# LMC2001 High Precision, 6MHz Rail-To-Rail Output Operational Amplifier

**Check for Samples: LMC2001**

## FEATURES

- **($V_s$ = 5V, $R_L$ = 10K to $V^+$ /2, Typ. Unless Noted)**
- **Low Specified $V_{os}$ 40µV**
- **$e_n$ with No 1/f 85nV/$\sqrt{Hz}$**
- **High CMRR 120dB**
- **High PSRR 120dB**
- **High $A_{VOL}$ 137dB**
- **Wide Gain-Bandwidth Product 6MHz**
- **High Slew Rate 5V/µs**
- **Low Supply Current 750µA**
- **Rail-To-Rail Output 30mV from Either Rail**
- **No External Capacitors Required**

## APPLICATIONS

- **Precision Instrumentation Amplifiers**
- **Thermocouple Amplifiers**
- **Strain Gauge Bridge Amplifier**

## DESCRIPTION

The LMC2001 is a new precision amplifier that offers unprecedented accuracy and stability at an affordable price and is offered in miniature (SOT23-5) package. This device utilizes patented techniques to measure and continually correct the input offset error voltage. The result is an amplifier which is ultra stable over time, and temperature. It has excellent CMRR and PSRR ratings, and does not exhibit the familiar 1/f voltage and current noise increase that plagues traditional amplifiers. The combination of the LMC2001 characteristics makes it a good choice for transducer amplifiers, high gain configurations, ADC buffer amplifiers, DAC I-V conversion, and any other 5V application requiring precision and/or stability.

Other useful benefits of the LMC2001 are rail-to-rail output, low supply current of 750µA, and wide gain-bandwidth product of 6MHz. The LMC2001 comes in 5 pin SOT23 and 8 pin SOIC. These extremely versatile features found in the LMC2001 provide high performance and ease of use.

## Connection Diagrams

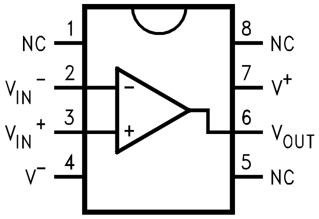

**Figure 1. 8-Pin SOIC (Top View)**

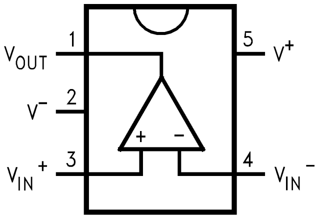

**Figure 2. 5-Pin SOT23 (Top View)**

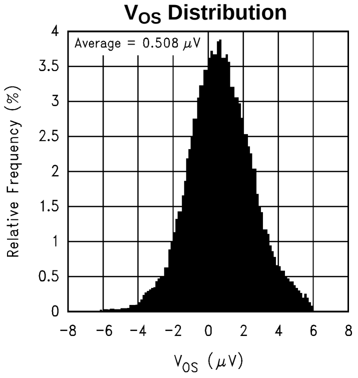
**$V_{OS}$ Distribution**

**Figure 3.**

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

## ABSOLUTE MAXIMUM RATINGS[1][2]

| | | |
|---|---|---|
| ESD Tolerance[3] | Human Body Model | 2000V |
| | Machine Model | 100V |
| Differential Input Voltage | | ± Supply Voltage |
| Supply Voltage ($V^+$ - $V^-$) | | 5.6V |
| Current At Input Pin | | 30mA |
| Current At Output Pin | | 30mA |
| Current At Power Supply Pin[4] | | 50mA |
| Lead Temperature (soldering, 10 sec) | | 260°C |
| Storage Temperature Range | | -65°C to 150°C |
| Junction Temperature ($T_J$)[5] | | 150°C |

(1) Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not ensured. For ensured specifications and test conditions, see the ELECTRICAL CHARACTERISTICS.
(2) If Military/Aerospace specified devices are required, please contact the Texas Instruments Sales Office/ Distributors for availability and specifications.
(3) Human body model, 1.5kΩ in series with 100pF. Machine model, 200Ω in series with 100pF.
(4) Output currents in excess of ±30mA over long term may adversely affect reliability.
(5) The maximum power dissipation is a function of $T_{J(max)}$, $\theta_{JA}$, and $T_A$. The maximum allowable power dissipation at any ambient temperature is $P_D = (T_{J(max)} - T_A)/\theta_{JA}$. All numbers apply for packages soldered directly onto a PC board.

## OPERATING RATINGS[1]

| | | |
|---|---|---|
| Supply voltage | | 4.75V to 5.25V |
| Temperature Range | LMC2001AI | $-40°C \le T_J \le 85°C$ |
| | LMC2001AC | $0°C \le T_J \le 70°C$ |
| Thermal resistance ( $\theta_{JA}$) | D Package, 8-pin Surface Mount | 180°C /W |
| | M5 Package, SOT23-5 | 274°C /W |

(1) Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not ensured. For ensured specifications and test conditions, see the ELECTRICAL CHARACTERISTICS.

## DC ELECTRICAL CHARACTERISTICS

Unless otherwise specified, all limits ensured for $T_J = 25°C$, $V^+ = 5V$, $V^- = 0V$, $V_{CM} = 2.5V$, $V_O = 2.5V$ and $R_L > 1M\Omega$. **Boldface** limits apply at the temperature extremes.

| Symbol | Parameter | Conditions | Typ[1] | Limit[2] | Units |
|---|---|---|---|---|---|
| $V_{OS}$ | Input Offset Voltage | See[3] | 0.5 | 40<br>**60** | μV<br>max |
| | Offset Calibration Time | | 5 | 30 | ms |
| $TCV_{OS}$ | Input Offset Voltage | See[4] | 0.015 | | μV/°C |
| | Long-Term Offset Drift | See[5] | 0.006 | | μV/month |
| | Lifetime $V_{OS}$ drift | See[5] | 2.5 | 5 | μV Max |
| $I_{IN}$ | Input Current | See[6] | -3 | | pA |
| $I_{OS}$ | Input Offset Current | | 6 | | pA |
| $R_{IND}$ | Input Differential Resistance | | 9 | | MΩ |

(1) Typical values represent the most likely parametric norm.
(2) All limits are specified by testing or statistical analysis, unless otherwise noted.
(3) The limits are set by the accuracy of high speed automatic test equipment. For the typical $V_{OS}$ distribution, see the curve (Figure 4).
(4) Precision bench measurement of more than 300 units. More than 65% of units had less than 15nV /°C $V_{OS}$ drift.
(5) Ensured Vos Drift is based on 280 devices operated for 1000 hrs at 150°C (equivalent to 30 years @ 55ºC).
(6) Specified by design only.

