

A Specification for EMI Hardened Operational Amplifiers

National Semiconductor
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Introduction

The number of electronic (mobile) devices in the world is still increasing. With this increase of transmitting devices, the electromagnetic interference (EMI) between those devices and other equipment becomes a bigger challenge. This raises the need for equipment and therefore integrated circuits that are more robust to the presence of Electromagnetic waves (EM) in the air. Therefore National Semiconductor developed op amps with increased EMI robustness to overcome the issues of electromagnetic interference. Along with these EMI hardened op amps a parameter has been introduced to unambiguously specify the EMI robustness of an op amp: EMI Rejection Ratio (EMIRR). This application note presents the background, details and usage of the EMIRR parameter.

The next section starts with a description of how RF signals can be picked up and transferred to the op amp pins. Subsequently, a qualitative description of the interaction of the RF signal and the op amp is given. To be able to compare different op amps on their EMI robustness, the EMI Rejection Ratio (EMIRR) is defined. The EMIRR is a parameter that quantitatively describes the effect that an RF signal has on op amp performance. The definition of EMIRR is discussed along with a straightforward method to measure the EMIRR. Finally two typical applications will be discussed showing the advantage of EMI hardened op amps.

EMI and Op Amps

To be able to describe the performance of op amps with respect to their EMI robustness, firstly a model needs to be derived that describes how the signals of disturbing (RF) sources might end up at the op amp pins. This requires the identification of possible coupling paths from an interfering (RF) source to the op amp (electronic victim device). Secondly, the actual interaction between the received signal at the op amp pins and the op amp circuitry need to be considered.

An interfering or disturbing (RF) signal can arrive at the op amp via two different types of coupling paths:

- Radiation
- Conduction

Interference via radiation arises when an electronic victim device itself picks up the EM waves. Whether this will happen depends on the frequency of the EM wave and the susceptibility of the electronic device for that frequency. This susceptibility largely depends on the size of the electronic victim device relative to the wavelength of the disturbing EM waves. In the case of interference via conduction, other devices, such as cables and PCB traces connected to the victim device, act as the receiving device, i.e. antenna for EM waves. Subsequently, the received signals (voltages and currents) are transferred in a conductive way to the victim device.

Since the dimensions of an op amp IC are so small (a few mm) compared to the wavelength of the disturbing RF signals (several cm in the GHz range to tens of cm in the hundreds of MHz range), disturbances will dominantly arrive in a conductive way at the op amp pins. These conductive disturbances on the pin of the op amp can be represented by (RF)

voltages and currents which are received by the PCB and connecting wires. These voltages and currents might interfere with the op amp and jeopardize proper behavior. The fact that disturbances arrive mainly in a conductive way implies that, when determining the EMI robustness of an op amp, it is sufficient to consider conductively received disturbances. So, conductive measurements suffice to determine the EMI robustness of op amps. No tests need to be performed in expensive EMI chambers.

RF signals interfere with op amps via the non-linearity of the op amp circuitry. The highest non-linearity is obtained for signals with a frequency that falls outside the band of the op amp circuit, i.e. for frequencies at which the overall feedback is virtually zero. This non-linearity results in the detection of the so called out-of-band signals. The obtained effect is that the amplitude modulation of the out-of-band signal is down-converted into the base band. This base band can easily overlap with the band of the op amp circuit.

As an example *Figure 1* shows the equivalent input offset voltage of an op amp for a detected RF carrier with on-off keying. It is assumed that the op amp is connected in unity gain ($A_V = 1$) which means that the obtained output voltage variation is equivalent to the input offset voltage variation. Clearly the offset voltage varies in the rhythm of the on-off keying of the RF carrier.

