Noise in Inverting Gain Configuration



Noise at the output is given as E_O, where

$$(6)\quad E_O = \left(1+\frac{R_2}{R_S+R_1}\right)\cdot\sqrt{(e_N)^2+\left(e_{R_1+R_S\|R_2}\right)^2+\left(i_N\cdot\left[\frac{(R_S+R_1)\cdot R_2}{R_S+R_1+R_2}\right]\right)^2}\quad [\,V_{RMS}\,]$$

$$(7)\quad e_{R_1+R_S\|R_2} = \sqrt{4\cdot k_B\cdot T(K)\cdot\left[\frac{(R_S+R_1)\cdot R_2}{R_S+R_1+R_2}\right]}\quad \left[\frac{V}{\sqrt{Hz}}\right]$$ Thermal noise of $(R_1 + R_S) \| R_2$

$$(8)\quad k_B = 1.38065\cdot 10^{-23}\quad \left[\frac{J}{K}\right]$$ Boltzmann Constant

$$(9)\quad T(K) = 237.15 + T(°C)\quad [\,K\,]$$ Temperature in kelvins

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where

- e_N is the voltage noise of the amplifier. For the OPA165x, e_N = 4.3 nV/√Hz at 1 kHz.
- i_N is the current noise of the amplifier. For the OPA165x, i_N = 6 fA/√Hz at 1 kHz.

Note: For additional resources on noise calculations, see *TI's Precision Labs Series*.

Figure 8-1. Noise Calculation in Gain Configurations

8.2 Typical Applications

8.2.1 Preamplifier Circuit for Vinyl Record Playback With Moving-Magnet Phono Cartridges

The noise and distortion performance of the OPA165x is exceptional in applications with high source impedances, which makes these devices an excellent choice in preamplifier circuits for moving magnet phono cartridges. The high source impedance of the cartridge, and high gain required by the RIAA playback curve at low frequency, requires an amplifier with both low input current noise and low input voltage noise.

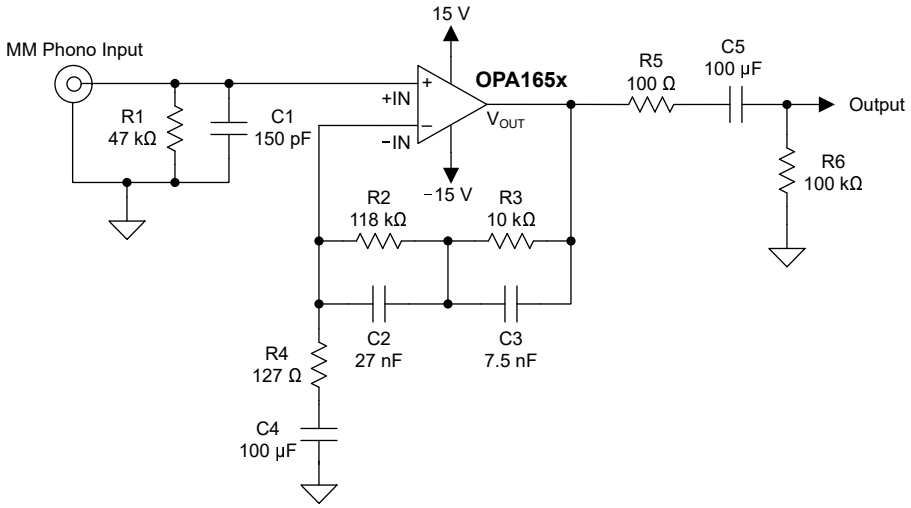

Figure 8-2. Preamplifier Circuit for Vinyl Record Playback With Moving-Magnet Phono Cartridges (Single Channel Shown)

8.2.1.1 Design Requirements

- Gain: 40 dB (1 kHz)
- RIAA accuracy: ±0.5 dB (100 Hz to 20 kHz)
- Power supplies: ±15 V

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8.2.1.2 Detailed Design Procedure

Vinyl records are recorded using an equalization curve specified by the Recording Institute Association of America (RIAA). The purpose of this equalization curve is to decrease the amount of space occupied by a groove on the record and therefore maximize the amount of information able to be stored. Proper playback of music stored on the record requires a preamplifier circuit that applies the inverse transfer function of the recording equalization curve. The combination of the recording equalization and the playback equalization results in a flat frequency response over the audio range, as Figure 8-3 shows.

