VIII. Lab 8: Operational Amplifiers II

A. Introduction

In this lab, we will study the input offset of several op-amps, build an integrator circuit and explore how it works, and use a low-voltage, low-power RRIO op-amp to build a photodiode amplifier circuit.

B. Procedure

1. Op-amp input offset

As a reminder, Figure VIII-1 shows the pin-outs for the LF411 op-amp.

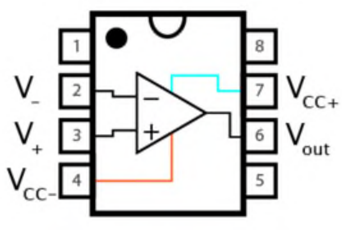


Figure VIII-1. Pin-outs for the LF411 op-amp

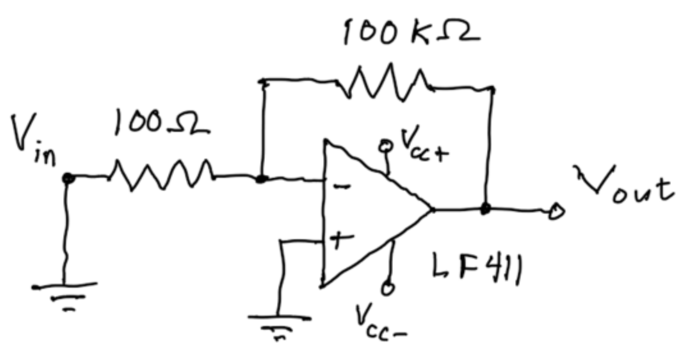


Figure VIII-2. Circuit to measure the input offset voltage of an op-amp.

Build the circuit shown in Figure VIII-2. Use $V_{CC\pm} = \pm 15\text{ V}.$ Since this is an inverting amplifier with a closed-loop gain of $G = -1000$, we expect the output voltage to be $V_{out} = -1000V_{in} = 0$, since $V_{in} = 0.$ Measure V_{out} with a digital multimeter. What voltage do you find?

You should have found that the output voltage is *not* zero. The reason for this is that op-amps have an *input offset voltage*, denoted as V_{OS} (sometimes also denoted as V_{IO}). This is due to the fact that the op-amp has a differential input stage, and it behaves in an ideal way only if the two sides of the input stage are precisely identical. In practice they're slightly different and this causes the circuit to have the input offset. The equivalent circuit for the real op-amp including this effect is shown in Figure VIII-3.

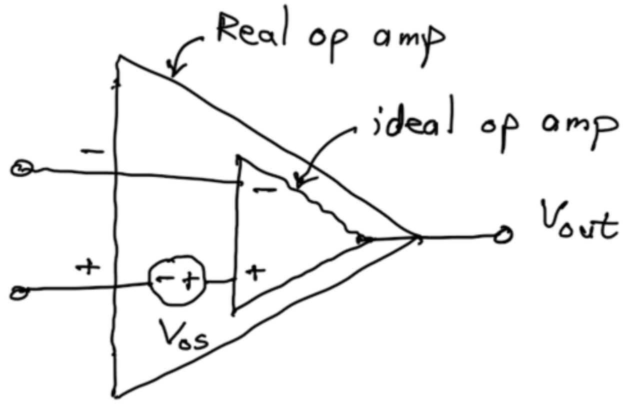


Figure VIII-3. Equivalent circuit for a real op-amp with input offset voltage.

It's possible to show that in the circuit of Figure VIII-2, the voltage output with the real op-amp is $V_{out} = GV_{OS}$.[2] Thus, you can use your measured value of V_{out} to determine V_{OS}.

Try it with two other LF411 op-amps. (Remember it is good practice when changing a circuit to turn the power off, make the changes, and then turn the power back on. Also watch out that you put the replacement op-amp in the same way as the first one.) Are the input offset voltages the same, or different?

Try the measurement with three other op-amps: an LM741, an OPA227, and an LTC1150. The pin-outs for the plus/minus inputs, output, and power leads are the same on these op-amps, and they will also all operate with ± 15 V supply, so you can just substitute each op-amp into the same place in the circuit without rewiring anything. Again, it is best to turn the power off when making changes to a circuit, and please make sure that each op-amp is positioned correctly.

