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TI Precision Designs: Reference Design

Op Amp with Single Discrete Bipolar Transistor Output Drive

TEXAS INSTRUMENTS

TI Precision Designs

TI Precision Designs are analog solutions created by TI's analog experts. Reference Designs offer the theory, component selection, and simulation of useful circuits. Circuit modifications that help to meet alternate design goals are also discussed.

Circuit Description

Driving a low resistance load with a precision amplifier is an important requirement for many systems. This function can be achieved with power op amps, but cost may be prohibitive. This precision design shows how to achieve high output drive capability using a precision amplifier and a simple low cost discrete bipolar transistor.

Design Resources

Design Archive	All Design files
TINA-TI™	SPICE Simulator
OPA188	Product Folder
OPA140	Product Folder
OPA827	Product Folder
OPA211	Product Folder

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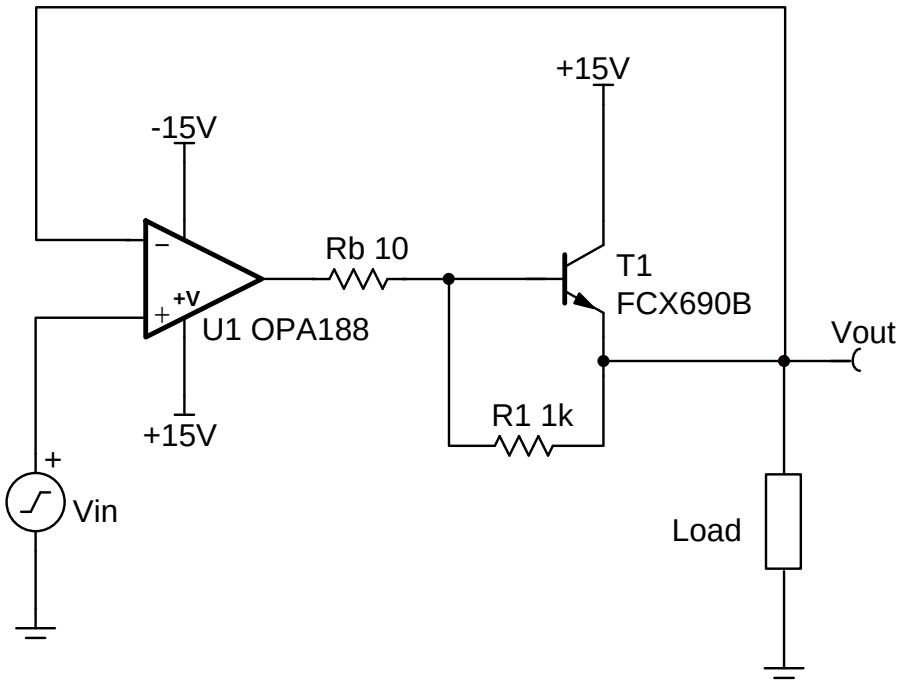

1 Design Summary

The design requirements are as follows:

- Supply Voltage: ±15V
- Input: ±12V
- Output: 0V to +12V, 50Ω load (source only)
- Output: -12V to +12V, 10kΩ (source / sink)
- Ambient Temperature Range: -40C to 65C

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured transfer function of the design.

Table 1. Summary of Simulated and Calculated Performance

	Test Condition	Calculated	Simulated
Max Junction Temperature	Ta = 65C	135.3C	-na-
Total Error	0V<Vin<12V RL = 50Ω	±8.1µV	-5.6 µV
Total Error	0V<Vin<12V RL = 10kΩ	±8.1µV	-5.6 µV
Total Error	-12V<Vin<0V RL = 10kΩ	±8.1µV	-5.6 µV

