Technical Report

August 2011

EMI Rejection Ratio of Operational Amplifiers

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ABSTRACT

This application report introduces the concept of electromagnetic interference rejection ratio (EMIRR IN+) as a measure of the immunity of an operational amplifier to responding to electromagnetic interference (EMI). Texas Instruments has developed the ability to accurately measure and quantify the immunity of an operational amplifier over a broad frequency spectrum extending from 10 MHz to 6 GHz. Definitions, equations, and example calculations of EMIRR IN+ are provided, as well as a discussion of how to measure EMIRR IN+. EMI coupling and RF circuit concepts are also reviewed for the reader's benefit. This report shows the reader how to apply the EMIRR IN+ parameter when EMI is a concern in a given circuit design. The EMIRR IN+ parameter is now being tested for all new and many existing operational amplifiers available from Texas Instruments.

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1 Introduction

Electromagnetic interference (EMI) is becoming a greater concern for both system designers and application engineers as more electronic applications move to wireless communication platforms. Today's applications are using denser component spacing, placing mixed-signal analog and digital devices even closer together. EMI can have detrimental effects in these systems. Fortunately, the issue of EMI is receiving more attention and being addressed, resulting in circuit design techniques and semiconductor products that offer increased EMI immunity.

EMI susceptibility and immunity tests have been in place for many years. These tests are intended to help determine if a product will show robust EMI performance once in production. In many cases, these tests are often required to ensure that the products meet certain compliance specifications and regulatory requirements before shipment to customers and original equipment manufacturers. This testing can prove to be time-consuming and costly; therefore, it is desirable to achieve high initial pass rates. Often, EMI testing must be performed at an accredited laboratory that has the proper equipment, and multiple visits are typically required to resolve compliance failures. Consequently, board and system-level designers should be concerned with EMI at the beginning of the design process. Development and production of devices that deliver excellent EMI performance, complemented with designs that apply good layout and shielding techniques, result in excellent EMI immunity.

The EMI immunity of operational amplifiers (op amps) is very important because op amps are found in a tremendous range of circuits where they are used to amplify and condition signals. Texas Instruments has begun to address this issue by designing op amps and other linear devices with input EMI filters to increase EMI immunity. The initial effectiveness of these EMI filters has been qualitatively observed when compared to parts without the EMI filter. Texas Instruments now has the ability to accurately measure and specify a quantitative op amp metric for EMI immunity, known as the *EMI rejection ratio*. The EMIRR metric allows op amps to be directly compared in terms of EMI immunity. Equipped with this information, designers can now select the best performing devices for EMI-sensitive applications. This approach offers board and system-level designers a significant advantage and helps avoid the costly expenses of additional design cycles.

1.1 How EMI Enters Systems and Devices

EMI can enter a system (or device) through either conduction or radiation, or both. Radiated EMI is not discussed in detail here, because all interfering EMI signals are eventually converted to conducted EMI. Radiated EMI is most often conducted by printed circuit board (PCB) traces or wires that lead to active devices such as op amps. The physical length of these traces and wires can make them effective antennas at microwave and radio frequencies (RF). Additionally, EMI-sensitive devices may be placed within a shielded container that highly attenuates such radiated signals. In these cases, the wires and connections in and out of the container form the only conduction path for the EMI signals into the devices.

Conducted EMI, on the other hand, can originate from several sources (see Ref. 1). In addition to radiated EMI signals, conducted EMI may enter a system through the power mains or may be generated by the system itself. Switching power supplies, for example, can be a source of EMI.

Return currents from one circuit to ground can couple into another circuit if both circuits share a common impedance to ground (also known as *ground bounce*), as illustrated in Figure 1.