Op Amp	Price, ea. Digikey Qnty. of 10	Type	Operating Supply Voltage Range (V)	Voltage Output Range Low, High	Short-circuit Output Current (mA)	Input Offset Voltage, Typical	Input Offset drift, Typical	Input bias current	Slew rate (V/μs)	Gain-BW Product (MHz)	Input Voltage Noise @ 1 kHz (nV/$\sqrt{\text{Hz}}$)
LM741	$0.74	BJT	±10 to ±22	V- +3 V+ -3	25	1 mV	15 μV/°C	80 nA	0.5	1	40
LF411	$1.39	JFET	±3.5 to ±18	±13.5 (Vs = ±15)	25	0.8 mV	10 μV/°C	50 pA	13	3	18
OPA227	$4.18	BJT	±2.5 to ±18	V- + 2 to V+ -2	45	5 μV	0.7 μV/°C 0.2 μV/month	2.5 nA	2.3	8	3
LTC1150	$8.62	CMOS	4.75 to 32	V- to V+ - 2	130	0.5 μV,	0.01 μV/°C 50 nV/$\sqrt{\text{month}}$	10 pA	3	2.5	80, but no 1/f noise

Table VIII-1. Properties of some of the op-amps in the lab.

[2] To be precise, there is another effect that can cause an error in the output voltage, which is the effect of the *input bias current*. However this is usually quite a bit smaller than the effect of input offset voltage, especially with the small value of the 100 Ω input resistor. The bias current can be important in precision circuits with higher values of input resistance.

Some of the key specifications for these op-amps is shown in Table VIII-1. The LM741 is the first widely successful op-amp, and still used as a bipolar transistor “jelly bean” op amp. The LF411 is a “jelly beam op-amp with JFET inputs. The biggest difference between the LF411 and the LM741 is that the input bias current is that LF411 bias current is about 1,000 times smaller than that of the LM741 due to its JFET inputs. It is also faster and quieter than the LM741. The OPA 227 is a precision bipolar transistor op-amp. It has much lower input offset voltage than the first two and also has much lower noise than any of the other op-amps in the table. Finally, the LTC1150 is a “zero-drift chopper” CMOS op-amp. It includes additional internal circuit to measure the input offset voltage and feedback a correction signal to eliminate the offset. This feature does give some downsides for general purpose applications, but this op-amp excels at applications requiring measurements of very small DC voltages due to its extremely low offset and drift.

For the LF411 and LM741 op-amp, it’s possible to adjust the offset to zero using the circuit shown in Figure VIII-4. Input offset nulling for the LM741 and LF411 op-amp. The OPA227 also includes offset nulling but with a slightly different circuit. We won’t have you try the offset nulling in this lab right now, but if you have time at the end of the lab please try it and see how it works.

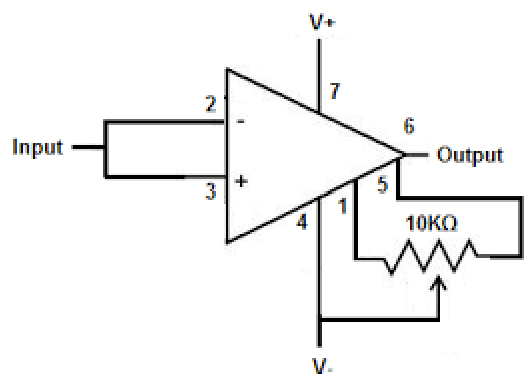


Figure VIII-4. Input offset nulling for the LM741 and LF411 op-amp.

Since the offset of an op-amp can either be very low or nulled, the offset drift is often the more important specification. This gives the change of the op-amp offset with temperature. Since the temperature will vary in a way that cannot be predicted, this contribution to the offset can’t easily be nulled out and will limit the performance of the op-amp.

Whether the input offset is important will of course depend on the size of the offset and the sensitivity of the application to the offset. Milli-volt level offsets might not be important for a circuit processing volt-level signals. However it may be very important in a circuit that is required to process millivolt-level DC signals.