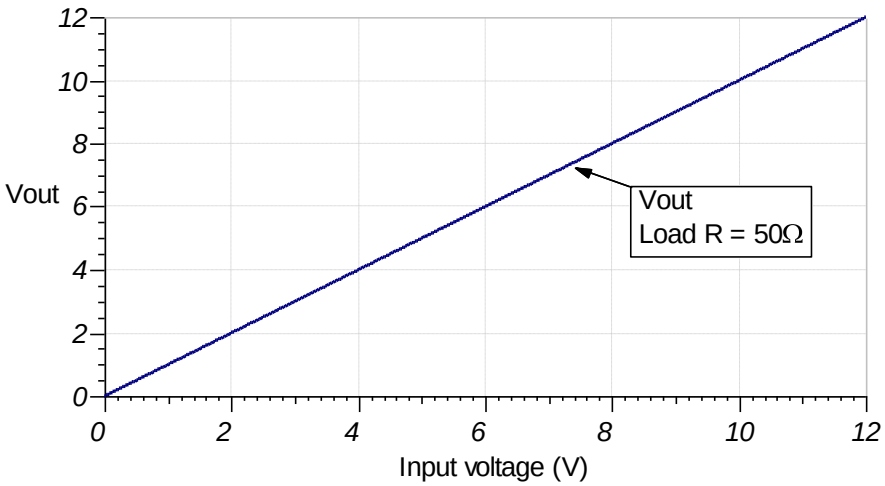

Figure 1: Simulated Transfer Function

2 Theory of Operation

Figure 2 shows the full schematic for the design. The overall circuit acts as a buffer (Gain = 1) with the ability to source large output currents. The transistor T1 increases the output drive from milliamps to hundreds of milliamps. The transistor T1 can source current (about 300mA in this design), but cannot sink current. The amplifier can directly sink small amounts of current through R1. The sinking capability is helpful for absorbing small transients that can occur such as the discharge of a capacitive load. The resistor in series with the base (Rb) provides short circuit protection, and some amplifier output isolation from the transistors parasitic capacitance. Because the transistor T1 is inside the feedback loop, the dc accuracy of this circuit is controlled by the op amp U1.

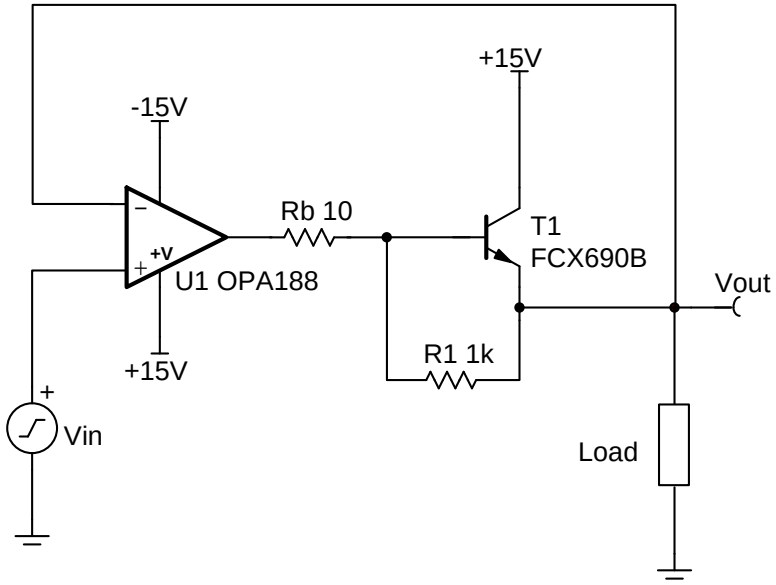

Figure 2: Complete Circuit Schematic

2.1 Selecting the Type of Output Transistor

This precision design uses a NPN bipolar transistor. The bipolar transistor is a low cost, simple approach to increasing the output drive. The bipolar output compliance is limited by the base to emitter turn on voltage (approximately 0.7V) and the saturation voltage (approximately 0.2V). This example uses wide (±15V) supplies so the compliance limitations are not significant relative to the output range. However, if this circuit were adapted for low voltage single supply (i.e. 3V or 5V) the compliance limitations would be more significant.

Most distributor web sites offer a parametric search tool to help select the best transistor for a given application. Sections 2.2 to 2.8 describe the key parameters that can be used in a search tool to select your transistor.

2.2 Selecting the Output Transistor: Transistor Power Maximum Rating

The transistor maximum power rating is a key criterion for selecting a discrete bipolar transistor. The maximum dc power is dissipated in the transistor when the output voltage is one half the power supply voltage (see Figure 3). In this example the maximum power is 1.125W (see Equation (1)), so 2W was used as a search criterion for the transistor.