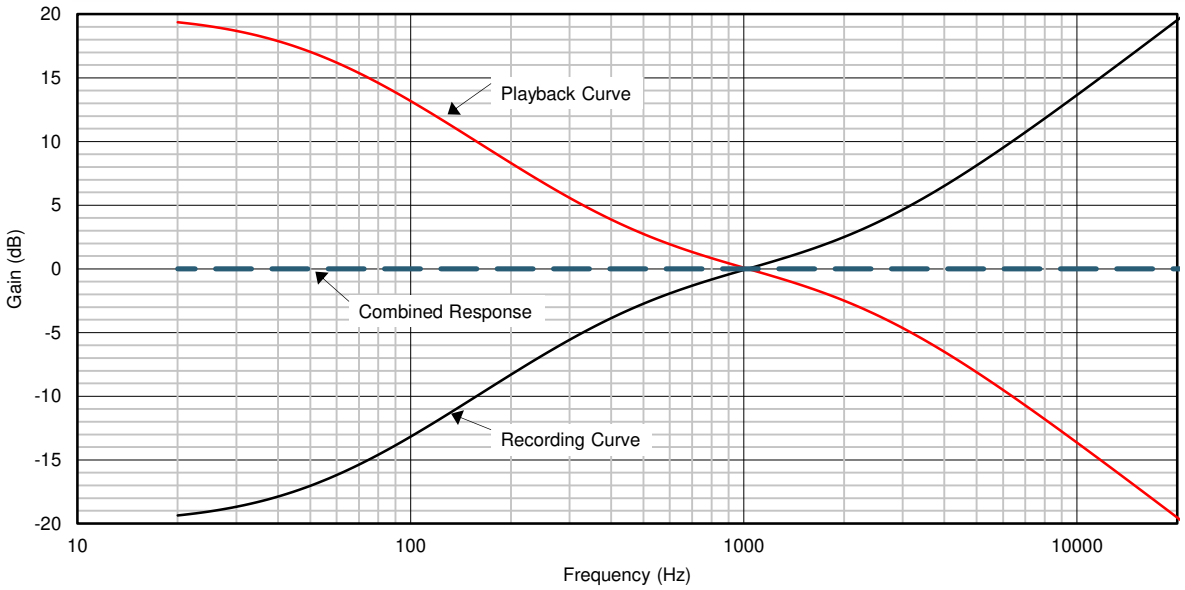

Figure 8-3. RIAA Recording and Playback Curves Normalized at 1 kHz

The basic RIAA playback curve implements three time constants: 75 µs, 380 µs, and 3180 µs. An IEC amendment was later added to the playback curve and implements a pole in the curve at 20 Hz with the intent of protecting loudspeakers from excessive low frequency content. Rather than strictly adhering to the IEC amendment, this design moves this pole to a lower frequency to improve low frequency response and still provide protection for loudspeakers.

Resistor R1 and capacitor C1 are selected to provide the proper input impedance for the moving magnet cartridge. Cartridge loading is specified by the manufacturer in the cartridge datasheet and is absolutely crucial for proper response at high frequency. 47 kΩ is a common value for the input resistor, and the capacitive loading is usually specified from 200 pF to 300 pF per channel. This capacitive loading specification includes the capacitance of the cable connecting the turntable to the preamplifier, as well as any additional parasitic capacitances at the preamplifier input. Therefore, the value of C1 must be less than the loading specification to account for these additional capacitances.

The output network consisting of R5, R6, and C5 serves to ac couple the preamplifier circuit to any subsequent electronics in the signal path. 100-Ω resistor R5 limits in-rush current into coupling capacitor C5 and prevents parasitic capacitance from cabling from causing instability. R6 prevents charge accumulation on C5. Capacitor C5 is chosen to be the same value as C4; for simplicity however, the value of C5 must be large enough to avoid attenuating low-frequency information.

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The feedback resistor elements must be selected to provide the correct response within the audio bandwidth. In order to achieve the correct frequency response, the passive components in Figure 8-2 must satisfy Equation 1, Equation 2, and Equation 3:

$$R_2 \times C_2 = 3180\ \mu s \tag{1}$$

$$R_3 \times C_3 = 75\ \mu s \tag{2}$$

$$(R_2 \,||\, R_3) \times (C_2 + C_3) = 318\ \mu s \tag{3}$$

R2, R3, and R4 must also be selected to meet the design requirements for gain. The gain at 1 kHz is determined by subtracting 20 dB from gain of the circuit at very low-frequency (near dc), as shown in Equation 4:

$$A_{1kHz} = A_{LF} - 20\ dB \tag{4}$$

Therefore, the low frequency gain of the circuit must be 60 dB to meet the goal of 40 dB at 1 kHz and is determined by resistors R2, R3, and R4 as shown in Equation 5:

$$A_{LF} = 1 + \frac{R_3 + R_2}{R_4} = 1000\ (60\ dB) \tag{5}$$

Because there are multiple combinations of passive components that satisfy these equations, a spreadsheet or other software calculation tool is the easiest method to examine resistor and capacitor combinations.

Capacitor C4 forces the gain of the circuit to unity at dc in order to limit the offset voltage at the output of the preamplifier circuit. The high-pass corner frequency created by this capacitor is calculated by Equation 6:

$$F_{HP} = \frac{1}{2\pi R_4 C_4} \tag{6}$$

The circuit described in Figure 8-2 is constructed with 1% tolerance resistors and 5% tolerance NP0, C0G ceramic capacitors without any additional hand sorting. The large value of C4 typically requires an electrolytic type to be used. However, electrolytic capacitors have the potential to introduce distortion into the signal path. This circuit is constructed using a bipolar electrolytic capacitor specifically intended for audio applications.

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8.2.1.3 Application Curves

The deviation from the ideal RIAA transfer function curve is shown in Figure 8-4 and normalized to an ideal gain of 40 dB at 1 kHz. The measured gain at 1 kHz is 0.05 dB less than the design goal, and the maximum deviation from 100 Hz to 20 kHz is 0.18 dB. The deviation from the ideal curve can be improved by hand-sorting resistor and capacitor values to their ideal values. The value of C4 can also be increased to reduce the deviation at low frequency.

A spectrum of the preamplifier output signal is shown in Figure 8-5 for a 10 mV_{RMS}, 1-kHz input signal (1-V_{RMS} output). All distortion harmonics are below the preamplifier noise floor.