## DC ELECTRICAL CHARACTERISTICS (continued)

Unless otherwise specified, all limits ensured for $T_J$ = 25°C, $V^+$ = 5V, $V^-$= 0V, $V_{CM}$ = 2.5V, $V_O$ = 2.5V and $R_L$ > 1MΩ. **Boldface** limits apply at the temperature extremes.

| Symbol | Parameter | Conditions | Typ(1) | Limit(2) | Units |
|---|---|---|---|---|---|
| CMRR | Common Mode Rejection Ratio | $0V \le V_{CM} \le 3.5V$ | 120 | 100 | dB<br>min |
| | | $0.1V \le V_{CM} \le 3.5V$ | **110** | **90** | dB<br>min |
| PSRR | Power Supply Rejection Ratio | $4.75V \le V^+ \le 5.25V$ | 120 | 95<br>**90** | dB<br>min |
| $A_{VOL}$ | Large Signal Voltage Gain(7) | $R_L$ = 10kΩ | 137 | 105<br>**100** | dB<br>min |
| | | $R_L$ = 2kΩ | 128 | 95<br>**90** | |
| $V_O$ | Output Swing | $R_L$ = 10kΩ to 2.5V<br>$V_{IN}$(diff) = ±0.5V | 4.975 | 4.955<br>**4.955** | V<br>min |
| | | | 0.030 | 0.060<br>**0.060** | V<br>max |
| | | $R_L$ = 2kΩ to 2.5V<br>$V_{IN}$(diff) = ±0.5V | 4.936 | | V |
| | | | 0.075 | | V |
| $I_O$ | Output Current | Sourcing, $V_O$ = 0V<br>$V_{IN}$(diff) = ±0.5V | 5.9 | 4.1<br>**1.5** | mA<br>min |
| | | Sinking, $V_O$ = 5V<br>$V_{IN}$(diff) = ±0.5V | 14.5 | 4.5<br>**1.5** | mA<br>min |
| $I_S$ | Supply Current | | 0.75 | 1.0<br>**1.2** | mA<br>max |

(7) $V^+$ = 5V, $V_{CM}$ = 2.5V, and $R_L$ connected to 2.5V. For Sourcing tests, $2.5V \le V_O \le 4.8V$. For Sinking tests, $0.2V \le V_O \le 2.5V$.

## AC ELECTRICAL CHARACTERISTICS

$T_J$ = 25°C, $V^+$ = 5V, $V^-$= 0V, $V_{CM}$ = 2.5V, $V_O$ = 2.5V, and $R_L$ > 1MΩ.

| Symbol | Parameter | Conditions | | Typ(1) | Units |
|---|---|---|---|---|---|
| SR | Slew Rate | $A_V$ = +1, $V_{IN}$ = 3.5Vpp | | 5 | V/µs |
| GBW | Gain-Bandwidth Product | | | 6 | MHz |
| $\theta_m$ | Phase Margin | | | 75 | Deg |
| $G_m$ | Gain Margin | | | 12 | dB |
| $e_n$ | Input-Referred Voltage Noise | f = 0.1Hz | | 85 | nV/ √Hz |
| $e_n$p-p | Input-Referred Voltage Noise | $R_S$ = 100Ω, DC to 10Hz | | 1.6 | µVpp |
| $i_n$ | Input-Referred Current Noise | f = 0.1Hz | | 180 | fA/ √Hz |
| THD | Total Harmonic Distortion | f = 1kHz, Av = -2<br>$R_L$ = 10kΩ,$V_O$ = 4.5Vpp | | 0.02 | % |
| trec | Input Overload Recovery Time | | | 50 | ms |
| $T_S$ | Output Settling time | See(2)<br>$A_V$ = +1, 1V step | 1% | 250 | ns |
| | | | 0.1% | 400 | |
| | | | 0.01% | 3200 | |
| | | See(2)<br>$A_V$ = −1, 1V step | 1% | 80 | |
| | | | 0.1% | 860 | |
| | | | 0.01% | 1400 | |

(1) Typical values represent the most likely parametric norm.

(2) Settling times shown correspond to the worse case (positive or negative step) and does not include slew time. See the Application Note section for test schematic.

## TYPICAL PERFORMANCE CHARACTERISTICS

$T_A$=25C, $V_S$= 5V unless otherwise specified.