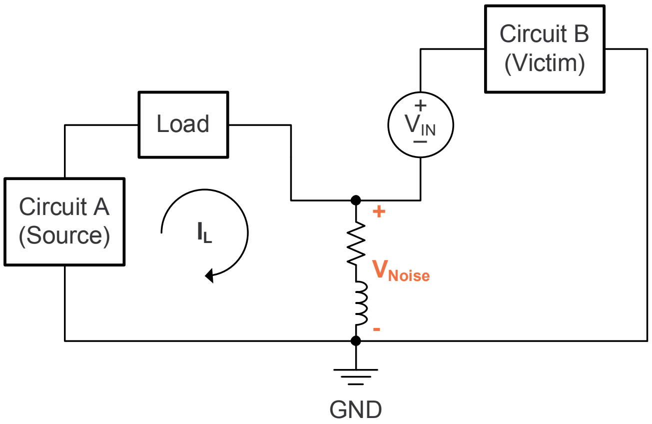


Figure 1. Common Impedance to Ground

EMI can also be generated inside a system by fast-changing data and clock signals that capacitively or inductively couple to a neighboring circuit. Fast voltage transients in circuits similar to that shown in Figure 2 can cause displacement currents in nearby capacitively-coupled circuits. Fast current transients can also inductively couple elsewhere in the circuit, and induce voltages across conductors that form current loops as modeled in Figure 3. EMI threats can come from both external and internal sources in a system; therefore, decoupling and filtering are employed at all interfaces to the outside world and often directly at the sensitive devices.

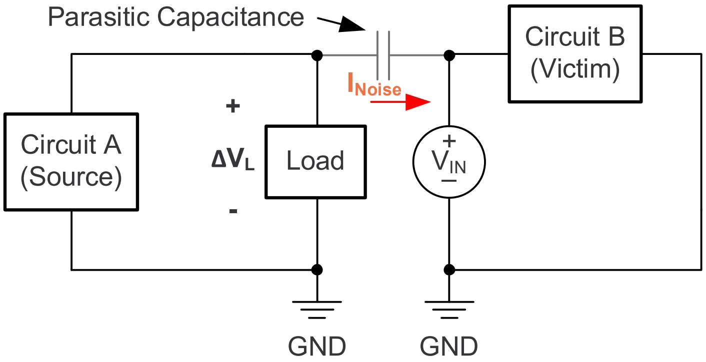


Figure 2. Capacitive Current Coupling

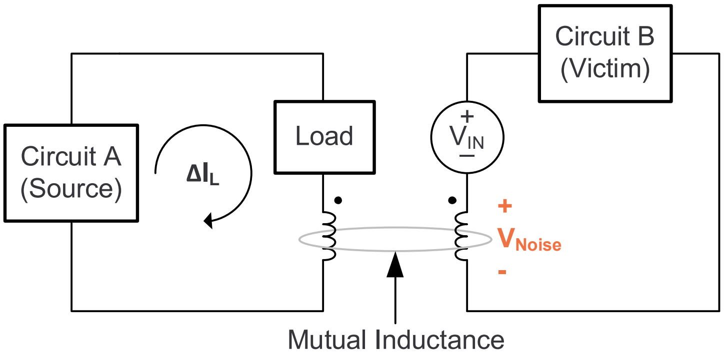


Figure 3. Inductive Voltage Coupling

1.2 How EMI Affects Op Amps

The most common op amp response to EMI is a shift in the dc offset voltage that appears at the op amp output. Conversion of a high-frequency EMI signal to dc is the result of the nonlinear behavior of the internal diodes formed by silicon p-n junctions inside the device. This behavior is referred to as *rectification* because an ac signal is converted to dc. The small RF signal rectification generates a small dc voltage in the op amp circuitry. When this rectification occurs in the op amp signal path, the effect is amplified and may appear as a dc offset at the op amp output. Figure 4 shows an oscilloscope screenshot of an op amp output shift that occurs as an RF signal is applied to the op amp input. This effect is undesirable because it adds to the offset error; therefore, EMIRR is a useful metric to describe how effectively an op amp *rejects* rectifying EMI.