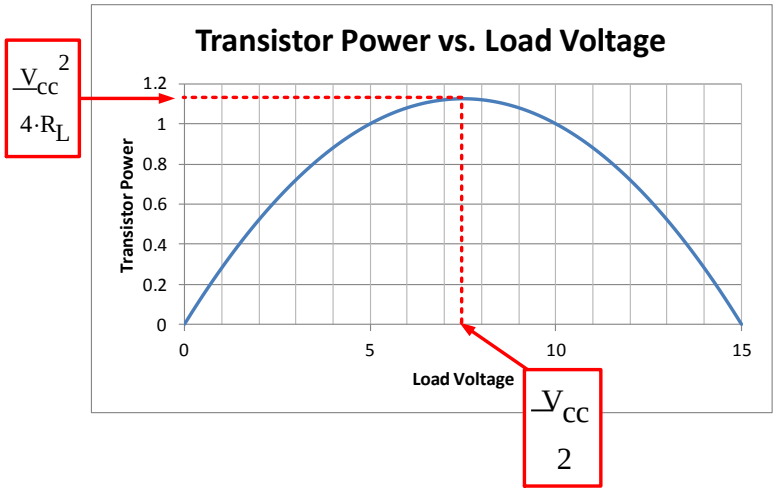

Figure 3: dc Power vs. Output Signal

$$P_{max} = \frac{V_{cc}^2}{4R_L} = \frac{(15V)^2}{4(50\Omega)} = 1.125W \quad (1)$$

2.3 Selecting the Output Transistor: Vce breakdown

The normal expected collector to emitter voltage for this example is Vcc (15V). However, the system uses dual supply, so under a fault condition it may be possible to have both the positive and negative supply across the transistor (i.e. 30V). For this reason Vce breakdown criteria was set to Vce > 40V to provide sufficient design margin.

2.4 Maximum Op Amp Output Current for Linear Response

The op amp has limited output current drive ability. Furthermore, at high currents the op amp will become non-linear. The open loop gain specification and its associated test conditions can be used to determine an op amp output current that assures good linearity. Table 2 is an excerpt from the OPA188 data sheet giving the minimum A_{OL} specification tested under specific load resistance and output swing conditions. Using the data sheet information you can determine an output current that will provide good linearity. Note that good A_{OL} implies good linearity. In this example the amplifier can output 1.5mA (Equation (2)) and still have good linearity (i.e. A_{OL} > 130dB).

Table 2: Open Loop Gain Specification from OPA188 Data Sheet

PARAMETERS	CONDITIONS	OPA188			UNIT
		MIN	TYP	MAX	
AOL Open-loop voltage gain	RL = 10kΩ, (V–) + 0.5 V < V_O < (V+) – 0.5 V	130	136		dB

$$I_{out\_good\_lin} = \frac{V_{cc}}{R_{L-test}} = \frac{15V}{10k\Omega} = 1.5mA \quad (2)$$

Where

$I_{out\_good\_lin}$ = maximum op amp output current for good linearity. Taken from Aol test conditions.

V_{cc} = maximum output voltage

$R_{L\text{-}test}$ = load used for Aol test conditions

2.5 Selecting the Output Transistor: Transistor Current Gain (h_{fe})

The objective of the transistor is to increase the output drive capability of the amplifier. Bipolar transistors amplify the current applied to the base by the current gain h_{fe}. The current gain needs to be large enough to minimize the op amp output current to assure linear operation (op amp output current < Iout_good_lin).

In this example the load current is 0.3A (see Equation (3)). The collector current of the transistor is approximately equal to the load current (see Equation (4)). Equation (5) is the general relationship for current gain. Equation (6) calculates the minimum require current gain to minimize the op amp output drive requirements. Thus, in this example the current gain must be greater than 200 A/A to insure linear operation of the amplifier.

$$I_{load-max} = \frac{V_{cc}}{R_L} = \frac{15V}{50} = 300mA \quad (3)$$

$$I_c \approx I_e \approx I_{load} \quad (4)$$

$$h_{fe} = \frac{I_c}{I_b} \quad (5)$$

$$h_{fe-min} \approx \frac{I_{load-max}}{I_{out\_good\_lin}} = \frac{300mA}{1.5mA} = 200\ A/A \quad (6)$$