**$V_{OS}$ Distribution**

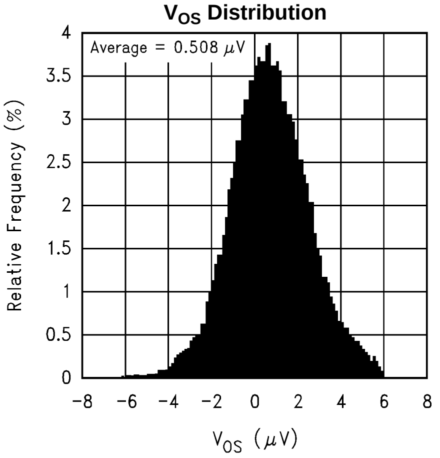

**Figure 4.**

**$V_{OS}$ vs. $V_S$**

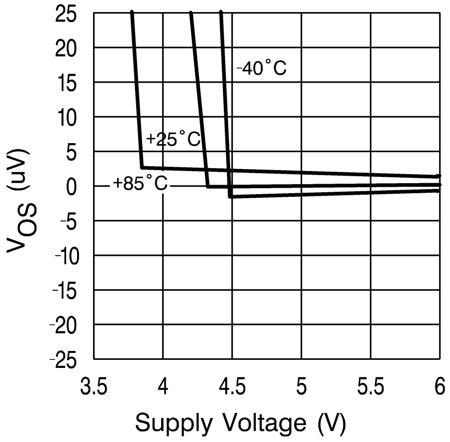

**Figure 5.**

**$V_{OS}$ vs. $V_{CM}$**

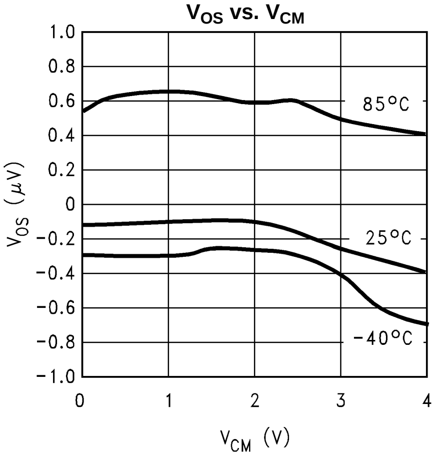

**Figure 6.**

**$+I_{IN}$ vs. $V_{CM}$**

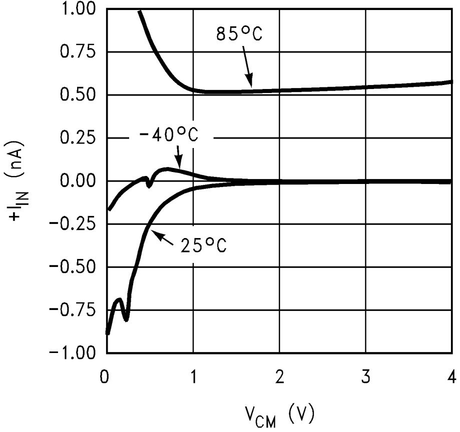

**Figure 7.**

**$-I_{IN}$vs. $V_{CM}$**

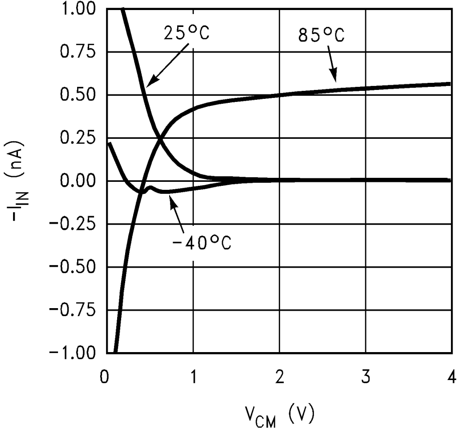

**Figure 8.**

**$e_N$ vs. Frequency**

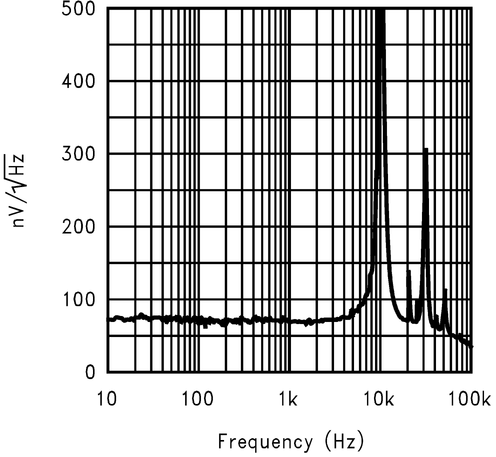

**Figure 9.**

## TYPICAL PERFORMANCE CHARACTERISTICS (continued)

$T_A$=25C, $V_S$= 5V unless otherwise specified.

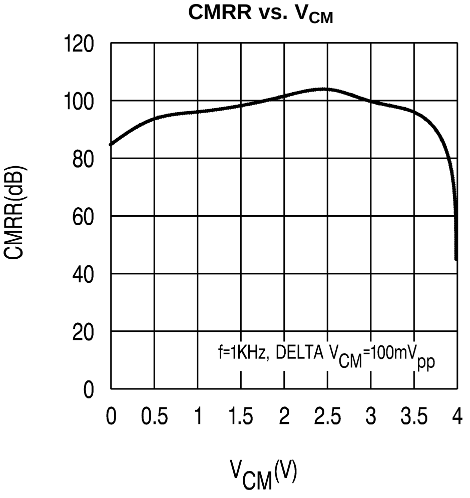

Figure 10.

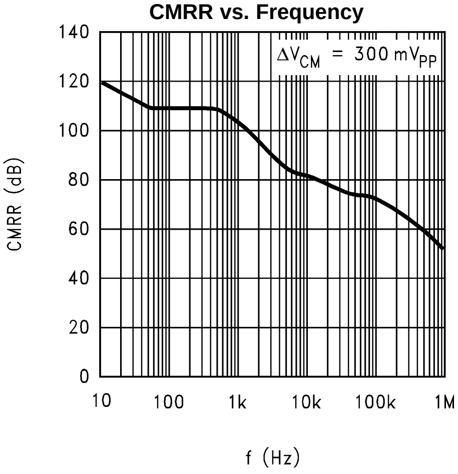

Figure 11.

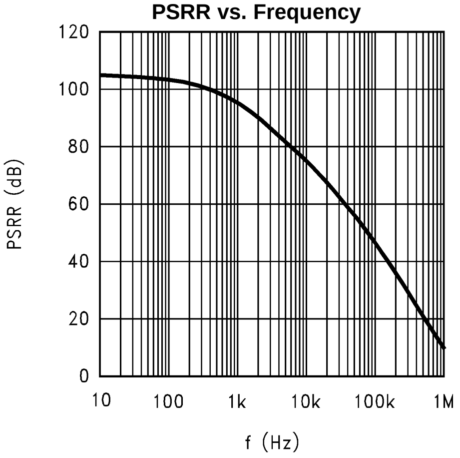

Figure 12.