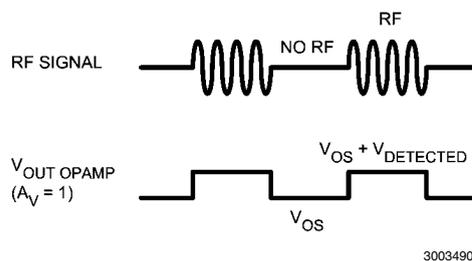


FIGURE 1. Offset Voltage Variation Due to a Detected RF Signal

The key in describing the EMI robustness of an op amp is to link the level of the applied RF signal to the resulting level of offset voltage variation.

EMIRR Definition

To identify EMI robust op amps, a parameter is needed that quantitatively describes the EMI performance. A quantitative measure enables the comparison and the ranking of op amps on their EMI robustness. This application note introduces the EMI Rejection Ratio (EMIRR). This parameter describes the resulting input-referred offset voltage shift of an op amp as a result of an applied RF carrier (interference) with a certain frequency and level. The definition of EMIRR is given by:

$$EMIRR_{V_{RF_PEAK}} = 20 \log \left(\frac{V_{RF_PEAK}}{\Delta V_{OS}} \right)$$

where V_{RF_PEAK} is the amplitude of the applied unmodulated RF signal (V) and ΔV_{OS} is the resulting input-referred offset voltage shift (V).

In this definition the RF signal level is included as a condition at which the EMIRR is determined. This is required as the relation between the resulting offset voltage shift and the RF signal level is quadratic (the details on this quadratic relation is beyond the scope of this application note). An example of the resulting offset shift (ΔV_{OS}) versus applied RF level (RF peak voltage) is depicted in *Figure 1* (section *EMIRR Measurement* describes in more detail the measurement setup used for obtaining these results). The curve is shown on a LOG-LOG scale to clearly show the quadratic nature of the offset voltage shift versus RF level, i.e. the curve has a slope of two. The curve is limited at the bottom end of the signal range as for the corresponding relatively low RF signal levels the resulting offset shift is below the resolution of the measurement setup (noise). For op amps with a relatively high sensitivity (low EMIRR), the curve might saturate for higher RF input levels. This is a result of the offset shift that becomes very large, such that the op amp clips.

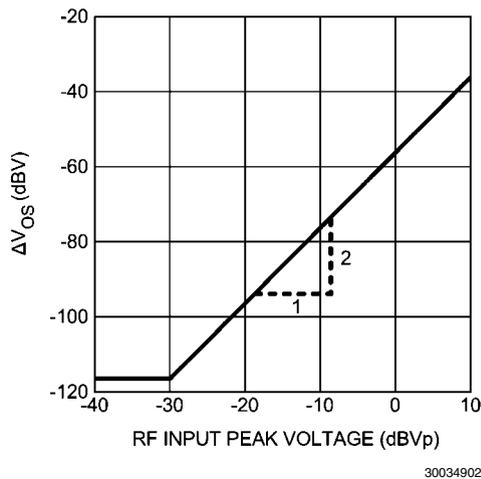


FIGURE 2. Measured Input Referred Offset Voltage Shift vs. Applied RF Peak Level

The effect of the quadratic relation (between applied RF level and resulting offset voltage shift) on the EMIRR is easily illustrated. In the definition of EMIRR, ΔV_{OS} is replaced by an expression accounting for the quadratic dependency on the RF signal level, yielding

$$\begin{aligned} EMIRR_{V_{RF_PEAK}} &= 20 \log \left(\frac{V_{RF_PEAK}}{\Delta V_{OS}} \right) \\ &= 20 \log \left(\frac{V_{RF_PEAK}}{C \cdot V_{RF_PEAK}^2} \right) \\ &= 20 \log \left(\frac{1}{C \cdot V_{RF_PEAK}} \right) \end{aligned}$$

This equation shows that for a double RF signal level the EMIRR is 6 dB lower, i.e. doubling the RF level quadruples the offset voltage shift.