For your report: provide a table of the input offset voltages that you measured for each op-amp, and comment on whether the values obtained agree with what is on the op-amp specification sheet. If you find values that don’t agree, comment on why that might have occurred. Hint: see this document: https://www.analog.com/media/en/training-seminars/tutorials/MT-037.pdf, and take note of the comment on thermoelectric potentials.

2. Op-Amp Integrator

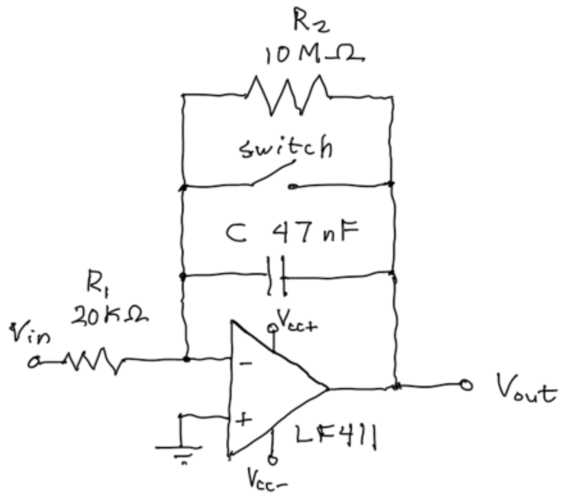


Figure VIII-5. Op amp damped integrator circuit.

Build the circuit shown in Figure VIII-5. This is a *damped integrator* circuit. For the switch, use one of the SPDT switches at the bottom of your protoboard. You may need to test how it works with an Ohm-meter, just to make sure you can open and close the connection between the two wires and that you know which switch position is open and which is closed. For now, leave the switch open. Drive your circuit with a 1 Volt amplitude square wave with zero offset and a frequency of about 100 Hz, and monitor both V_{in} and V_{out} with an oscilloscope.

When you first turn the circuit on, you may find that V_{out} is sitting at the positive or negative voltage rail. (To see whether this is so, set the vertical sensitivity for V_{out} to 5 V/div.) If so, that is happening because this circuit has a gain of 500 for DC voltages, so it only takes an offset of about 30 mV in your square wave input to send the output voltage to one of the rails. To correct this problem, engage the offset feature of the function generator and adjust it so that the average level of the signal drops to something in the ballpark of a volt or less.

For your report: show the display of V_{in} and V_{out} for this circuit for all three types of input waveform: Square, triangle, and sinusoidal. Compare each result to the output voltage waveform expected with the resistor R_2 left out, *i.e.* $V_{out}(t) \approx V_{out}(0) - \int_0^t \frac{V_{in}(t')}{R_1 C} dt'$. Repeat for a frequency near 1 kHz.

Next, return to a square wave input with about 100 Hz frequency, and remove resistor R_2 from the circuit.

For your report: Does your circuit behave differently with R_2 removed? If so, how is it different? What is the purpose of R_2 in this circuit?

Next, set the function generator to produce a square wave with a voltage amplitude of about 0.1 Volt and a frequency of about 10 kHz. Leave resistor R2 out. At this point the integrator will be responding more to the offset than to the square wave. Adjust the offset so that the output voltage is not too far from zero and is moving slowly but visibly.

For your report: describe what happens now when you close the switch. Why does this happen?

Integrators are sometimes used with switches like this so that integrations can be started from zero volts to integrate some specific pulsed waveform at some specific starting time. An FET is sometimes used for the switch. In this case R_2 is not necessary.

For your report: In lab 2 you built the passive component version of this integrator. What are the differences between the op-amp and passive versions of the integrator in terms of the conditions for the circuit to accurately integrate the input voltage? Also in lab 2 we noted that the circuit for an integrator is the same as the circuit for a low-pass filter. The same is true here. In this lab, we've used the circuit shown in Figure VIII-5 in a regime where it is best considered as an integrator. Under what conditions would it be better to consider the circuit as a low-pass filter?

3. Battery-operated photodiode circuit.

a) Low power, low-voltage, rail-to-rail op-amps.

The advantage of the ± supply voltages that are standard for many op-amps is that we can naturally accommodate both positive and negative input voltages. However in some applications we have a input single that is always positive. In this case it would desirable to operate the op-amp with the negative supply at ground and the positive supply at $+V_S$ since that would allow us to use one power supply rather than two. However this won't work well for most op-amps since they cannot accept an input that is closer than about 1 Volt to the negative supply.