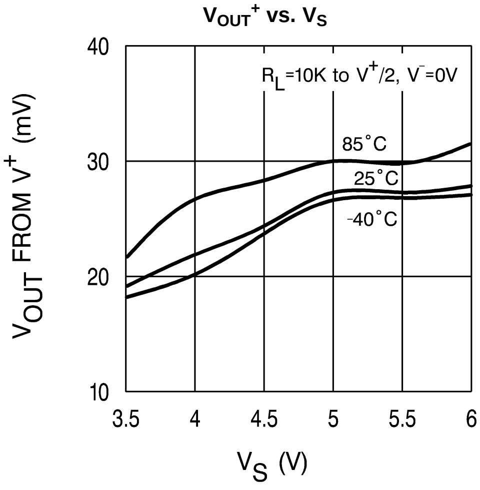

Figure 13.

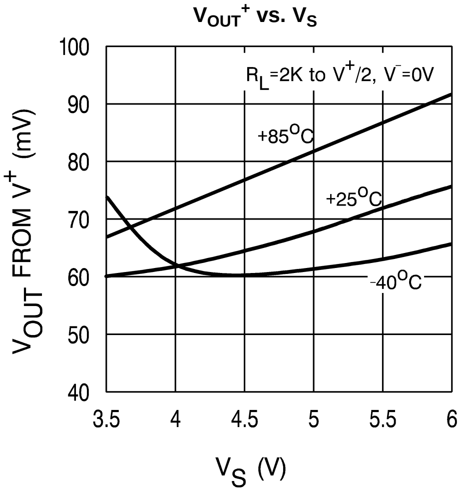

Figure 14.

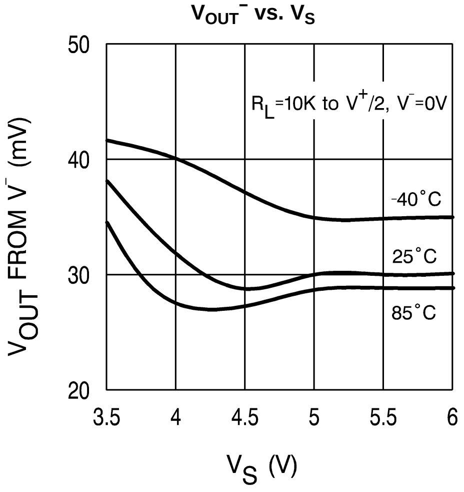

Figure 15.

## TYPICAL PERFORMANCE CHARACTERISTICS (continued)

$T_A$=25C, $V_S$= 5V unless otherwise specified.