For the EMIRR a standard test condition of 100 mV_p is used, which is equivalent to -20 dBV_p. For EMI hardened op amps it might be necessary, however, to use larger signals for obtaining an offset shift well beyond the noise level of the measurement test circuit. In that case it is required to indicate the used RF level when specifying the EMIRR. It should be noted that EMIRR numbers obtained for different RF signal levels hamper the comparison of the corresponding op amps. Therefore, it is preferable to convert the EMIRR obtained for an RF signal level other than 100 mV_p to the standard EMIRR. The expression for this conversion is obtained by scaling the used signal level, $V_{RF_PEAK_B}$, to 100 mV_p according to:

$$\begin{aligned} EMIRR &= 20 \log \left(\frac{100 \text{ mV}_P}{\Delta V_{OS}} \right) \\ &= 20 \log \left(\frac{V_{RF_PEAK_B}}{\Delta V_{OS}} \cdot \frac{100 \text{ mV}_P}{V_{RF_PEAK_B}} \right) \\ &= EMIRR_{V_{RF_PEAK_B}} + 20 \log \left(\frac{100 \text{ mV}_P}{V_{RF_PEAK_B}} \right) \end{aligned}$$

For example, assume $EMIRR_{1V}$ is measured for an op amp. Converting this to the standard EMIRR yields:

$$\begin{aligned} EMIRR &= EMIRR_{1V_P} + 20 \log \left(\frac{100 \text{ mV}_P}{1V} \right) \\ &= EMIRR_{1V_P} - 20 \text{ dB} \end{aligned}$$

The interpretation of the EMIRR parameter is straight forward. When two op amps have an EMIRR which differ by 20 dB, the resulting error signal as a result of EMI, when used in identical setups, differ by 20 dB as well. So, the higher the EMIRR the more robust the op amp.

EMIRR Measurement

Measuring EMIRR is straightforward and requires three basic actions:

1. Applying an RF signal in a well defined way to an op amp pin under test.
2. Measuring the offset voltage with the RF signal switched off and again with the RF signal switched on.
3. Calculate the resulting offset voltage shift from which the EMIRR can be obtained.

The EMIRR is a measure to compare the EMI performance of op amps. To have a fair comparison, it is a prerequisite that the conditions for these EMIRR measurements are equal, and that the influence of the test setup, such as instruments and test board, are kept to a minimum. The presented measurement test circuit and method ensures that the EMIRR measurements are accurate and repeatable. The core is a simple board with standard components. The equipment used is standard off the shelf as well, such as a power supply, an RF generator, and a multi-meter. Special attention needs to be paid to the way the RF signal is applied to the pin under test, i.e. the setup and test board need the careful treatment of an RF setup. It should be noted that when a higher resolution is required, the EMIRR can also be determined by using an AM

modulated RF carrier and then with a spectrum analyzer measuring the level of the down converted amplitude modulation. In this case, for the EMIRR calculation some correction factors are required to account for the different way of measuring.

As the disturbing RF signal can come in through all of the op amp pins, EMIRR tests are described for all op amp pins individually:

- IN+
- IN-
- V_{DD}
- V_{SS}
- V_{OUT}

Before discussing the setup for each of the pins, first some general remarks and guidelines are given that need to be considered when building the test circuit and taking the measurements.

OP AMP CONFIGURATION

To have best defined RF levels on the pin under test, no op amp feedback elements should be in the RF signal path. Therefore, if possible, the op amp should be connected in a unity-gain configuration. This yields the lowest level of RF filtering due to the feedback network.