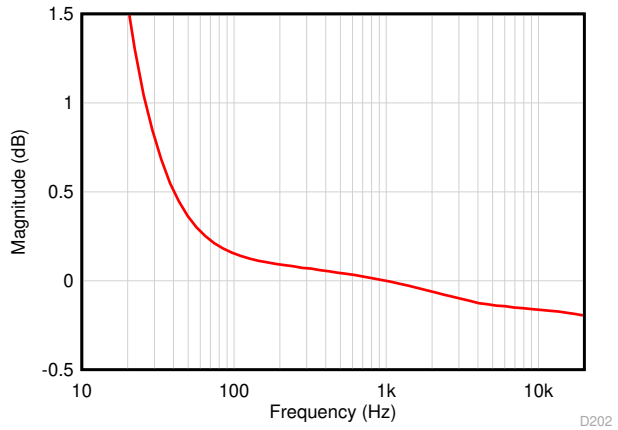

Figure 8-4. Measured Deviation From Ideal RIAA Response

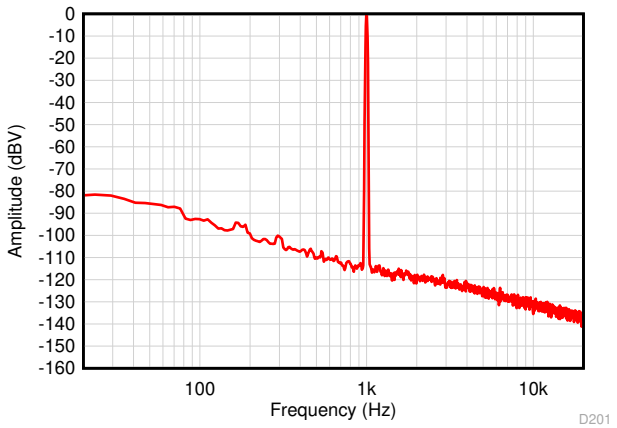

Figure 8-5. Output Spectrum for a 10-mV_{RMS}, 1-kHz Input Signal

8.2.2 Composite Headphone Amplifier

Figure 8-6 shows the BUF634A buffer inside the feedback loop of the OPA165x to increase the available output current for low-impedance headphones. If the BUF634A is used in wide-bandwidth mode, no additional components beyond the feedback resistors are required to maintain loop stability.

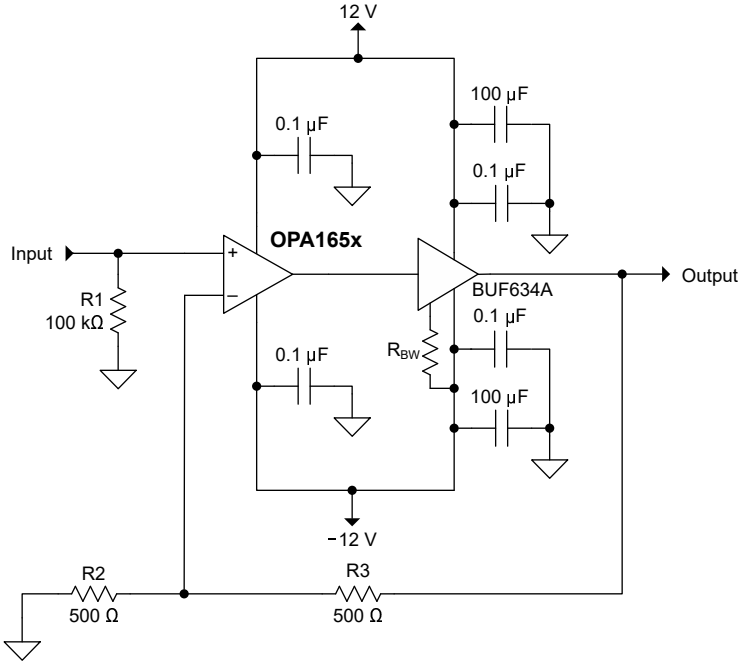

Figure 8-6. Composite Headphone Amplifier (Single-Channel Shown)

8.2.2.1 Application Curves

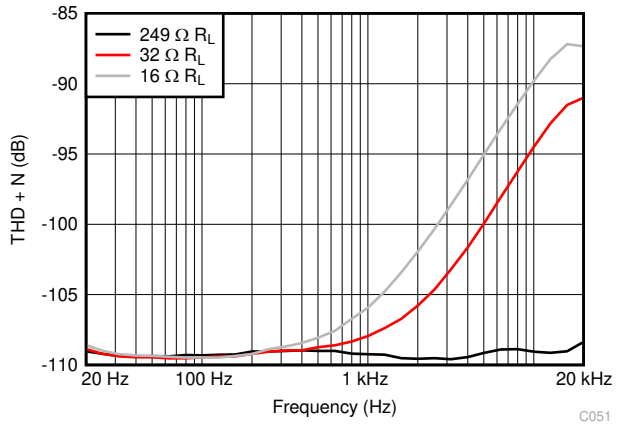

Figure 8-7. THD+N vs Frequency for a 5-V_{PP} (1.77-V_{RMS}) Input Signal

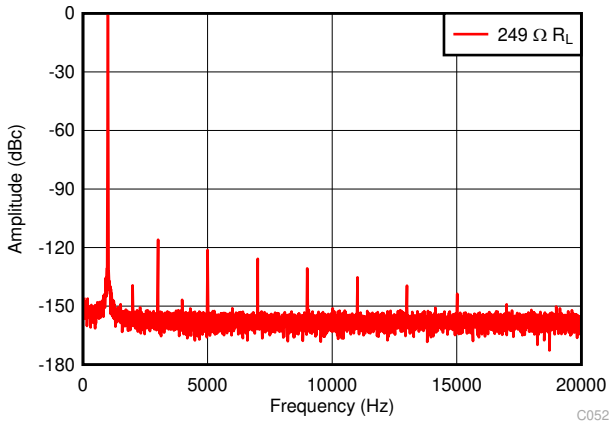

Figure 8-8. FFT for a 5-V_{PP} (1.77-V_{RMS}), 1-kHz Input Signal

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8.2.3 Baxandall Tone Control

Figure 8-9 gives an example of ultra-low noise and THD tone control. This circuit provides 20 dB of gain at the first stage, followed by two separate tone controls for bass and treble. The passive circuit is designed to yield a flat gain response with the potentiometers both set to 50%.