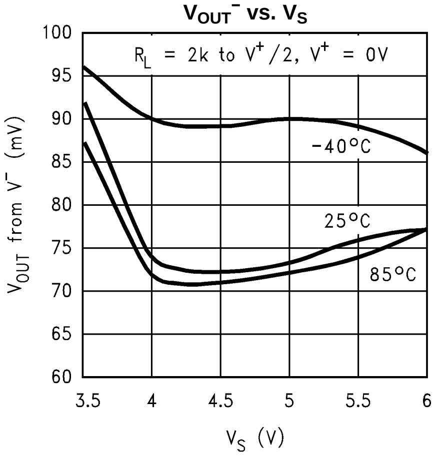
**$V_{OUT}^-$ vs. $V_S$**

**Figure 16.**

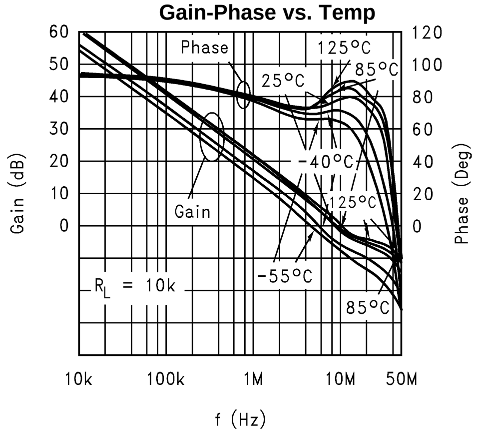
**Gain-Phase vs. Temp**

**Figure 17.**

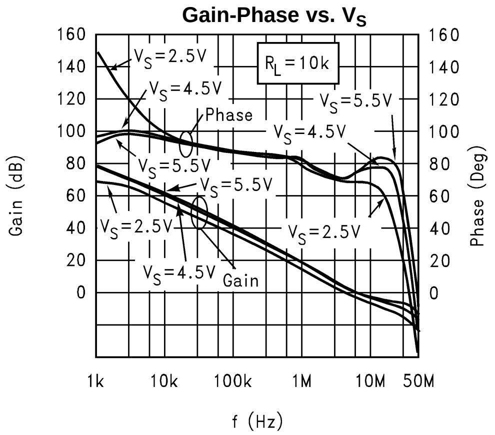
**Gain-Phase vs. $V_S$**

**Figure 18.**

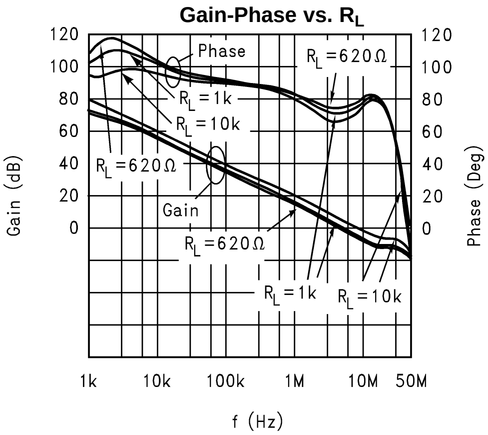
**Gain-Phase vs. $R_L$**

**Figure 19.**

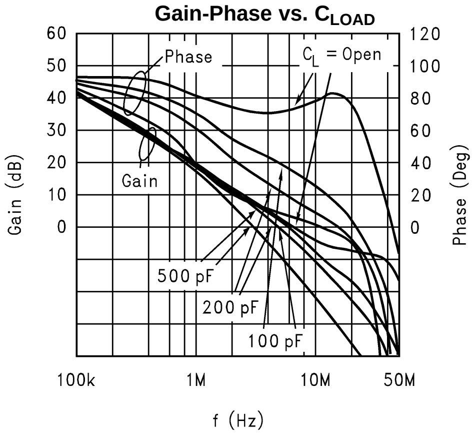
**Gain-Phase vs. $C_{LOAD}$**

**Figure 20.**

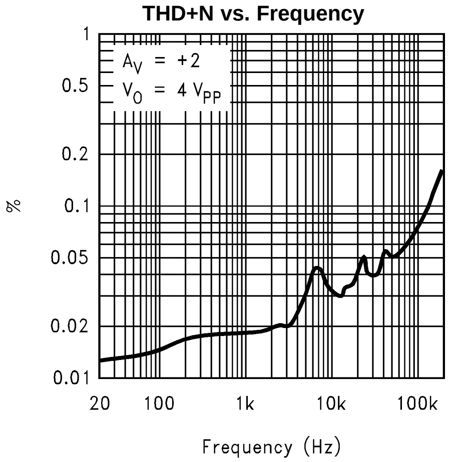
**THD+N vs. Frequency**

**Figure 21.**

## TYPICAL PERFORMANCE CHARACTERISTICS (continued)

$T_A$=25C, $V_S$= 5V unless otherwise specified.

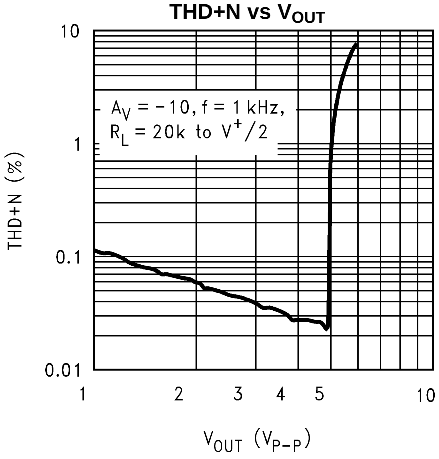

**Figure 22.**

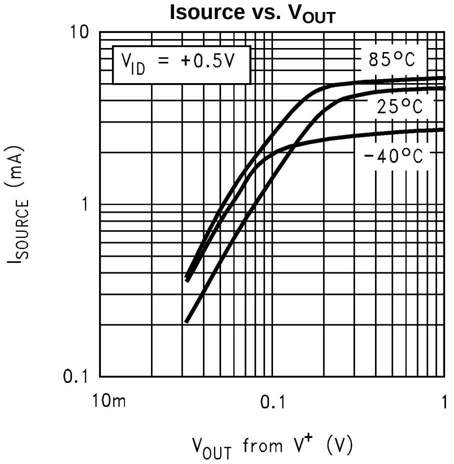

**Figure 23.**

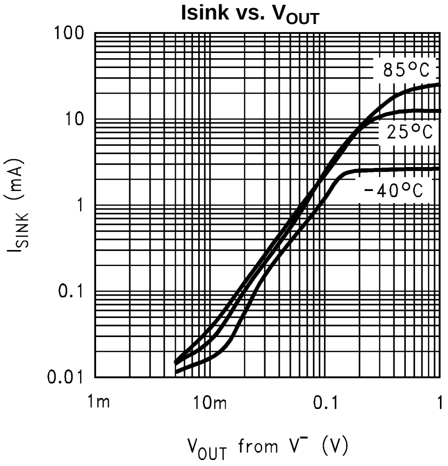

**Figure 24.**

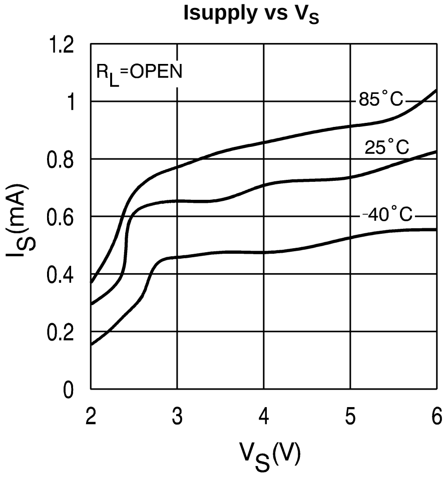

**Figure 25.**

## APPLICATION INFORMATION

### The Benefits of LMC2001 No 1/f Noise

Using patented methods, the LMC2001 eliminates the 1/f noise present in other amplifiers. This noise which increases as frequency decreases is a major source of measurement error in all DC coupled measurements. Low frequency noise appears as a constantly changing signal in series with any measurement being made. As a result, even when the measurement is made rapidly, this constantly changing noise signal will corrupt the result. The value of this noise signal can be surprisingly large. For example: If a conventional amplifier has a high frequency noise level of $10nV/\sqrt{Hz}$ and a noise corner of 10 Hz, the RMS noise at 0.001 Hz is $1\mu V/\sqrt{Hz}$

This is equivalent to a 6µV peak-to-peak error. In a circuit with a gain of 1000, this produces a 6mV peak-to-peak output error. This number of 0.001 Hz might appear unreasonably low but when a data acquisition system is operating for 17 minutes it has been on long enough to include this error. In this same time, the LMC2001 will only have a 0.51mV output error. This is more than 13.3 times less error.

Keep in mind that this 1/f error gets even larger at lower frequencies.

At the extreme, many people try to reduce this error by integrating or taking several samples of the same signal. This is also doomed to failure because the 1/f nature of this noise means that taking longer samples just moves the measurement into lower frequencies where the noise level is even higher.

The LMC2001 eliminates this source of error. The noise level is constant with frequency so that reducing the bandwidth reduces the errors caused by noise.

Another source of error that is rarely mentioned is the error voltages caused by the inadvertent thermocouples created when the common “Kovar type” package lead materials are soldered to a copper printed circuit board. These steel based leadframe materials can produce over 35uV/°C when soldered onto a copper trace. This can result in thermocouple noise that is equal to the LMC2001 noise when there is a temperature difference of only 0.0014°C between the lead and the board!

For this reason, the leadframe of the LMC2001 is made of copper. This results in equal and opposite junctions which cancel this effect. The extremely small size of the SOT-23 package results in the leads being very close together. This further reduces the probability of temperature differences and hence decreases thermal noise.