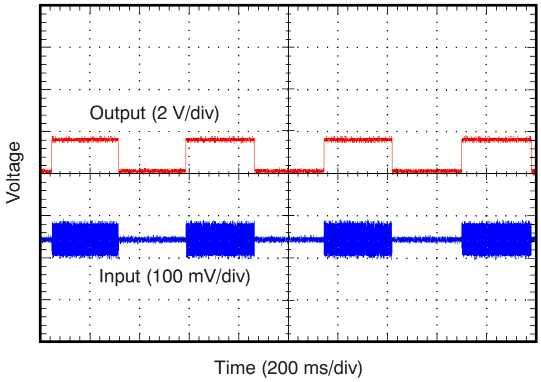
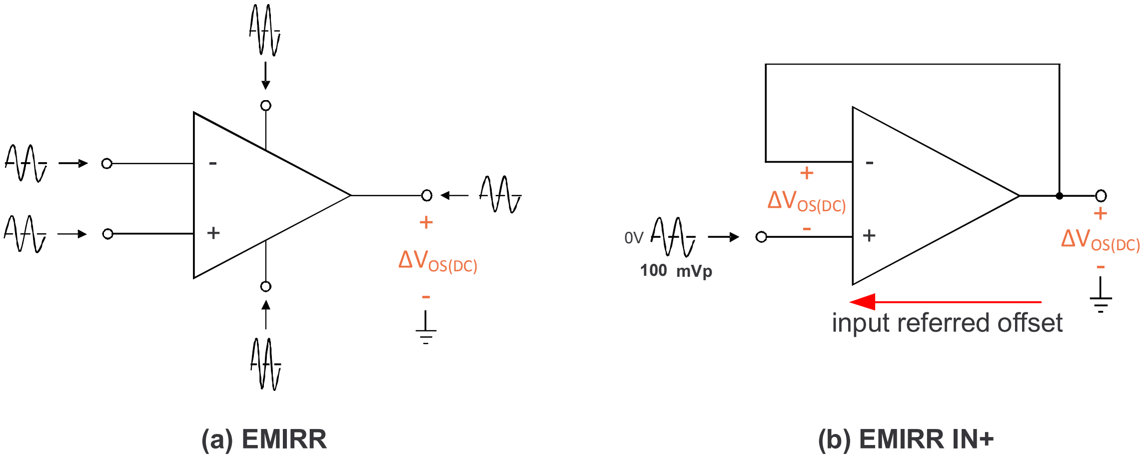


Figure 4. Oscilloscope Image of Op Amp Output and Input (Gain = 100, GBW = 18 MHz, RF Input = 300-MHz CW)

2 Defining EMIRR IN+

EMI rejection ratio, or *EMIRR*, is a metric that is used to specify the EMI immunity of an op amp. Measurement of EMIRR can be performed in several ways, and thus a distinction between EMIRR IN+ and EMIRR will be made here. EMIRR can be measured by injecting an RF signal into any op amp pin; the resulting dc offset shift [ΔV_{OS}(dc)] is observed, as shown in Figure 5**(a)**. However, when the noninverting input is selected as the dedicated measurement pin for the injected RF signal, the specification is referred to as *EMIRR IN+*. This configuration is illustrated in Figure 5**(b)**.



(a) EMIRR **(b) EMIRR IN+**

Figure 5. EMIRR and EMIRR IN+ Measurement Comparison

The op amp input pins exhibit the least EMI rejection compared to the power supply, output, or any other op amp pin. The inputs are the most sensitive to EMI because changes in dc bias voltage or current in the input circuitry are amplified. Both inputs exhibit nearly equal susceptibility because they are balanced and have symmetrical layouts. Other op amp terminals yield very low gain to the output, and changes on these pins do not disturb the op amp output voltage significantly. Therefore, EMIRR IN+ describes the minimum ability of the device to reject rectifying EMI signals. Another benefit to measuring the dc offset at the op amp output in the noninverting configuration is that doing so allows the offset to be referred back to the input and thus be equated to a change in the input offset voltage. This technique is useful for measuring op amps in various gain configurations, and is also more representative of real-world applications. Additionally, it will be shown that this configuration is the most practical for measuring op amp EMI immunity.

2.1 Calculating EMIRR IN+

EMIRR IN+ is measured in decibels (dB), similar to power-supply rejection ratio (PSRR) and common-mode rejection ratio (CMRR) parameters. EMIRR IN+ is a logarithmic ratio where higher decibel values correspond to better rejection and higher immunity. EMIRR IN+ is calculated by Equation 1.

$$EMIRR\ IN+(dB) = 20 \cdot \log\left(\frac{V_{RF\_PEAK}}{\Delta V_{OS}}\right) + 20 \cdot \log\left(\frac{V_{RF\_PEAK}}{100mV_P}\right) \tag{1}$$

V_{RF_PEAK} is the peak amplitude of the applied RF voltage. ΔV_{OS} is the dc voltage offset shift that takes place in response to the applied RF. ΔV_{OS} is the input referred change in offset voltage. The second logarithmic term in the equation references the EMIRR IN+ to an input signal of 100 mV_P. The quadratic relationship between V_{RF_PEAK} and ΔV_{OS} requires a point of reference, making the EMIRR IN+ different from a typical linear decibel ratio. This quadratic relationship is more apparent when Equation 1 is solved for ΔV_{OS}, as shown in Equation 2. Doubling V_{RF_PEAK} quadruples ΔV_{OS}.

$$\Delta V_{OS} = \left(\frac{V_{RF\_PEAK}^{\ 2}}{100mV_P}\right) \cdot 10^{-\left(\frac{EMIRR\ IN+(dB)}{20}\right)} \tag{2}$$

The following example shows how to calculate and apply EMIRR IN+.