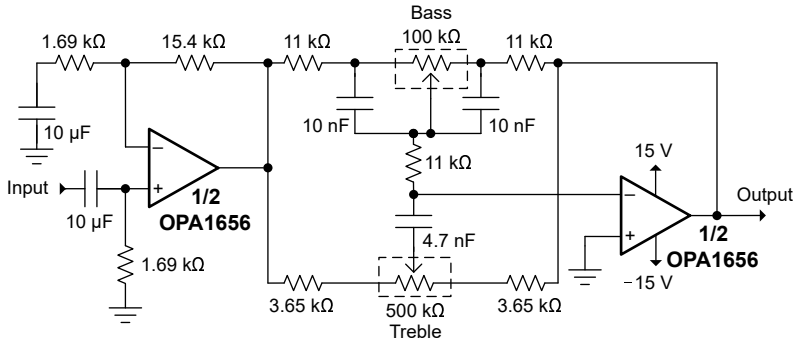

Figure 8-9. Dual Potentiometer Baxandall Tone Control

8.2.3.1 Application Curves

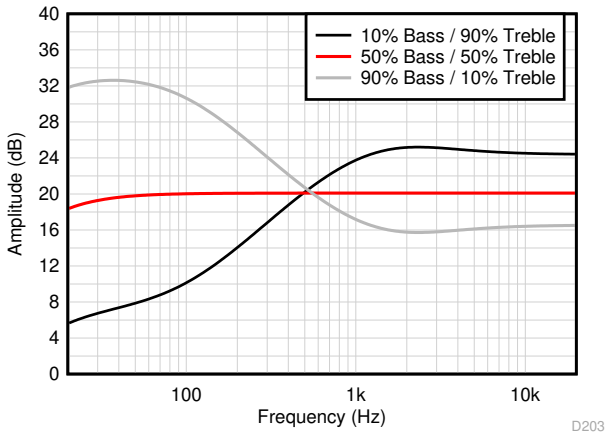

Figure 8-10. Amplitude vs Frequency for Various Tone-Control Settings

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8.2.4 Guitar Input to XLR Output

The OPA165x are an excellent choice for guitar input circuits as a result of the high input impedance and ultra-low noise performance. Figure 8-11 gives an example of a basic guitar input circuit to differential XLR schematic. The logarithmic taper potentiometer shown in this circuit provides 6 dB of gain at 0%, and 40 dB of gain at 100%. The rail-to-rail output swing of the OPA165x allows for a high amplitude swing at the outputs of the differentially configured amplifiers, while maintaining very low distortion performance. A 10-µF dc blocking capacitor is used in the feedback of the noninverting stage to remove any dc offset as a result of the amplifier offset voltage. However, this dc blocking capacitor can be eliminated for applications that are not sensitive to low dc offsets.

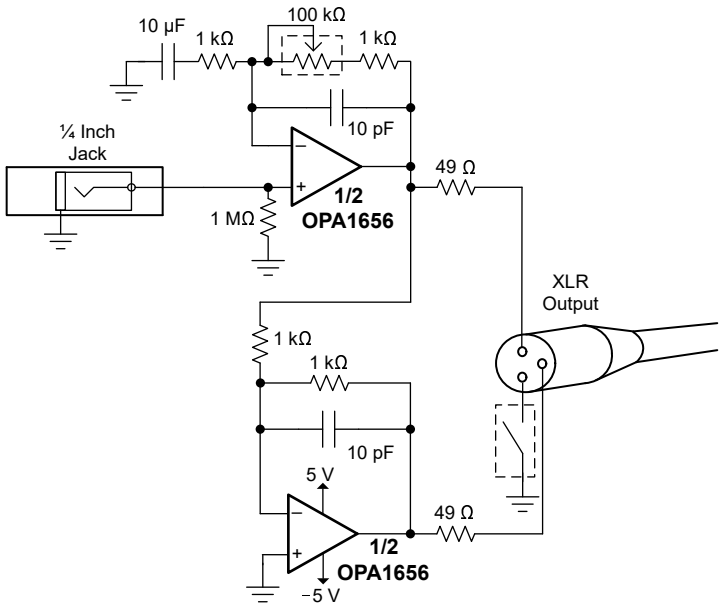

Figure 8-11. Guitar Input to XLR Output Schematic

8.2.4.1 Application Curves

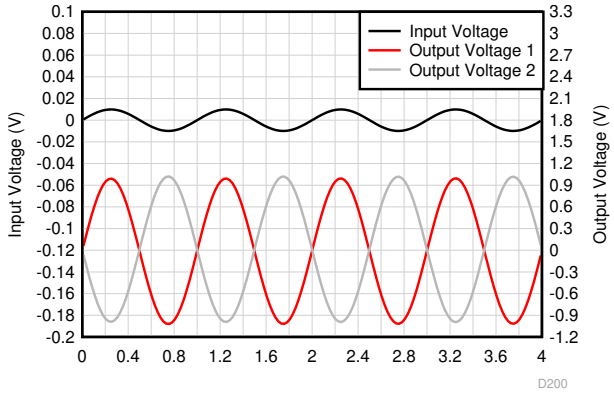

Figure 8-12. 1-kHz Input Signal Transient Simulation

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9 Power Supply Recommendations

The OPA165x are specified for operation from 4.5 V to 36 V (±2.25 V to ±18 V); many specifications apply from –40°C to +125°C. Parameters that can exhibit significant variance with regard to operating voltage or temperature are presented in the *Typical Characteristics* section.

The OPA165x operate with as little as 4.5 V between the supplies and with up to 36 V between the supplies. However, some applications do not require equal positive and negative output voltage swing. With the OPA165x, power-supply voltages are not required to be equal. For example, the positive supply can be set to 25 V with the negative supply at –5 V.