Single-supply op amps are designed to work with a single supply, *i.e.* with their negative supply voltage at ground. In order to accommodate small input signals near ground, their common-mode input voltage range extends to the negative supply. Also, the output voltage swing can reach the negative supply voltage or very close to it.

Rail-to-rail (RR) op-amps go even further, with a voltage range that extends from the negative to the positive supply. This capability can exist only for the input voltage (RRI op-amp), to the output voltage only (RRO op-amp), or to both (RRIO op-amp). Rail-to-rail op-amps are useful not only for single supply operation, but for operation with low single supply voltages such as 5 Volts. That is because with such a low supply voltage, you don't want to lose a volt or two in your voltage range to a limited voltage swing of the input or output. Finally, there are special *low-power RRIO* op-amps, which are not only RRIO but also consume very low power. These are especially suited to battery-power operation.

Of course, nothing comes for free, and compromises in other areas of op-amp performance must be made in order to realize the low-power RRIO features. There is nice discussion of these compromises in Horowitz and Hill if you're interested.

In this lab, we have one low supply voltage, low-power RRIO op-amp, the MCP602. Some of the specifications for this op-amp are appended to the end of this chapter.

One important thing to notice about the MCP602 is that it *must* be operated with a low voltage between the positive and negative supply. The allowed supply voltage range is 2.7 V to 6.0 V. If you put it into one of your circuits with a $\pm 15\ \mathrm{V}$ supply (30 volt difference), you will probably burn it out.

The MCP602 is a *dual* op-amp. That means you get two op-amps in the same package, even though the package is a DIP8 like the others you've used. For this reason the pin-out is different, as shown in Figure VIII-6. Since the 8 pins are all used up for positive and negative supply, inputs, and outputs, there are no pins on the op-amp for offset compensation.

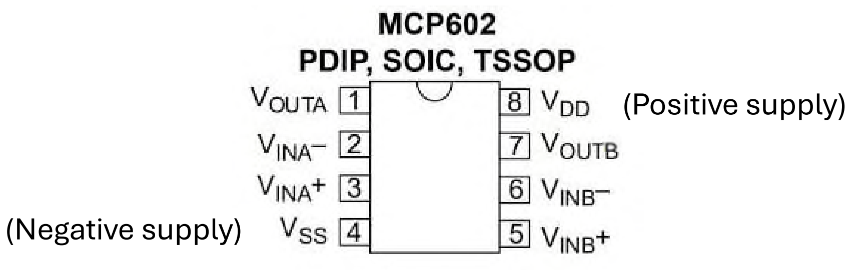


Figure VIII-6. Pin-out of the MCP602

b) <u>Battery-powered photodiode amplifier</u>

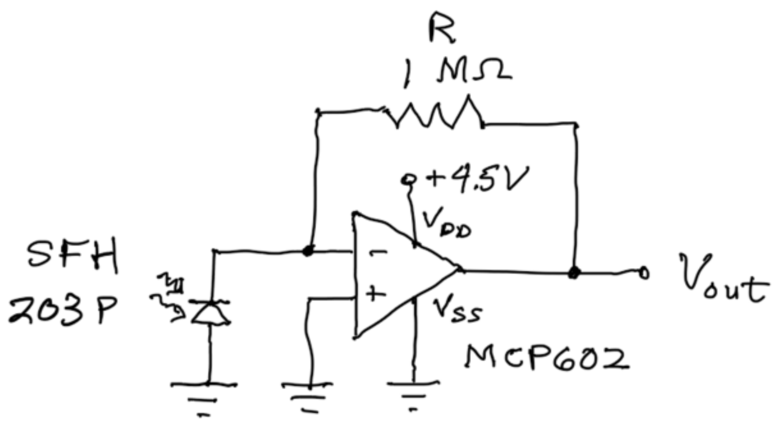


Figure VIII-7. Battery-power photodiode amplifier

Build the circuit shown in Figure VIII-7. Use one of the individual breadboards for your circuit instead of the large Global Specialities protoboard. For your power supply, use one of the 3X AAA battery packs that we have, which will supply about 4.5 V. The SFH203P is a silicon photodiode with a sensitive area about 1 mm in size. As with most diodes, the shorter leg is the cathode and the longer leg is the anode.