### Overload Recovery

The LMC2001 recovers from input overload much faster than most chopper stabilized opamps. Recovery, from driving the amplifier to 2X the full scale output, only requires about 50ms. Most chopper stabilized amplifiers will take from 250ms to several seconds to recover from this same overload. This is because large capacitors are used to store the unadjusted offset voltage.

The wide bandwidth of the LMC2001 enhances performance when it is used as an amplifier to drive loads that inject transients back into the output. A to Ds and multiplexers are examples of this type of load. To simulate this type of load, a pulse generator producing a 1V peak square wave was connected to the output through a 10pF capacitor. (Figure 26) The typical time for the output to recover to 1% of the applied pulse is 80ns. To recover to 0.1% requires 860ns. This rapid recovery is due to the wide bandwidth of the output stage and large total GBW.

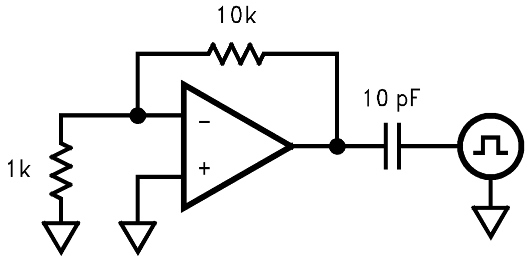

Figure 26.

### No External Capacitors Required

The LMC2001 does not need external capacitors. This eliminates the problems caused by capacitor leakage and dielectric absorption, which can cause delays of several seconds from turn-on until the amplifier is settled.

## More Benefits

The LMC2001 offers the benefits mentioned above and more. It is rail-to-rail output and consumes only 750µA of supply current while providing excellent DC and AC electrical performance. In DC performance, the LMC2001 achieves 120dB of CMRR, 120dB of PSRR and 137dB of open loop gain. In AC performance, the LMC2001 provides 6MHz of gain-bandwidth product and 5V/µs of slew rate.

## How the LMC2001 Works

The LMC2001 uses new, patented techniques to achieve the high DC accuracy traditionally associated with chopper stabilized amplifiers without the major drawbacks produced by chopping. The LMC2001 continuously monitors the input offset and corrects this error. The conventional chopping process produces many mixing products, both sums and differences, between the chopping frequency and the incoming signal frequency. This mixing causes large amounts of distortion, particularly when the signal frequency approaches the chopping frequency. Even without an incoming signal, the chopper harmonics mix with each other to produce even more trash. If this sounds unlikely or difficult to understand, look at the plot (Figure 27), of the output of a typical (MAX432) chopper stabilized opamp. This is the output when there is no incoming signal, just the amplifier in a gain of -10 with the input grounded. The chopper is operating at about 150Hz, the rest is mixing products. Add an input signal and the mess gets much worse. Compare this plot with Figure 28 of the LMC2001. This data was taken under the exact same conditions. The auto zero action is visible at about 11kHz but note the absence of mixing products at other frequencies. As a result, the LMC2001 has very low distortion of 0.02% and very low mixing products.

## Input Currents

The LMC2001 input current is different than standard bipolar or CMOS input currents in that it appears as a current flowing in one input and out the other. Under most operating conditions, these currents are in the picoamp level and will have little or no effect in most circuits. These currents increase to the nA level when the common-mode voltage is near the minus supply. (see the TYPICAL PERFORMANCE CHARACTERISTICS) At high temperatures such as 85°C, the input currents become larger, 0.5nA typical, and are both positive except when the Vcm is near $V^{-}$. If operation is expected at low common-mode voltages and high temperature, do not add resistance in series with the inputs to balance the impedances. Doing this can cause an increase in offset voltage.

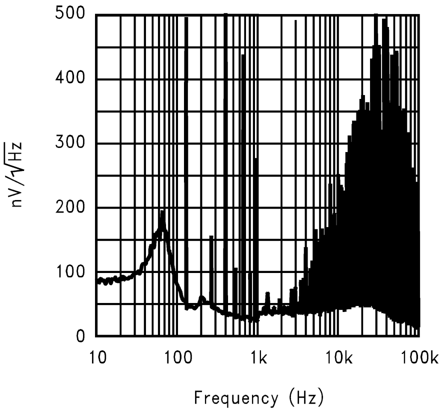

**Figure 27.**

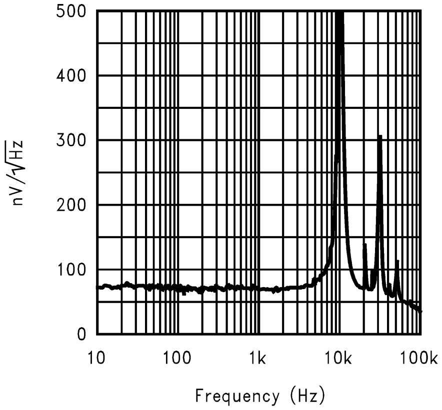

Figure 28.

This Strain-Gauge (Figure 29) amplifier provides high gain (1006 or 60 dB) with very low offset and drift. Using the resistors tolerance as shown, the worst case CMRR will be greater than 90 dB. The common-mode gain is directly related to the resistor mismatch and is independent of the differential gain that is set by R3. The worst case common-mode gain is −54 dB. This gain becomes even lower, improving CMRR, if the resistor ratio matching is improved.

$$A_V \text{ Diff} = 1 + \frac{R1}{R2} + \frac{2R1}{R3} \quad (1)$$

## Extending Supply Voltages and Output Swing by Using a Composite Amplifier Configuration:

In cases where substantially higher output swing is required with higher supply voltages, arrangements like the ones shown in Figure 30, and Figure 31 could be used (pin numbers shown are for SOIC-8 package). These configurations utilize the excellent DC performance of the LMC2001 while at the same time allow the superior voltage and frequency capabilities of the LM6171 to set the dynamic performance of the overall amplifier. For example, it is possible to achieve ±12V output swing with 300MHz of overall GBW (Av=100) while keeping the worst case output shift due to Vos less than 4mV. The LMC2001 output voltage is kept at about mid-point of it's overall supply voltage and it's input common mode voltage range allows the $V^-$ terminal to be grounded in one case (Figure 30, inverting operation) and tied to a small non-critical negative bias in another (Figure 31, non-inverting operation). Higher closed loop gains are also possible with a corresponding reduction in realizable bandwidth. Table 1 shows some other closed loop gain possibilities along with the measured performance in each case