10 Layout

10.1 Layout Guidelines

For best operational performance of the device, use good printed-circuit board (PCB) layout practices, including:

- Noise can propagate into analog circuitry through the power pins of the circuit as a whole and of op amp itself. Bypass capacitors are used to reduce the coupled noise by providing low-impedance power sources local to the analog circuitry.
  - Connect low-ESR, 0.1-µF ceramic bypass capacitors between each supply pin and ground, placed as close to the device as possible. A single bypass capacitor from V+ to ground is applicable for single-supply applications.
- Separate grounding for analog and digital portions of circuitry is one of the simplest and most-effective methods of noise suppression. One or more layers on multilayer PCBs are usually devoted to ground planes. A ground plane helps distribute heat and reduces electromagnetic interference (EMI) noise pickup. Physically separate digital and analog grounds, observing the flow of the ground current.
- To reduce parasitic coupling, run the input traces as far away from the supply or output traces as possible. If these traces cannot be kept separate, crossing the sensitive trace perpendicular is much better as opposed to in parallel with the noisy trace.
- Place the external components as close to the device as possible. As illustrated in Figure 10-1, keeping R_F and R_G close to the inverting input minimizes parasitic capacitance.
- Keep the length of input traces as short as possible. Always remember that the input traces are the most sensitive part of the circuit.
- Consider a driven, low-impedance guard ring around the critical traces. A guard ring can significantly reduce leakage currents from nearby traces that are at different potentials.
- Cleaning the PCB following board assembly is recommended for best performance.
- Any precision integrated circuit can experience performance shifts resulting from moisture ingress into the plastic package. Following any aqueous PCB cleaning process, baking the PCB assembly is recommended to remove moisture introduced into the device packaging during the cleaning process. A low-temperature, post-cleaning bake at 85°C for 30 minutes is sufficient for most circumstances.

10.1.1 Power Dissipation

The OPA165x op amps are capable of driving 600-Ω loads with a power-supply voltage up to ±18 V and full operating temperature range. Internal power dissipation increases when operating at high supply voltages. Copper leadframe construction used in the OPA165x improves heat dissipation compared to conventional materials. Circuit board layout can also help minimize junction temperature rise. Wide copper traces help dissipate the heat by acting as an additional heat sink. Temperature rise can be further minimized by soldering the devices to the circuit board rather than using a socket.

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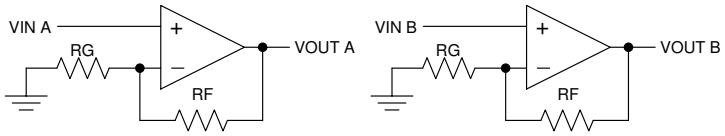
10.2 Layout Example



(Schematic Representation)

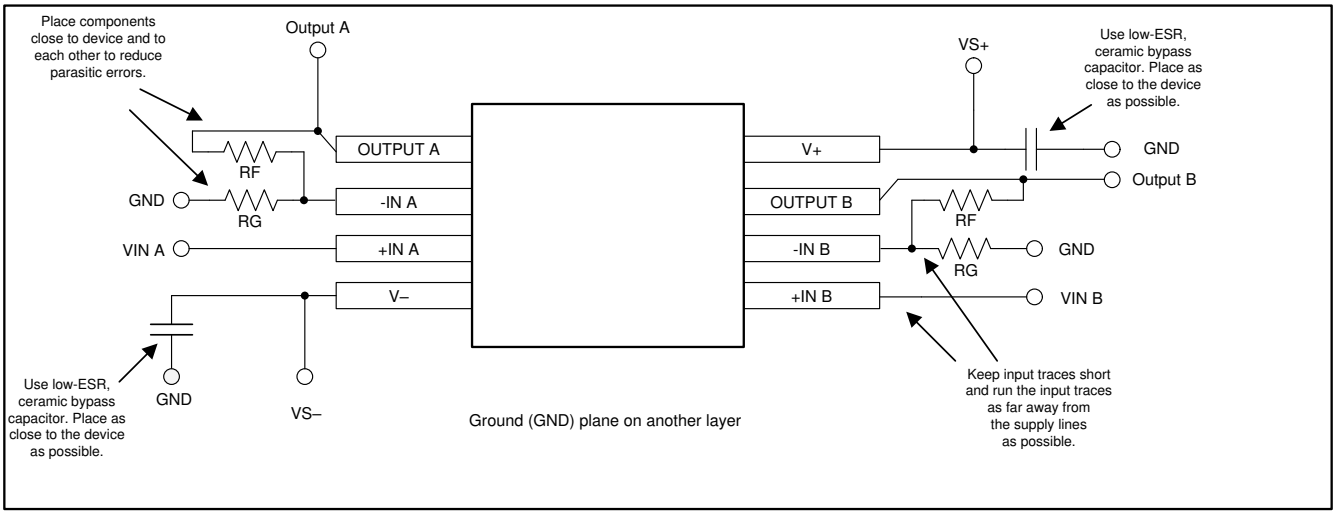


Figure 10-1. Operational Amplifier Board Layout for Noninverting Configuration

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11 Device and Documentation Support

11.1 Device Support

11.1.1 Development Support

11.1.1.1 PSpice® for TI

PSpice® for TI is a design and simulation environment that helps evaluate performance of analog circuits. Create subsystem designs and prototype solutions before committing to layout and fabrication, reducing development cost and time to market.

11.1.1.2 TINA-TI™ Simulation Software (Free Download)

TINA™ is a simple, powerful, and easy-to-use circuit simulation program based on a SPICE engine. TINA-TI™ simulation software is a free, fully-functional version of the TINA software, preloaded with a library of macro models in addition to a range of both passive and active models. TINA-TI simulation software provides all the conventional dc, transient, and frequency domain analysis of SPICE, as well as additional design capabilities.