Example 1. EMIRR IN+ Calculation

Consider an RF signal of 100 mV_P at 900 MHz that is coupled into an input terminal of an op amp by way of conduction. At 900 MHz, the op amp EMIRR IN+ performance is 60 dB. Applying Equation 2, substituting 60 dB for the EMIRR IN+ and 100 mV_P for V_{RF_PEAK} yields Equation 3. The resulting dc input-referred voltage shift is 100 µV.

$$\Delta V_{OS} = \left(\frac{100\ mV_P^{\,2}}{100\ mV_P} \right) \cdot 10^{-\left(\frac{60\ dB}{20} \right)} = 100\ mV \cdot 10^{-3} = 100\ \mu V\ (DC) \qquad (3)$$

If the op amp is configured as a unity-gain buffer, then the output voltage shift will also be 100 µV.

For comparison, consider a second op amp with an EMIRR IN+ of 20 dB at 900 MHz, in a noninverting gain configuration with a gain of 100. Applying Equation 2 again, the input-referred voltage shift is 10 mV, as shown in Equation 4.

$$\Delta V_{OS}\ (Input\ Offset) = 20 \cdot \log \left(\frac{100mV_p^{\,2}}{100mV_p} \right) \cdot 10^{-\left(\frac{20dB}{20} \right)} = 10mV\ (dc) \qquad (4)$$

The resulting output voltage shift of 1 V is calculated as shown in Equation 5. The output shift is 1 V because the input-referred offset shift is multiplied by the amplifier gain.

$$\Delta V_{OS}\ (Output\ Offset) = 10mV \cdot 100\ (gain\ of\ amplifier) = 1V\ (dc) \qquad (5)$$

It is difficult to predict the exact level of RF signal that enters the op amp input. The RF signal amplitude of 100 mV_P used in this example is a large signal level to illustrate a worst-case estimate of offset shift as a result of EMI. This illustration shows that an op amp with low EMIRR IN+ configured with a large gain is very susceptible to EMI-induced errors. RF energy with comparable levels may be encountered in cell phones, GPS devices, or other wireless applications that operate within industrial, scientific, and medical (ISM) frequency bands.

NOTE: The actual voltage offset observed at the op amp output may not always appear to follow the simple gain relationship of $A_V = 1 + R_F/R_I$. This difference is a result of the complex ac impedance of the feedback and ac leakage paths that vary with frequency. The resulting dc rectified signal may therefore vary over frequency and produce an apparent change in the amplifier gain.

3 Measuring Op Amp Input and Output Voltages

Characterization of the EMIRR IN+ for an op amp requires the application of an RF signal to the op amp input while measuring the resulting dc offset voltage at the output. Applying known RF voltages to the op amp input proves to be non-trivial. In this section, the challenges of configuring and measuring the EMIRR IN+ of an op amp are discussed.

3.1 Op Amp Biasing

Op amp inputs are biased with a dc common-mode voltage halfway between the positive and negative supply rails for the EMIRR IN+ test configuration. This technique is the standard biasing condition for most specifications where the op amp behaves linearly. The RF input signal is superimposed on the common-mode voltage and is applied to the op amp input. The RF and dc signals each need separate supplies; these supplies must be isolated to prevent interference and protect the device from overvoltage conditions.

Isolation of the RF and dc signals is accomplished by the use of a bias tee. A bias tee can be modeled as a large capacitor and inductor, as shown in Figure 6. The three terminal bias tee has two inputs for RF and dc signals and one output for the superimposed RF and dc signal. The signals sources pass through the inputs to the output with minimal loss.