## Application Circuits

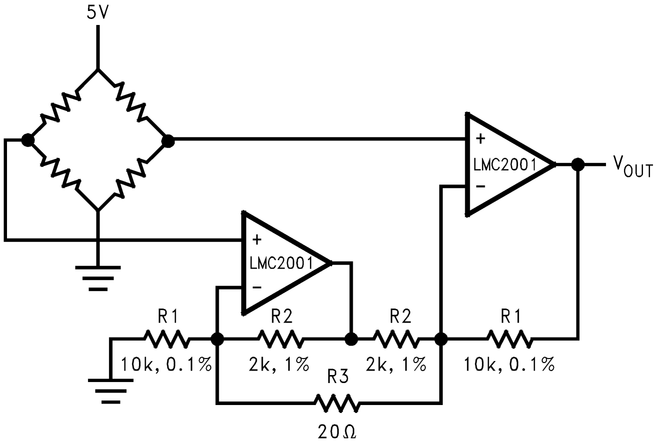

Figure 29. Single Supply Strain- Gauge Amplifier

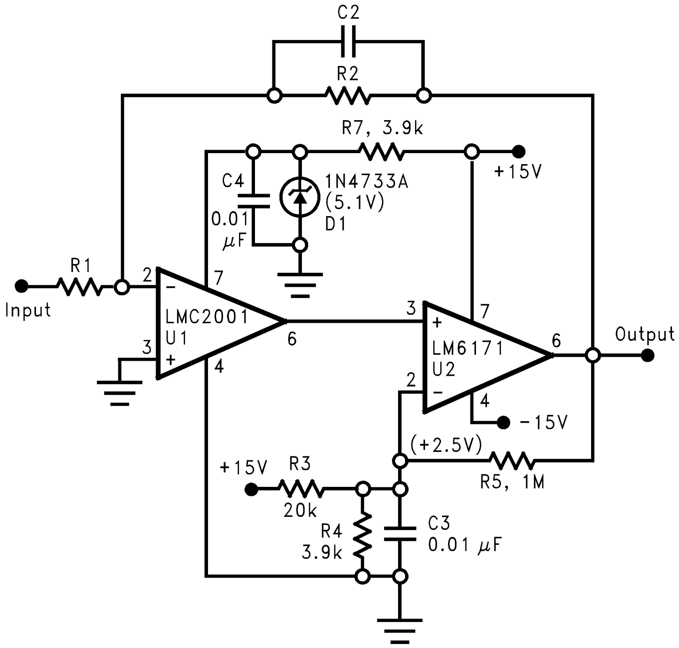

Figure 30. Inverting Composite Amplifier

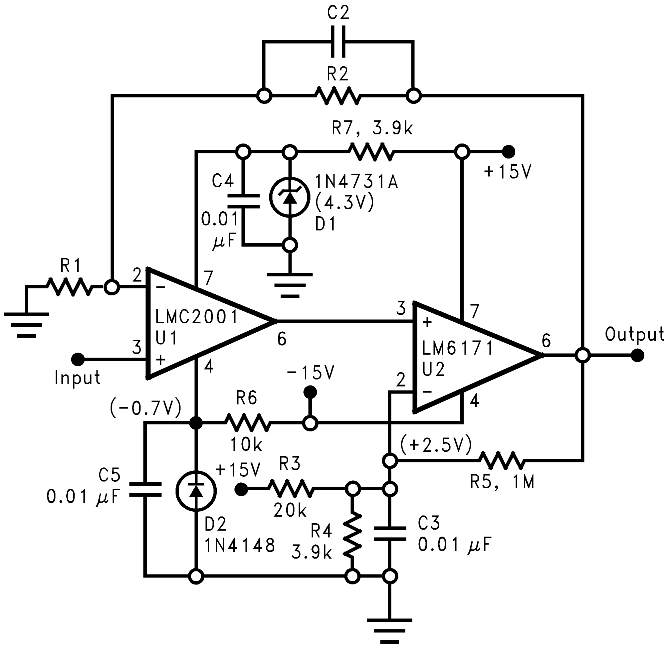

Figure 31. Non-Inverting Composite Amplifier

**Table 1. Composite Amplifier Measured Performance**

| Av | R1 | R2 | C2 | BW | SR | $e_{npp}$ |
|---|---|---|---|---|---|---|
| | (ohm) | (ohm) | (pF) | (MHz) | (V/us) | (mVpp) |
| 50 | 200 | 10K | 8 | 3.3 | 178 | 37 |
| 100 | 100 | 10K | 10 | 2.5 | 174 | 70 |
| 100 | 1K | 100K | 0.67 | 3.1 | 170 | 70 |
| 500 | 200 | 100K | 1.75 | 1.4 | 96 | 250 |
| 1000 | 100 | 100K | 2.2 | 0.98 | 64 | 400 |

In terms of the measured output peak-to-peak noise, the following relationship holds between output noise voltage, $e_{npp}$, for different closed loop gain, $A_v$, settings, where -3dB Bandwidth is BW:

$$\frac{e_{npp1}}{e_{npp2}} = \sqrt{\frac{BW1}{BW2}} \bullet \frac{A_V 1}{A_V 2} \qquad (2)$$

It should be kept in mind that in order to minimize the output noise voltage for a given closed loop gain setting, one could minimize the overall bandwidth. As can be seen from Equation 2 above, the improvement in output noise has a square law relationship to the reduction in BW.

In the case of the inverting configuration, it is also possible to increase the input impedance of the overall amplifier, by raising the value of R1, without having to increase the feedback resistor, R2, to impractical values, by utilizing a “T” network as feedback. See the LMC6442 data sheet (Application Notes section) for more details on this.