Available as a free download from the WEBENCH® Design Center, TINA-TI offers extensive post-processing capability that allows users to format results in a variety of ways. Virtual instruments offer the ability to select input waveforms and probe circuit nodes, voltages, and waveforms, creating a dynamic quick-start tool.

Note

These files require that either the TINA software (from DesignSoft™) or TINA-TI software be installed. Download the free TINA-TI software from the TINA-TI folder.

11.1.1.3 DIP Adapter EVM

The DIP Adapter EVM tool provides an easy, low-cost way to prototype small surface mount devices. The evaluation tool these TI packages: D or U (SOIC-8), PW (TSSOP-8), DGK (VSSOP-8), DBV (SOT-23-6, SOT-23-5 and SOT-23-3), DCK (SC70-6 and SC70-5), and DRL (SOT563-6). The DIP Adapter EVM may also be used with terminal strips or may be wired directly to existing circuits.

11.1.1.4 Universal Operational Amplifier EVM

The Universal Op Amp EVM is a series of general-purpose, blank circuit boards that simplify prototyping circuits for a variety of device package types. The evaluation module board design allows many different circuits to be constructed easily and quickly. Five models are offered, with each model intended for a specific package type. PDIP, SOIC, VSSOP, TSSOP and SOT-23 packages are all supported.

Note

These boards are unpopulated, so users must provide their own devices. TI recommends requesting several op amp device samples when ordering the Universal Op Amp EVM.

11.1.1.5 TI Precision Designs

TI Precision Designs are analog solutions created by TI's precision analog applications experts and offer the theory of operation, component selection, simulation, complete PCB schematic and layout, bill of materials, and measured performance of many useful circuits. TI Precision Designs are available online at http://www.ti.com/ww/en/analog/precision-designs/.

11.1.1.6 WEBENCH® Filter Designer

WEBENCH® Filter Designer is a simple, powerful, and easy-to-use active filter design program. The WEBENCH® Filter Designer allows the user to create optimized filter designs using a selection of TI operational amplifiers and passive components from TI's vendor partners.

Available as a web-based tool from the WEBENCH® Design Center, WEBENCH® Filter Designer allows the user to design, optimize, and simulate complete multistage active filter solutions within minutes.

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11.2 Documentation Support

11.2.1 Related Documentation

The following documents are recommended for reference when using the OPA165x, and are available for download at www.ti.com.

- Texas Instruments, *Source Resistance and Noise Considerations in Amplifiers* technical brief
- Texas Instruments, *Single-Supply Operation of Operational Amplifiers* application bulletin
- Texas Instruments, *Op Amp Performance Analysis* application bulletin
- Texas Instruments, *Compensate Transimpedance Amplifiers Intuitively* application report
- Texas Instruments, *Tuning in Amplifiers* application bulletin
- Texas Instruments, *Feedback Plots Define Op Amp AC Performance* application bulletin
- Texas Instruments, *Active Volume Control for Professional Audio* design guide

11.3 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. Click on *Subscribe to updates* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

11.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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11.6 Electrostatic Discharge Caution

This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

11.7 Glossary

TI Glossary — This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

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PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead finish/ Ball material (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
OPA1655DR	ACTIVE	SOIC	D	8	3000	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	OP1655	Samples
OPA1656ID	ACTIVE	SOIC	D	8	75	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	OP1656	Samples
OPA1656IDR	ACTIVE	SOIC	D	8	2500	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	OP1656	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".
RoHS Exempt: TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.
Green: TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) Lead finish/Ball material - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

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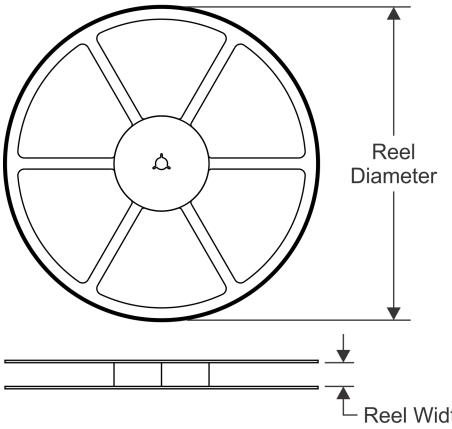
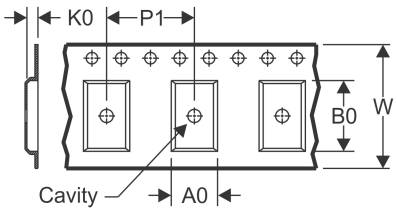
TAPE AND REEL INFORMATION