APPLYING THE RF SIGNAL

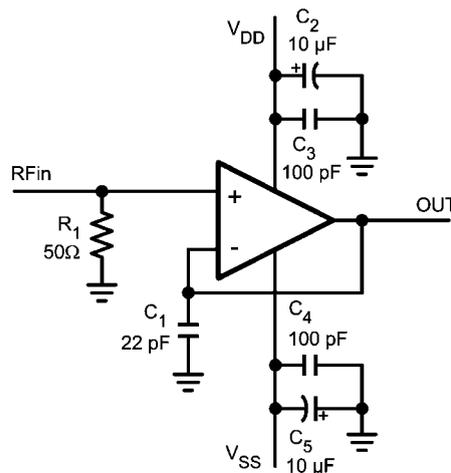
Care needs to be taken in how the RF signal is applied to the pin under test. Signals up to a few GHz will be used, so the whole RF signal path needs to match the characteristic impedance of the RF generator. This requires proper coaxial cabling from the generator to the test board. On the test board a 50Ω stripline needs to be used to bring the RF signal as close as possible to the pin under test. A 50Ω termination at the pin under test is also required. Setting up the test environment in this way ensures that the RF levels at the pin under test are well defined.

ISOLATING THE OTHER PINS

When the pin under test is tested, the other pins need to be decoupled for RF signals. This ensures that the obtained offset voltage shift is dominantly a result of coupling the RF signal to the pin under test. For this decoupling standard SMD components can be used.

TEST #1: COUPLING AN RF SIGNAL TO THE IN+ PIN

For testing the IN+ pin the op amp is connected in the unity gain configuration. Applying the RF signal is straightforward, as it can be connected directly to the IN+ pin. As a result, there are a minimum of disturbing components in the RF signal path. The circuit diagram is shown in *Figure 3*. The PCB trace from RFin to the IN+ pin should be a 50Ω stripline in order to match the RF impedance of the cabling and the RF generator. On the PCB a 50Ω termination is used. This 50Ω resistor is also used to set the bias level of the IN+ pin to ground level. The DC measurements are taken at the output of the op amp. As the op amp is in the unity gain configuration, the input referred offset voltage shift corresponds one-to-one to the measured output voltage shift.

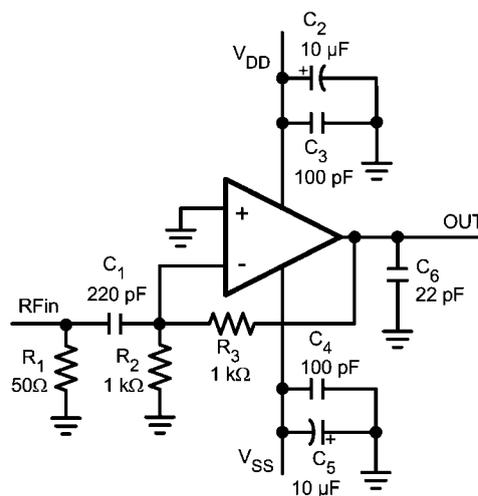


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FIGURE 3. Circuit Diagram for Coupling the RF Signal to the IN+ Pin

TEST #2: COUPLING AN RF SIGNAL TO THE IN- PIN

For coupling an RF signal to the IN- pin, the unity gain configuration as described for the IN+ pin cannot be used. In that configuration the RF signal would be applied not only to the IN- pin but to the output pin as well. For accurately measuring the EMIRR of the IN- pin, RF isolation is required for the output pin. Therefore a voltage gain configuration is used as depicted in *Figure 4*. The low-frequency gain, which applies to the resulting offset shift, is set to 2. The feedback resistor R_3 and the load capacitance isolate the output pin from the injected RF signal at the IN- pin.



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FIGURE 4. Circuit Diagram for Coupling the RF Signal to the IN- Pin

The gain of the feedback network is not important for the applied RF signal. Since the RF frequency is much higher than the Gain-Bandwidth-Product (GBP) of the op amp, the op amp configuration can be seen for RF signals as an open loop circuit. The gain of the op amp configuration is important for translating the obtained output voltage shift to an input referred offset voltage shift. The input referred offset voltage shift is calculated by dividing the measured output voltage shift by the voltage gain, which is 2 in this case.

Also for this PCB the signal path from RFin to the IN– pin should be a 50Ω stripline with appropriate termination. The RF signal is applied to the IN– pin via a coupling capacitor C₁. The parasitic series inductance of this capacitor needs to be compared to the 50Ω impedance of the RF signal path. So, an inductance of a few nH is acceptable when measuring up to a few GHz. As a result a standard SMD component can be used here.