## LMC2001 as ADC Input Amplifier

The LMC2001 is a great choice for an amplifier stage immediately before the input of an A/D converter (AC or DC coupled) see Figure 32 and Figure 33 because of the following important characteristics:

a. Very low offset voltage and offset voltage drift over time and temperature allow a high closed loop gain setting without introducing any short term or long term errors. For example, when set to a closed loop gain of 100 as the analog input amplifier of a 12 bit A/D converter, the overall conversion error over full operation temperature and 30 years life of the part (operating at 50°C) would be less than 5LSB.

b. Fast large signal settling time to 0.01% of final value (1.4 us) allows 12 bit accuracy at 100KHz or more sampling rate.

c. No flicker (1/f) noise means unsurpassed data accuracy over any measurement period of time, no matter how long. Consider the following opamp performance, based on a typical commercially available device, for comparison:

| | |
|---|---|
| **Opamp flatband noise** | 8nV/ $\sqrt{Hz}$ |
| **$1/f^{0.94}$ corner frequency** | 100Hz |
| **f(max)** | 100Hz |
| **Av** | 100 |
| **Measurement time** | 100 sec |

The example above, will result in about 3mVpp (2.5LSB) of output noise contribution due to the opamp alone, compared to about 420 uVpp (less than 1LSB) when that opamp is replaced with the LMC2001 which has no 1/f contribution. If the measurement time is increased from 100 sec. to 1 hr., the improvement realized by using the LMC2001 would be a factor of about 44 times (18.5mVpp compared to 420uV when LMC2001 is used) mainly because the LMC2001 accuracy is not compromised by increasing the observation time.

d. Copper lead frame construction minimizes any thermocouple effects which would degrade low level/high gain data conversion application accuracy (see discussion under “The Benefits of LMC2001 No 1/f Noise” section above).

e. Rail-to-Rail output swing maximized the ADC dynamic range in 5V single supply converter applications. Below are some typical block diagrams showing the LMC2001 used as an ADC amplifier (Figure 32 and Figure 33).

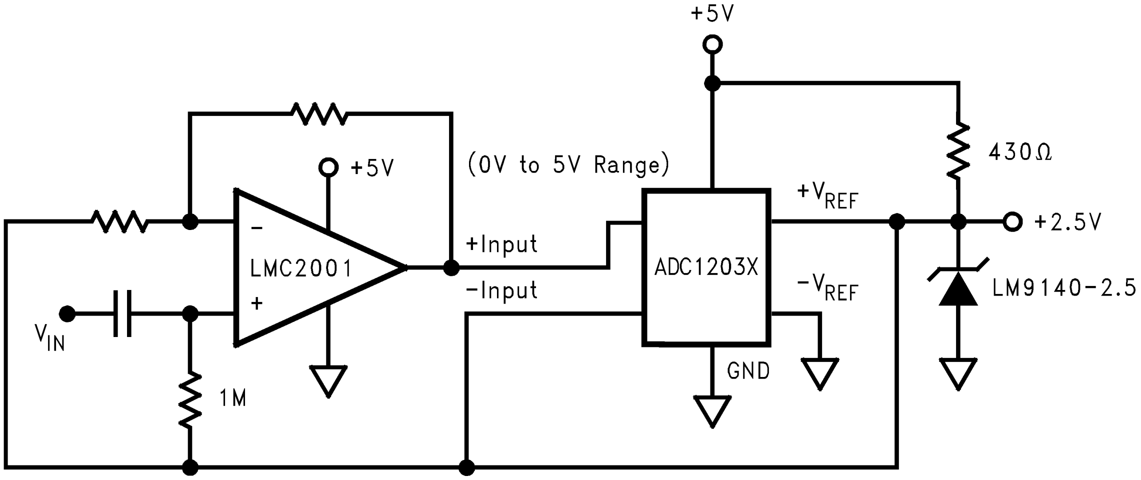

Figure 32.

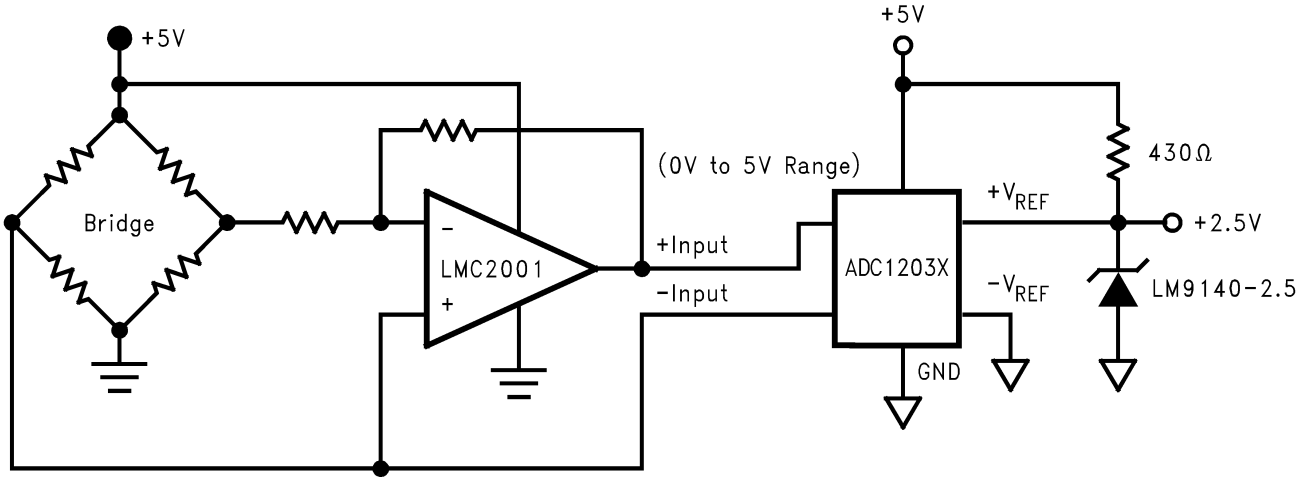

Figure 33.

## REVISION HISTORY

| **Changes from Revision C (April 2013) to Revision D** | **Page** |
|---|---|
| • Changed layout of National Data Sheet to TI format ........................................ | 13 |

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