2.6 Selecting the Output Transistor: Maximum Junction Temperature

The power dissipated in the transistor will cause self heating. It is important to confirm that the transistor self heating is kept below the maximum junction temperature of the device (150℃). Equation (7) shows how the transistors maximum junction temperature is calculated. The maximum ambient temperature (Ta-max = 65℃) and the transistor maximum power dissipation are determined by the design. The transistor thermal impedance θja depends on the selected transistor and package style. The maximum thermal impedance that will keep the junction temperature below 150℃ can be determined using Equation (8). In this example we must select a device with a thermal impedance less than 75.6℃/W.

$$T_{j-max} = P_{max}\theta_{ja} + T_{a-max} \tag{7}$$

$$\theta_{ja-max} = \frac{T_{j-max} - T_{a-max}}{P_{max}} = \frac{150℃ - 65℃}{1.125W} = 75.6℃/W \tag{8}$$

2.7 Selecting the Output Transistor: Package and Cost

The SOT89 package style was selected because it is widely used, so many drop in replacements are available. Also, the SOT89 is a leaded package making it easy to solder and inspect. Some other power transistor packages are leadless which has size advantages but is less convenient for prototyping.

After considering all other factors, the device cost was used to further refine the selection. In this example, the FCX690 was selected.

2.8 Selecting the Output Transistor: Summary

Table 3 summarizes the goals entered into the parametric search engine and the results for the selected device.

Table 3: Summary of Transistor Selection

Parameter	Goal	FCX690	Reference
P_{max}	>1.125W	2W	Equation (1)
V_{CE} Breakdown	>30V	45V	Section 2.3
h_{fe}	>200 A/A	500 A/A	Equation (6)
θ_{ja}	< 75.6℃/W	62.5℃/W	Equation (8)
Package	Small, Leaded	SOT89	-na-
Cost	Low	0.20	-na-

3 Component Selection

3.1 Op Amp Selection

The OPA188 was used in this example because it has excellent dc performance (i.e. offset, offset drift, CMRR, PSRR). This design is optimized for driving an accurate dc signal on a low resistance load.

3.2 Passive Component Selection

The resistor (Rb and R1) tolerance does not affect accuracy because transistor buffer is inside feedback loop. R1 is selected based on the sinking requirement for the design (Isink = VR1 / R1 = 0.7V / 1kΩ = 0.7mA).

4 Simulation

The TINA-TI™ schematic shown in Figure 4 includes the circuit values obtained in the design process.