For symmetry reasons it is expected that the positive and negative input have the same sensitivity for applied RF signals but with an opposite polarity for the obtained input referred offset shift. The input pins thus have the same EMIRR.

TEST #3, 4: COUPLING AN RF SIGNAL TO THE SUPPLY PINS

For coupling an RF signal to the supply pins, the op amp can again be connected in the unity gain configuration. A single PCB can serve for measuring the EMIRR for both supply pins, V_{DD} and V_{SS}. Figure 5 depicts the schematic. On this PCB both RF signal paths from the RF injection point to a supply pin should be a 50Ω stripline with a 50Ω termination. It is important to remove the decoupling capacitor on the pin that is under test. Thus, when injecting an RF signal on the V_{DD} pin, capacitor C₄ and C₅ should be removed, while capacitor C₆ and C₇ should be removed when injecting an RF signal on the V_{SS} pin. The inductors L₁ and L₂ are used to isolate the power supply sources from the RF signal. This prevents the sources from detecting the RF signal which might deteriorate the measurement accuracy.

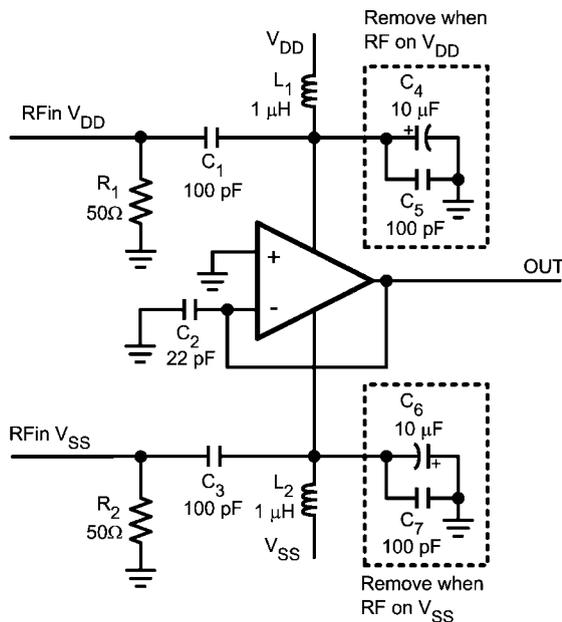
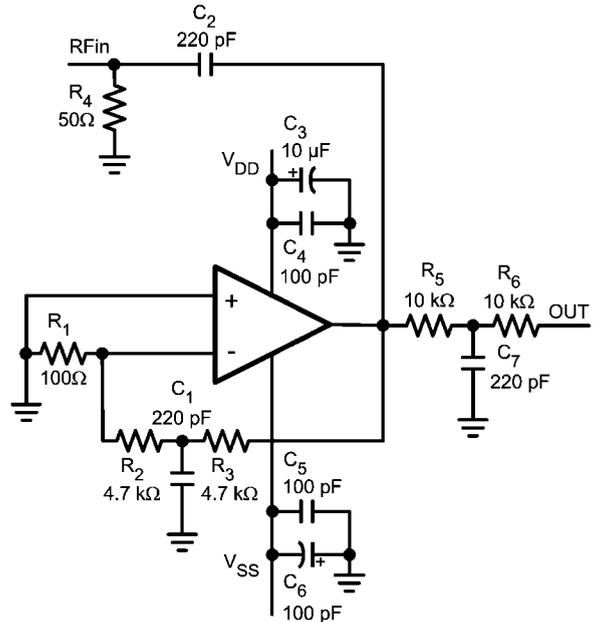