Turn your circuit on, and monitor V_{out} on the oscilloscope. The reason to monitor it on an oscilloscope rather than a multimeter is that it's possible your circuit will oscillate, due to the fact that the photodiode presents a capacitive impedance to the input. The circuit should output a voltage that is proportional to the light intensity hitting the photodiode. Check to see if the voltage is close to zero with something covering up the diode, and if it climbs with increasing light exposure. You can use your cell phone flashlight as a light source for this.

If your circuit output oscillates, this can be prevented by putting a capacitor in parallel with the resistor *R*. This is explained in this document from Texas Instruments (TI): https://www.ti.com/lit/ug/tidu535/tidu535.pdf?ts=1760627955880

Try different capacitors to see if you can get it to stop. If you need to, refer to the TI document for more help with this.

It could be that the voltage saturates at the negative supply (ground in our case) and does not start climbing until the light level is somewhat substantial. If this happens, bias the positive input of your amplifier as discussed in the TI document linked above.

For your report: Show stable output traces from the oscilloscope for (i) light blocked from the photodiode, (ii) room light only, and (iii) two or three different higher light intensities produced by illuminating the photodiode with your cell-phone flashlight.

This type of amplifier is referred to as a *transimpedance amplifier.* This means it converts and input current to an output voltage. In this case the input current is the photocurrent from the photodiode. What is the gain or your amplifier (output volts per input amp)? The typical conversion from light power to photodiode current is about 0.5 A/W. Using this information and the minimum signal level you could make out on the oscilloscope, what is the minimum light power you could detect with your photodiode and circuit? What is the light power hitting the photodiode for the largest signal that you saw?

C. MCP602 Specifications

Here I reproduce only the first three pages of the spec sheet. For additional information see the full specification sheet that is easily available online.

MICROCHIP

MCP601/1R/2/3/4

2.7V to 6.0V Single Supply CMOS Op Amps

Features

- Single-Supply: 2.7V to 6.0V
- Rail-to-Rail Output
- Input Range Includes Ground
- Gain Bandwidth Product: 2.8 MHz (typical)
- Unity-Gain Stable
- Low Quiescent Current: 230 µA/amplifier (typical)
- Chip Select ($\overline{CS}$): **MCP603 only**
- Temperature Ranges:
  - Industrial: -40°C to +85°C
  - Extended: -40°C to +125°C
- AEC-Q100 Qualified. See **Product Identification System (Automotive)**.

Typical Applications

- Portable Equipment
- A/D Converter Driver
- Photo Diode Pre-amp
- Analog Filters
- Data Acquisition
- Notebooks and PDAs
- Sensor Interface

Design Aids

- SPICE Macro Models
- FilterLab® Software
- Mindi™ Simulation Tool
- MAPS (Microchip Advanced Part Selector)
- Analog Demonstration and Evaluation Boards
- Application Notes

General Description

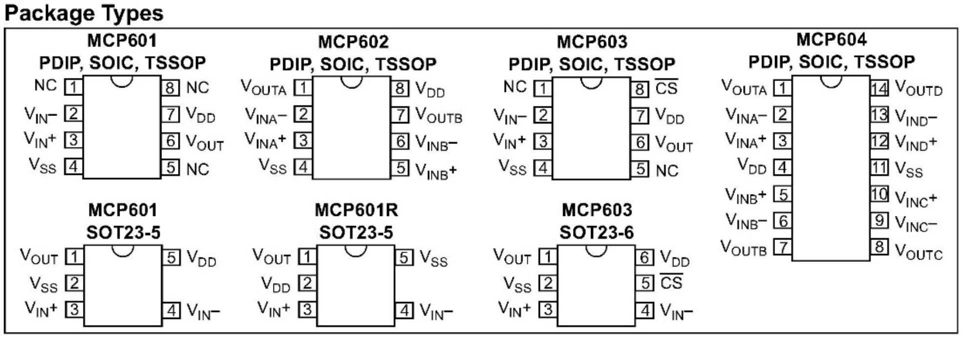
The Microchip Technology Inc. MCP601/1R/2/3/4 family of low-power operational amplifiers (op amps) are offered in single (MCP601), single with Chip Select ($\overline{CS}$) (MCP603), dual (MCP602), and quad (MCP604) configurations. These op amps utilize an advanced CMOS technology that provides low bias current, high-speed operation, high open-loop gain, and rail-to-rail output swing. This product offering operates with a single supply voltage that can be as low as 2.7V, while drawing 230 µA (typical) of quiescent current per amplifier. In addition, the common mode input voltage range goes 0.3V below ground, making these amplifiers ideal for single-supply operation.