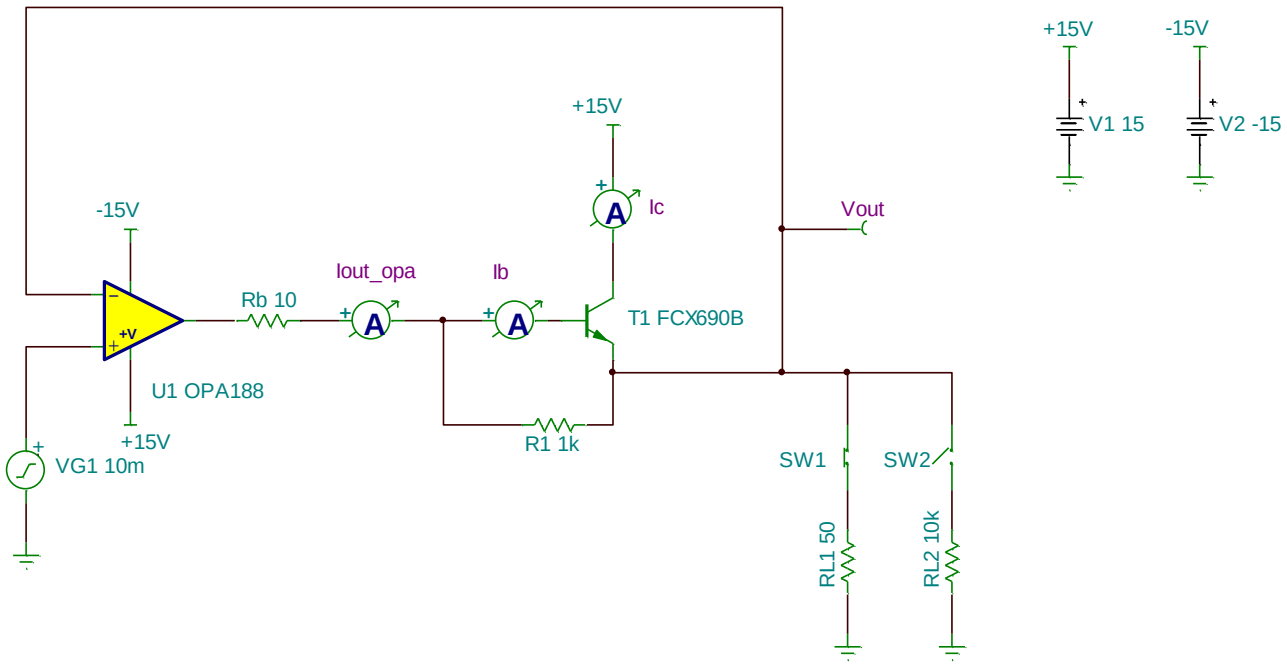

Figure 4: TINA-TI™ Schematic

4.1 Transfer Function

The result of the dc transfer function is shown in Figure 5 and Figure 6.

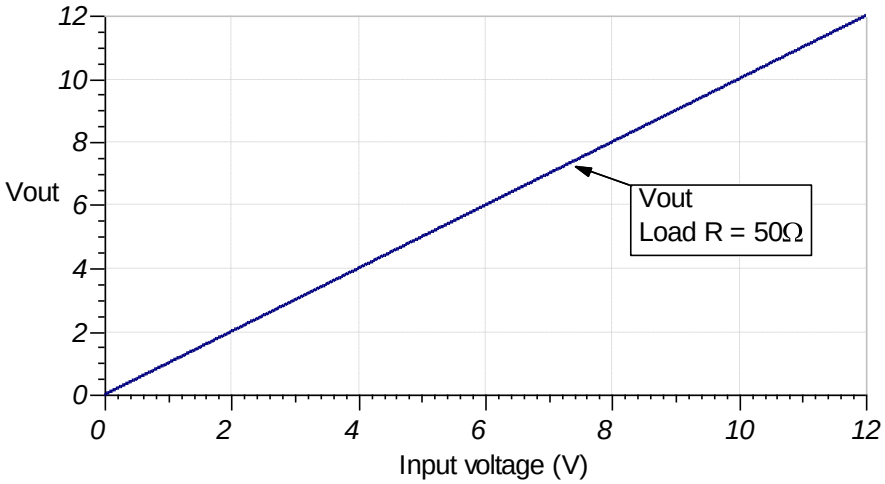

Figure 5: Transfer Function for 0V < Vin < 12V, RL = 50Ω (Source Only)

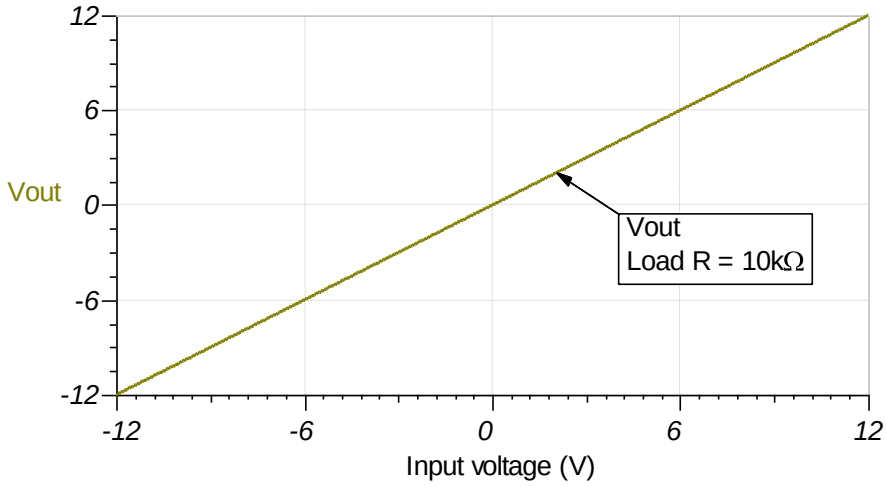

Figure 6: Transfer Function for -12V < Vin < 12V, RL = 10kΩ

4.2 Small Step Response and Stability

Figure 7 shows the circuit response to a small signal step. The response is well behaved and shows no overshoot which indicates that the circuit is stable. This simulation was performed with a 50Ω load. The 10kΩ load test also confirms stability.