FIGURE 5. Circuit Diagram for Coupling an RF Signal to Either of the Supply Pins

TEST #5: COUPLING AN RF SIGNAL TO THE OUTPUT PIN

Analogous to the circuit for testing the IN– pin, the circuit for testing the output pin requires a voltage gain configuration. When applying an RF signal to the output pin, the IN– pin needs to be isolated. As the sensitivity of the output pin is expected to be lower than the sensitivity of the input pin, a better isolation is needed for this case. The schematic for coupling an RF signal to the output pin is depicted in Figure

6. The resulting offset shift is again measured at the output. So, the equivalent input referred offset voltage shift is found by dividing the obtained output voltage shift by the gain of the configuration: $1 + (R_2 + R_3)/R_1$. Special attention needs to be paid to the isolation of the DC meter connected to the output. As the RF signal is applied to the same node where the resulting offset voltage shift needs to be measured, a low-pass filter (R₅, R₆, C₇) is placed between the RF injection node and the DC meter. This low-pass filter prevents the DC meter from detecting the applied RF signal which would directly affect the measurement results.



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FIGURE 6. Circuit Diagram for Coupling an RF Signal to the Output Pin

Measurement Procedure

The measurement procedure is the same for all five test circuits. To measure the input referred offset voltage shift needed for calculating the EMIRR, the following procedure can be used:

1. Measure V_{OUT} when the RF signal is off.
2. Measure V_{OUT} when the RF signal is on.
3. Translate measured V_{OUT} voltages to input referred voltages (divide by the circuit gain).
4. Subtract the two measured input referred voltages.
5. Verify if the offset shift is above the noise level of the op amp and the op amp is not saturated. If this is not the case choose another RF level and start the procedure again.
6. Calculate the EMIRR.
7. If needed, transform the results to an EMIRR based on a 100 mV_p RF signal.

Measurement Results for the LMV851/LMV852/LMV854

The five test circuits that are described in the previous sections are used to perform EMIRR measurements on the LMV851. The LMV851 is a single EMI hardened op amp with 8 MHz bandwidth. The supply voltages used are 2.5V on the

positive supply and -2.5V on the negative supply. Measurement results apply to the dual version, LMV852, and the quad version, LMV854, as well.

To characterize the sensitivity of the various pins two types of measurement results are presented:

- The EMIRR as a function of the frequency of the applied signal. The level of the signal is set to the standard level of 100 mV_P (-20 dBV_P).
- The EMIRR as a function of the level of the applied signal. The frequency is set to four typical values: 400 MHz, 900 MHz, 1.8 GHz, and 2.4 GHz.

EMIRR VS. FREQUENCY

Figure 7 depicts the EMIRR versus frequency for the various pins. The measurement is performed with a fixed RF level of -20 dBV_P and a varying RF signal frequency. The frequency range is 10 MHz to 1 GHz.

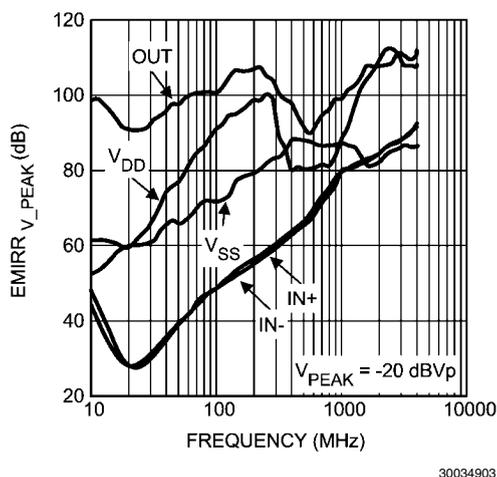


FIGURE 7. EMIRR vs. Frequency for IN+, IN-, V_{DD} , V_{SS} , and OUT

From these results several conclusions can be drawn. Firstly, it is clearly visible that the IN+ and IN- pin do have the same EMIRR. This was already noticed for reasons of input stage symmetry. Secondly, the V_{DD} , V_{SS} and OUT pins have a significantly higher EMIRR than the input pins. This is also quite logical as the inputs are meant to be sensitive for signals. It should be noted, however, that the supply and output pins are not generally more robust than the input pins. An op amp needs to be designed specifically for having high EMIRR for those pins as well.