REEL DIMENSIONS

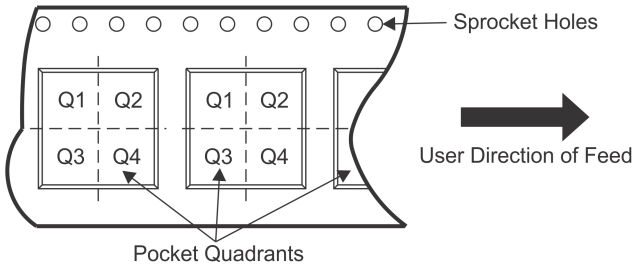


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

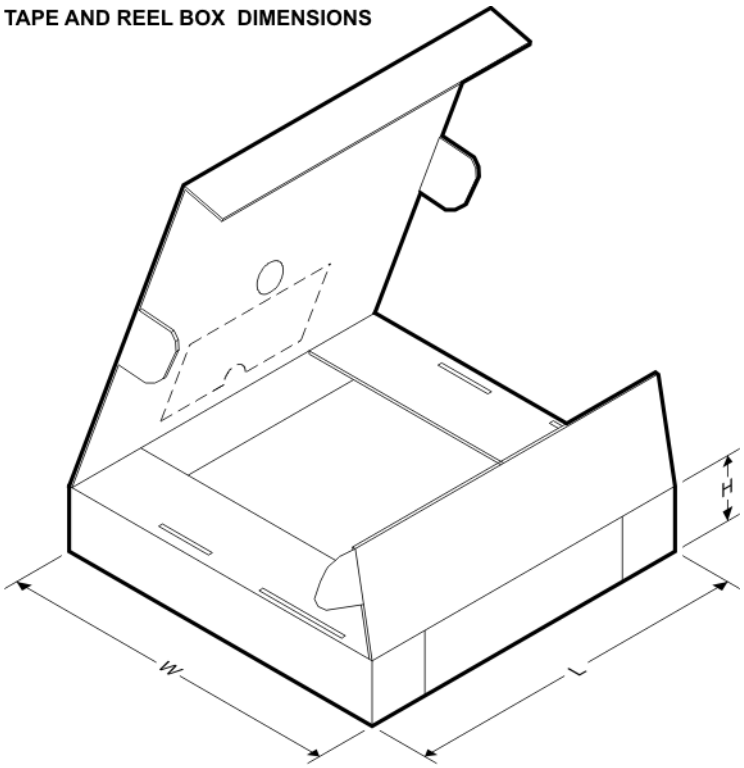
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
OPA1655DR	SOIC	D	8	3000	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
OPA1656IDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1

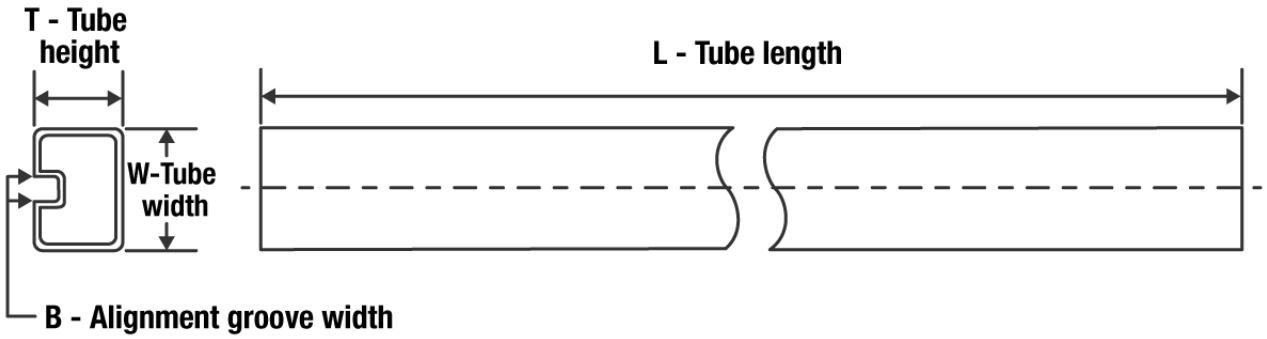
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

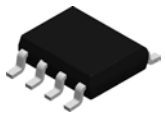
Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
OPA1655DR	SOIC	D	8	3000	853.0	449.0	35.0
OPA1656IDR	SOIC	D	8	2500	853.0	449.0	35.0

TUBE



*All dimensions are nominal

Device	Package Name	Package Type	Pins	SPQ	L (mm)	W (mm)	T (µm)	B (mm)
OPA1656ID	D	SOIC	8	75	506.6	8	3940	4.32