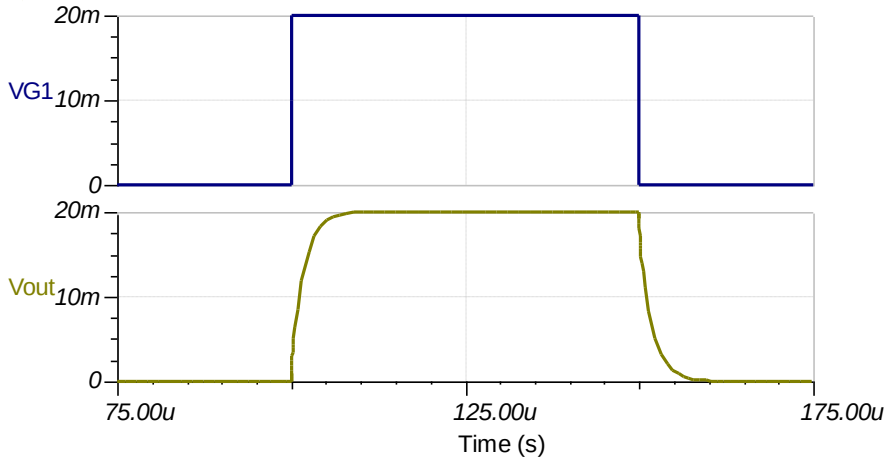

Figure 7: Small Signal Step Response (RL = 50Ω)

4.3 Large Step Response

Figure 8 shows the large signal step response. This simulation was performed with a 50Ω load. The rise time of the output signal is set by the amplifiers slew rate. The output transistor does not limit slew rate or bandwidth.

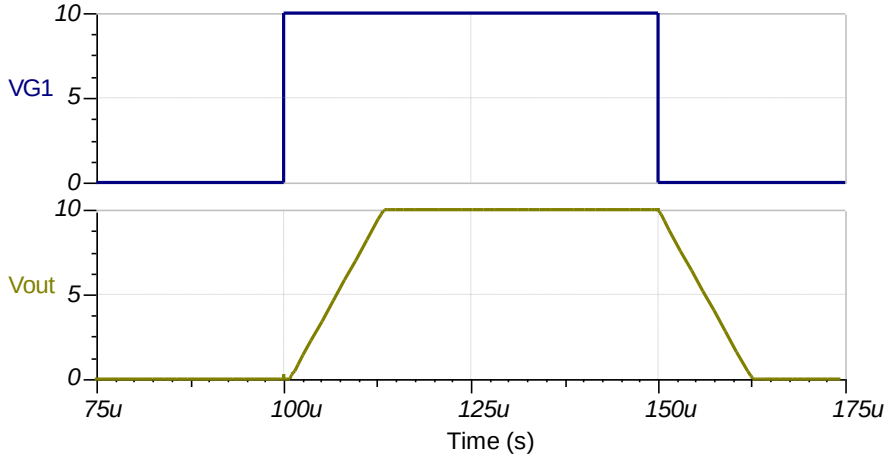

Figure 8: Large Signal Step Response (RL = 50Ω)

4.4 Amplifier Output Current

Figure 9 provides detail on the current flow in this his circuit. It is important to verify that the op amp does not need to provide current greater than the maximum linear output current derived in Section2.4. Note that some of the op amp output current is drawn directly by the load through R1. The remainder of the op amp current is drawn through the base of T1. The maximum amplifier output current from the simulation is about 1mA which is less than the limit from Section 2.4 ($I_{out\_good\_lin}$ = 1.5mA).