These devices are appropriate for low power, battery operated circuits due to the low quiescent current, for A/D convert driver amplifiers because of their wide bandwidth or for anti-aliasing filters by virtue of their low input bias current.

The MCP601, MCP602, and MCP603 are available in standard 8-lead PDIP, SOIC, and TSSOP packages. The MCP601 and MCP601R are also available in a standard 5-lead SOT-23 package, while the MCP603 is available in a standard 6-lead SOT-23 package. The MCP604 is offered in standard 14-lead PDIP, SOIC, and TSSOP packages.

The MCP601/1R/2/3/4 family is available in the Industrial and Extended temperature ranges and has a power supply range of 2.7V to 6.0V.

Package Types



 DS20001314H

1.0 ELECTRICAL CHARACTERISTICS

1.1 Absolute Maximum Ratings†

$V_{DD} - V_{SS}$ 7.0V
Current at Input Pins .... ±2 mA
Analog Inputs ($V_{IN}+$, $V_{IN}-$) .... V_{SS} – 1.0V to V_{DD} + 1.0V
All Other Inputs and Outputs .... V_{SS} – 0.3V to V_{DD} + 0.3V
Difference Input Voltage .... $|V_{DD} - V_{SS}|$
Output Short Circuit Current .... Continuous
Current at Output and Supply Pins .... ±30 mA
Storage Temperature .... –65°C to +150°C
Maximum Junction Temperature (T_J) .... +150°C
ESD Protection On All Pins (HBM; MM) .... ≥ 3 kV; 200V

† **Notice:** Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the operational listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability.

1.2 Electrical Specifications

DC ELECTRICAL SPECIFICATIONS

Electrical Specifications: Unless otherwise specified, T_A = +25°C, V_{DD} = +2.7V to +5.5V, V_{SS} = GND, V_{CM} = $V_{DD}/2$, $V_{OUT} \approx V_{DD}/2$, $V_L = V_{DD}/2$, and R_L = 100 kΩ to V_L, and $\overline{CS}$ is tied low. (Refer to Figure 1-2 and Figure 1-3).

Parameters	Sym	Min	Typ	Max	Units	Conditions
Input Offset						
Input Offset Voltage	V_{OS}	-2	±0.7	+2	mV	
Industrial Temperature	V_{OS}	-3	±1	+3	mV	T_A = -40°C to +85°C (**Note 1**)
Extended Temperature	V_{OS}	-4.5	±1	+4.5	mV	T_A = -40°C to +125°C (**Note 1**)
Input Offset Temperature Drift	$\Delta V_{OS}/\Delta T_A$	—	±2.5	—	µV/°C	T_A = -40°C to +125°C
Power Supply Rejection	PSRR	80	88	—	dB	V_{DD} = 2.7V to 5.5V
Input Current and Impedance						
Input Bias Current	I_B	—	1	—	pA	
Industrial Temperature	I_B	—	20	60	pA	T_A = +85°C (**Note 1**)
Extended Temperature	I_B	—	450	5000	pA	T_A = +125°C (**Note 1**)
Input Offset Current	I_{OS}	—	±1	—	pA	
Common Mode Input Impedance	Z_{CM}	—	10^{13}||6	—	Ω||pF	
Differential Input Impedance	Z_{DIFF}	—	10^{13}||3	—	Ω||pF	
Common Mode						
Common Mode Input Range	V_{CMR}	V_{SS} – 0.3	—	V_{DD} – 1.2	V	
Common Mode Rejection Ratio	CMRR	75	90	—	dB	V_{DD} = 5.0V, V_{CM} = -0.3V to 3.8V
Open-loop Gain						
DC Open-loop Gain (large signal)	A_{OL}	100	115	—	dB	R_L = 25 kΩ to V_L, V_{OUT} = 0.1V to V_{DD} – 0.1V
	A_{OL}	95	110	—	dB	R_L = 5 kΩ to V_L, V_{OUT} = 0.1V to V_{DD} – 0.1V
Output						
Maximum Output Voltage Swing	V_{OL}, V_{OH}	V_{SS} + 15	—	V_{DD} – 20	mV	R_L = 25 kΩ to V_L, Output overdrive = 0.5V
	V_{OL}, V_{OH}	V_{SS} + 45	—	V_{DD} – 60	mV	R_L = 5 kΩ to V_L, Output overdrive = 0.5V