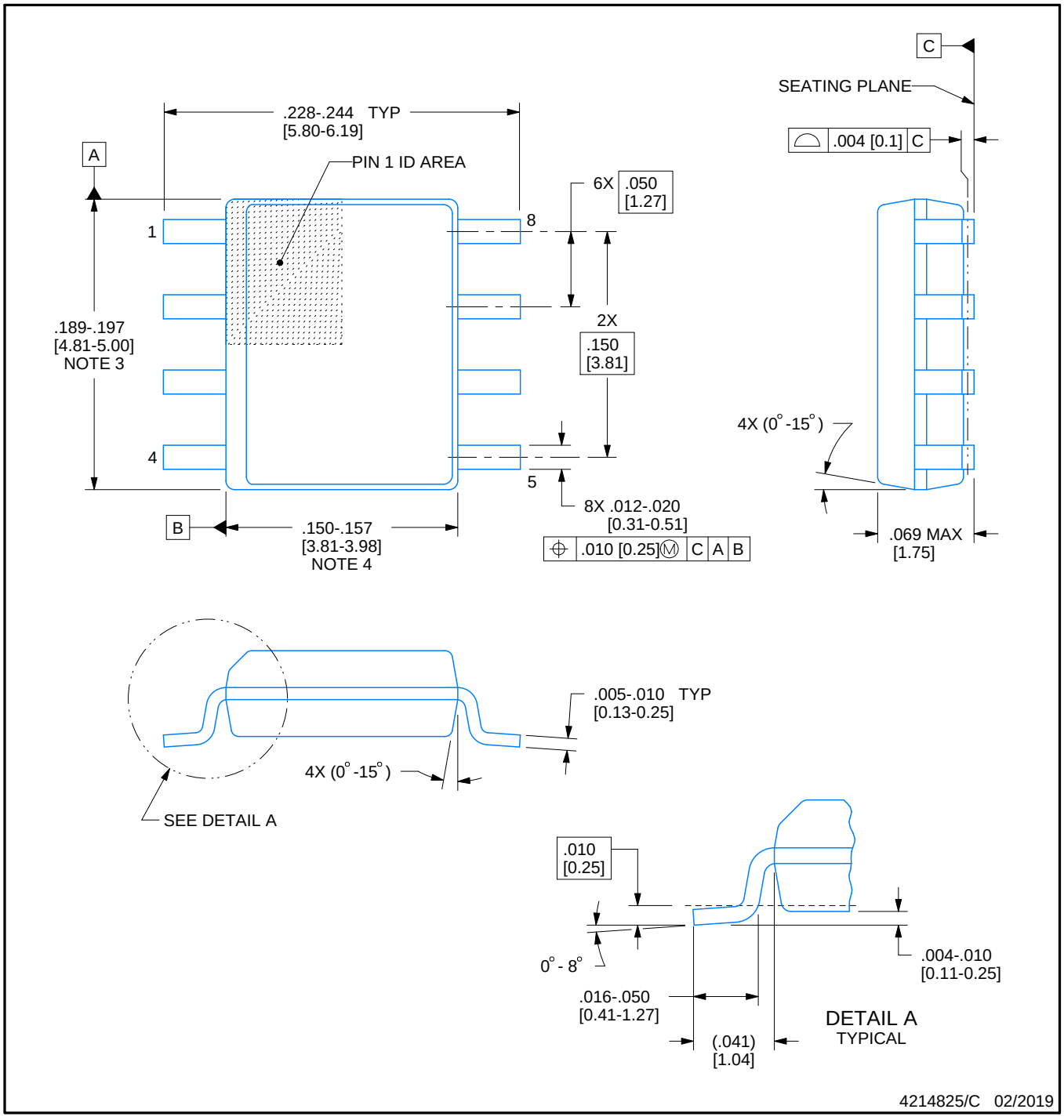


PACKAGE OUTLINE

D0008A

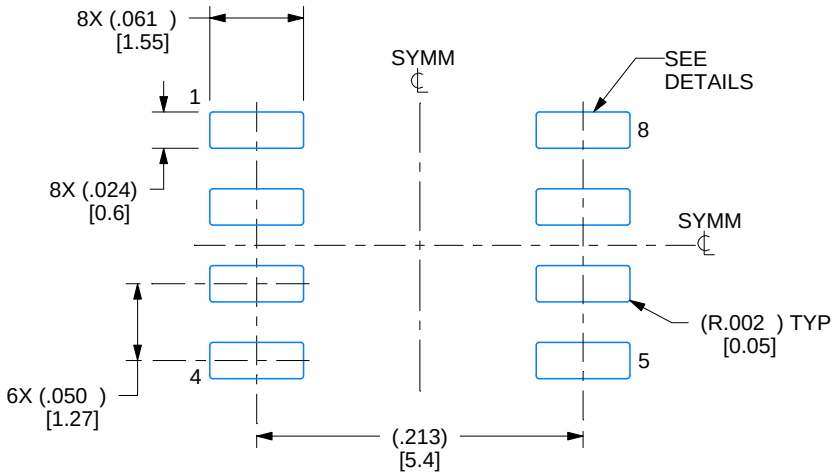
SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT

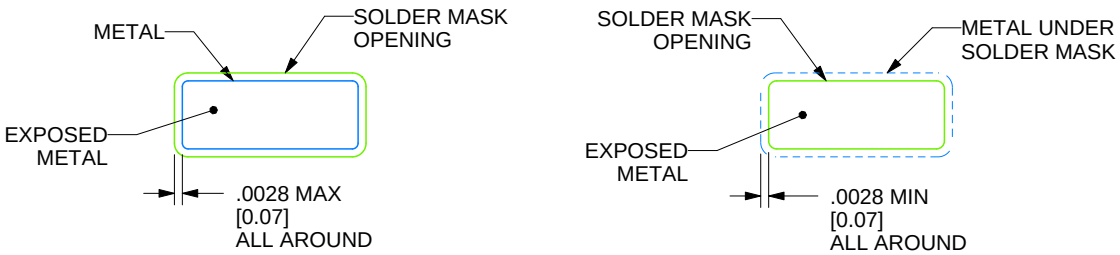


NOTES:

1. Linear dimensions are in inches [millimeters]. Dimensions in parenthesis are for reference only. Controlling dimensions are in inches. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed .006 [0.15] per side.
4. This dimension does not include interlead flash.
5. Reference JEDEC registration MS-012, variation AA.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:8X



SOLDER MASK DETAILS

4214825/C 02/2019

NOTES: (continued)

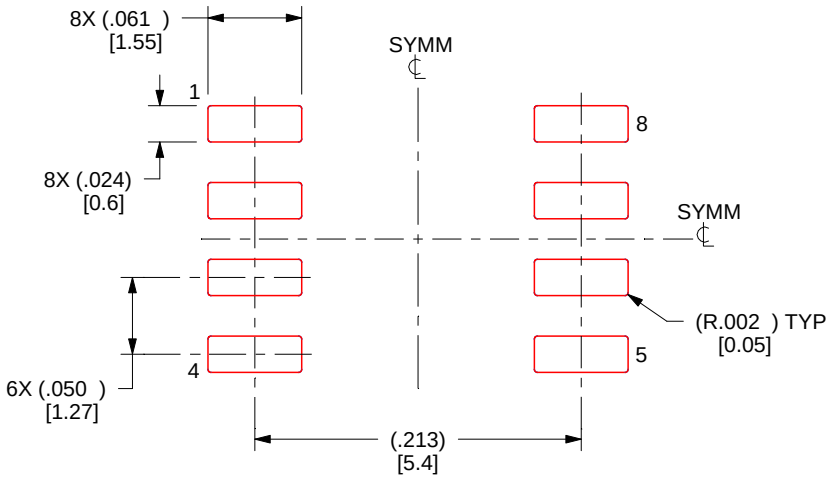
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.

EXAMPLE STENCIL DESIGN

D0008A

SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT



SOLDER PASTE EXAMPLE
BASED ON .005 INCH [0.125 MM] THICK STENCIL
SCALE:8X

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NOTES: (continued)

8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

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