EMIRR VS. POWER

Figure 8 depicts the EMIRR as a function of the RF peak level at four typical frequencies.

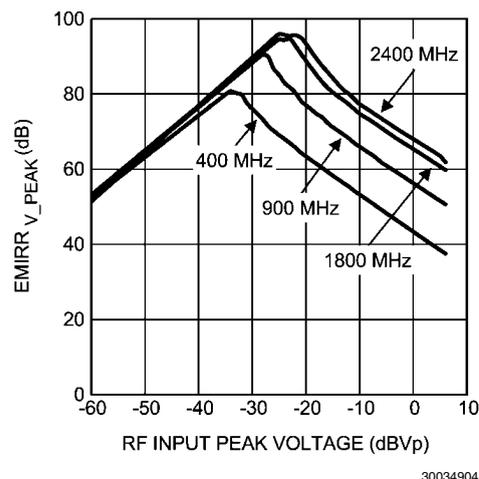


FIGURE 8. EMIRR vs. RF Input Peak Level for IN+

In this figure two areas can be distinguished. At the left side of the figure, the EMIRR increases as a function of input level; whereas, at the right side the EMIRR decreases as a function of the input level.

The left side of the figure is actually an artifact resulting from the limited accuracy of the measurement setup. For the relatively low input levels, the resulting offset voltage shift is well below the noise level. Thus, when calculating the EMIRR for that region, the ratio of the input level to the noise level is depicted. As the noise level is constant for the setup, an increasing EMIRR is obtained for increasing input signal level.

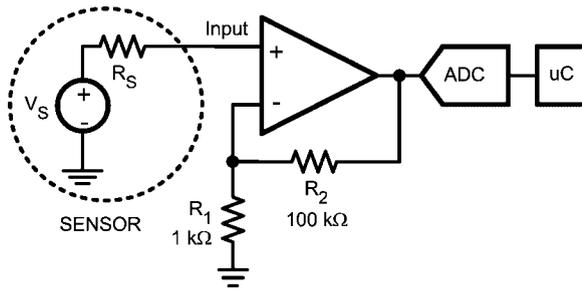
For the right side, the obtained offset-shift is well above the noise level. As the relation between offset voltage shift and RF input level is quadratic, the ratio as used in the EMIRR is inversely proportional to the RF input level, which is in line with the displayed slope of -1 .

Typical Applications and EMIRR

EMI hardened op amps can be used in a wide range of applications. Applications with sensors that produce relatively low signal levels especially benefit from the EMI robustness. These small signals can easily be deteriorated by an interfering RF signal. As the small signals require a large gain of the op amp circuit, the detected RF signals get amplified as well and might introduce a significant error in the overall signal processing path. An EMI hardened op amp minimizes the effect of interference that, once detected, propagates into the subsequent circuitry. Two examples are given to demonstrate the advantage of EMI hardened op amps. The first example describes a generic signal path application; the second example describes a test in which a cell phone interferes with a pressure sensor application.

SIGNAL PATH APPLICATION

In Figure 9 a typical signal path application is depicted with a sensor, an op amp and an ADC that connects to a microcontroller. The sensor can be a Ph-sensor or a thermocouple for instance, that produces a signal which needs to be measured. This signal is amplified by the op amp to match the ADC input range. Accordingly the ADC digitizes the signal such that it can be read by a microcontroller for further processing.



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FIGURE 9. Typical Signal Path Application

Suppose that this application is in an aggressive EM environment and that the interfering signal is mainly received by the sensor and its wiring. Consequently, an RF signal arrives at the input of the op amp. Further, assume that the RF signal at the input of the op amp is -20 dBV_p at 900 MHz and that the gain of the op amp configuration is 101x. The ADC used has a 10-bit resolution and a 5V input range. Two examples will be given to demonstrate the effect an interfering signal can have on the ADC measurement accuracy and thus on the overall performance.