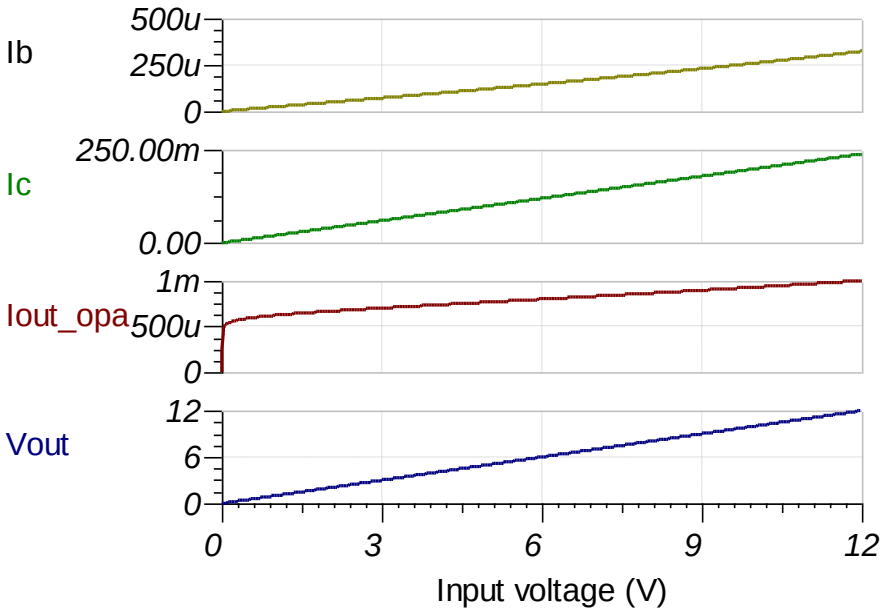

Figure 9: Analysis of Current Flow is Transistor Buffer Circuit

4.5 Simulated Results Summary

Table 4 summarizes the simulated and calculated performance of the design. The total error can be determined by using cursors on the dc transfer functions, or from hand calculations. The hand calculation results compare well to simulated results. The total error is from the op amp dc errors (i.e. Vos, CMRR). The total error can also be calculated from the typical data sheet values for Vos and CMRR (see Equation (8)(9) and (10)). The transistor has a voltage gain of 1V/V and is kept inside the amplifiers feedback loop. Thus, the transistor does not introduce any significant error.

$$V_{os-cmr} = \frac{V_{cm-range}}{10^{\frac{CMRR}{20}}} = \frac{12V}{10^{\frac{134dB}{20}}} = 2.1\mu V \tag{9}$$

$$V_{total-offset} = V_{os-cmr} + V_{os} = 2.1\mu V + 6\mu V = 8.1\mu V \tag{10}$$

Equation (11) shows the calculation for maximum junction temperature given the maximum power and ambient temperature.

$$T_{j-max} = P_{max}\theta_{ja} + T_{a-max} = (1.125W)(62.5℃/W) + 65℃ = 135.3℃ \tag{11}$$

Table 4. Comparison of Design Goals, Simulation, and Measured Performance

	Test Condition	Calculated	Simulated
Max Junction Temperature	Ta = 65C	135.3C	-na-
Total Error	0V<Vin<12V RL = 50Ω	±8.1µV	-5.6 µV
Total Error	0V<Vin<12V RL = 10kΩ	±8.1µV	-5.6 µV
Total Error	-12V<Vin<0V RL = 10kΩ	±8.1µV	-5.6 µV

5 Modifications

The method described in this TI Precision Design can be used for a wide range of different wide supply amplifiers. This method could also be used for low voltage single supply amplifiers, but compliance voltage may limit the usefulness for these applications. Table 5 provides examples of different amplifiers that can be used to achieve different design objectives.

Table 5. Brief Comparison of ±15V Supply Amplifiers

Output Amplifier	Design Objective	Vos uV	Vos Drift uV/degC	Iq uA	Voltage Noise nV/√Hz	GBW MHz	SR V/uS	Approx. Price US$ / 1ku
OPA188	DC Precision, Low Noise, Low Iq	6	0.03	450	8.8	2	0.8	0.8
OPA140	Wide Band, Low Noise, DC Precision	30	0.35	1800	8	11	20	1.55
OPA827	Wide Band, Low Noise, DC Precision	75	0.1	4800	4	22	28	3.75
OPA211	Wide Band, Low Noise, DC Precision	30	0.35	3600	1.1	80	27	3.45

6 About the Author

Arthur Kay is an applications engineering manager at TI where he specializes in the support of amplifiers, references, and mixed signal devices. Arthur focuses a good deal on industrial applications such as bridge sensor signal conditioning. Arthur has published a book and an article series on amplifier noise. Arthur received his MSEE from Georgia Institute of Technology, and BSEE from Cleveland State University.

7 Acknowledgements & References

7.1 Acknowledgements

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