Note 1: These specifications are not tested in either the SOT-23 or TSSOP packages with date codes older than YYWW = 0408. In these cases, the minimum and maximum values are by design and characterization only.

2: All parts with date codes November 2007 and later have been screened to ensure operation at V_{DD}=6.0V. However, the other minimum and maximum specifications are measured at 2.7V and/or 5.5V.

DC ELECTRICAL SPECIFICATIONS (CONTINUED)

Electrical Specifications: Unless otherwise specified, T_A = +25°C, V_{DD} = +2.7V to +5.5V, V_{SS} = GND, V_{CM} = $V_{DD}/2$, $V_{OUT} \approx V_{DD}/2$, $V_L = V_{DD}/2$, and R_L = 100 kΩ to V_L, and $\overline{CS}$ is tied low. (Refer to Figure 1-2 and Figure 1-3).

Parameters	Sym	Min	Typ	Max	Units	Conditions
Linear Output Voltage Swing	V_{OUT}	V_{SS} + 100	—	V_{DD} – 100	mV	R_L = 25 kΩ to V_L, A_{OL} ≥ 100 dB
	V_{OUT}	V_{SS} + 100	—	V_{DD} – 100	mV	R_L = 5 kΩ to V_L, A_{OL} ≥ 95 dB
Output Short Circuit Current	I_{SC}	—	±22	—	mA	V_{DD} = 5.5V
	I_{SC}	—	±12	—	mA	V_{DD} = 2.7V
Power Supply						
Supply Voltage	V_{DD}	2.7	—	6.0	V	(Note 2)
Quiescent Current per Amplifier	I_Q	—	230	325	µA	I_O = 0

Note 1: These specifications are not tested in either the SOT-23 or TSSOP packages with date codes older than YYWW = 0408. In these cases, the minimum and maximum values are by design and characterization only.

2: All parts with date codes November 2007 and later have been screened to ensure operation at V_{DD}=6.0V. However, the other minimum and maximum specifications are measured at 2.7V and/or 5.5V.

AC CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, T_A = +25°C, V_{DD} = +2.7V to +5.5V, V_{SS} = GND, V_{CM} = $V_{DD}/2$, $V_{OUT} \approx V_{DD}/2$, $V_L = V_{DD}/2$, and R_L = 100 kΩ to V_L, C_L = 50 pF, and $\overline{CS}$ is tied low. (Refer to Figure 1-2 and Figure 1-3).

Parameters	Sym	Min	Typ	Max	Units	Conditions
Frequency Response						
Gain Bandwidth Product	GBWP	—	2.8	—	MHz	
Phase Margin	PM	—	50	—	°	G = +1 V/V
Step Response						
Slew Rate	SR	—	2.3	—	V/µs	G = +1 V/V
Settling Time (0.01%)	t_{settle}	—	4.5	—	µs	G = +1 V/V, 3.8V step
Noise						
Input Noise Voltage	E_{ni}	—	7	—	μV_{P-P}	f = 0.1 Hz to 10 Hz
Input Noise Voltage Density	e_{ni}	—	29	—	nV/√Hz	f = 1 kHz
	e_{ni}	—	21	—	nV/√Hz	f = 10 kHz
Input Noise Current Density	i_{ni}	—	0.6	—	fA/√Hz	f = 1 kHz