Firstly, a standard op amp without any special EMI robustness is used. Such an op amp can have an EMIRR of 50 dB at 900 MHz, for instance. This means that for this situation the input referred offset voltage shifts about 0.32 mV as a result of the RF signal of -20 dBV_p . As a result of the gain of 101x the output voltage shift equals 32 mV.

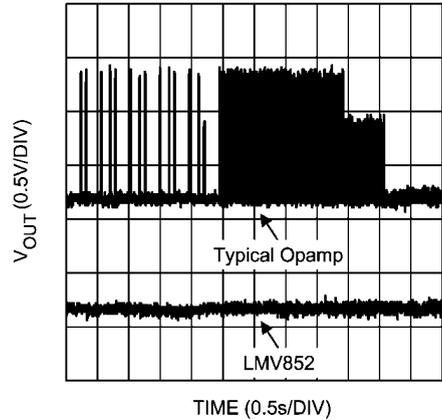
Secondly, an LMV851 EMI hardened op amp is placed in the application. The LMV851 has an EMIRR of about 80 dB at 900 MHz. This results in an input referred offset voltage shift of about $10 \mu\text{V}$, which is equivalent to 1 mV shift at the output. The ADC has a resolution of 10 bit with a 5V range. This means that one bit corresponds to $5/1024 = 4.88 \text{ mV}$. To be able to use the full measurement resolution without incorrect readings the error signal should not be larger than half a bit or 2.44 mV. The standard op amp has an output shift of 32 mV, which is equivalent to about 7-bits. The output shift of 1 mV for the LMV851 EMI hardened op amp is equivalent to 0.2-bit.

CELL PHONE CALL

The effect of electromagnetic interference is demonstrated in a setup where a cell phone causes interference with a pres-

sure sensor application (Figure 11). This application needs two op amps and therefore a dual op amp is used. The experiment is performed on two different dual op amps as in the previous example: a typical standard op amp and the dual LMV852 EMI hardened op amp. The op amps are connected to a single supply. The cell phone is placed in a fixed position a couple of centimeters from the op amps.

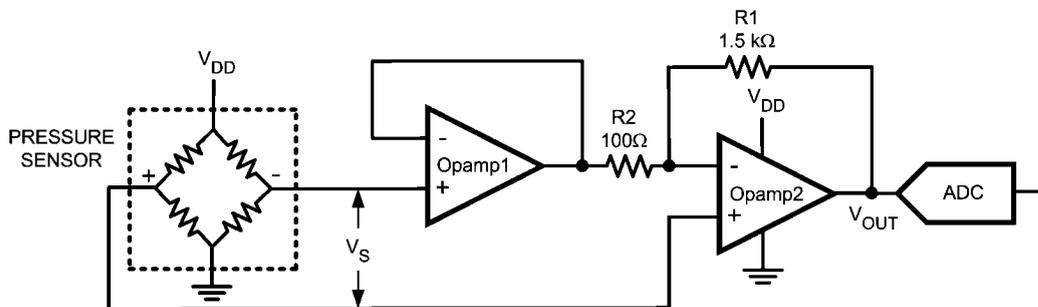
When the cell phone is called, the op amps detect the RF signal transmitted by the cell phone. The resulting effect on the output voltage of the second op amp is depicted in Figure 10.



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FIGURE 10. Comparing EMI Robustness

The difference between the two types of dual op amps is clearly visible. The typical standard dual op amp has an output voltage shift (disturbing signal) larger than 1V as a result of the RF signal transmitted by the cell phone. The LMV852 EMI hardened op amp does not show any significant disturbances. It should be noted that the relative size of the disturbances in the output signal for those two cases, is equal to the difference of the EMIRR for the two dual op amps used. So, the EMIRR enables an early selection of components for building an EMI robust application.



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FIGURE 11. Pressure Sensor Application

Notes

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Notes

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