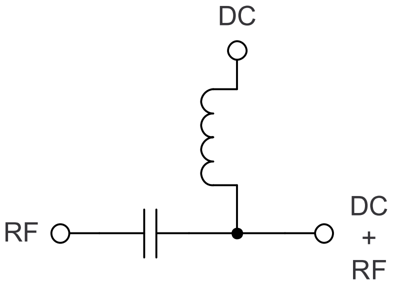
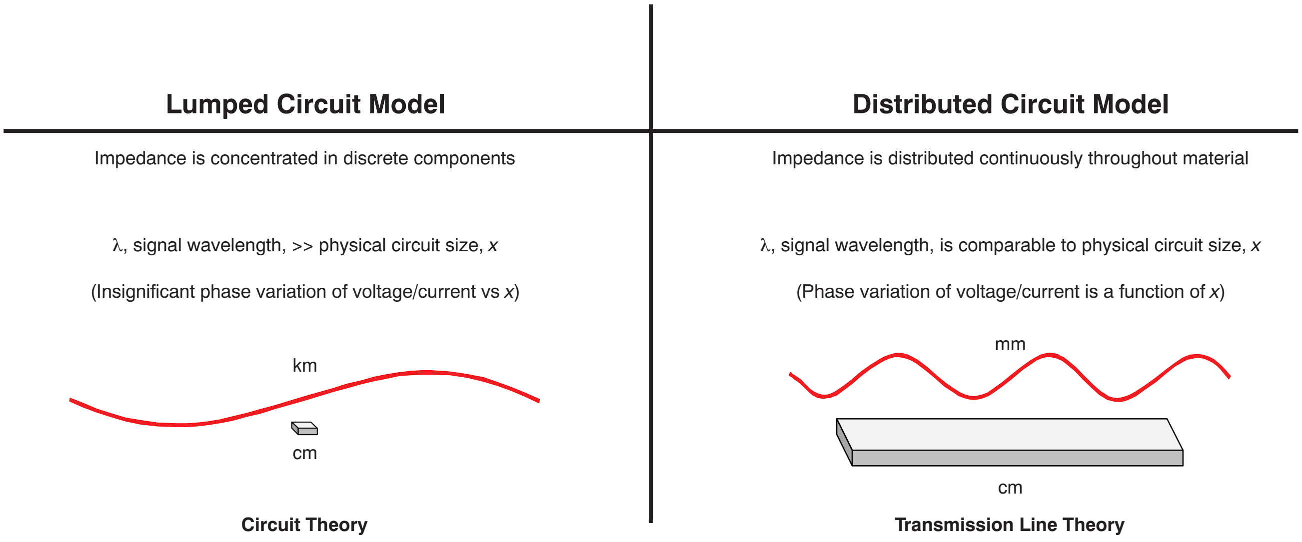


Figure 6. Bias Tee Circuit Model

3.2 *RF Considerations*

Basic ac circuit theory equations that many engineers are familiar with have limitations. These equations work well when concerned with relatively low signal frequencies. (Here, the discussion of low frequencies presumes that the wavelength of the signal in question is much larger than the physical dimensions of the circuit that is being analyzed). Long wavelengths, which correspond to low frequencies, undergo little phase change over short lengths. The voltages and currents of a long wavelength are uniform across short conductors in the circuit. This characteristic allows circuit behavior to be modeled as lumped elements connected with wires of zero impedance (or perfect conductors), such that voltages and currents are uniform along these conductors.

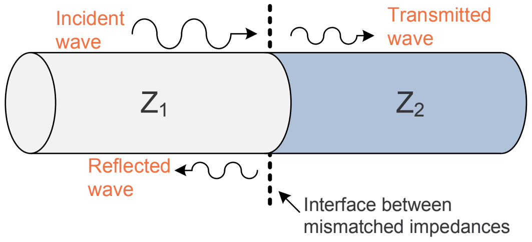
The *lumped circuit* model becomes less accurate as the frequency increases. A *distributed circuit* model must then be adopted to accurately describe the circuit behavior. At high signal frequencies, circuit dimensions become an important parameter relative to the frequency. As voltage and current waves travel along a conductor, phase changes become significant. These phase changes produce voltage and current maximas and minimas along the length of the conductor. Long conductors no longer behave as perfect conductors but as distributed impedances along the length of the circuit. The circuit can be modeled as distributed elements, or as a transmission line with ever-changing voltage and current levels along the conductor. These models are illustrated in Figure 7.



Lumped Circuit Model	**Distributed Circuit Model**
Impedance is concentrated in discrete components	Impedance is distributed continuously throughout material
λ, signal wavelength, >> physical circuit size, *x*	λ, signal wavelength, is comparable to physical circuit size, *x*
(Insignificant phase variation of voltage/current vs *x*)	(Phase variation of voltage/current is a function of *x*)
Circuit Theory	**Transmission Line Theory**

Figure 7. Lumped Circuit Model vs. Distributed Circuit Model

Another challenge when working with RF systems is impedance mismatch. Signals on a transmission line travel as voltage and current waves and are able to reflect at interfaces. Interfaces that occur where there is a change in impedance (from one transmission line to another or from a transmission line to a load) will cause wave reflections that are proportional to the degree of mismatch. This concept is illustrated in Figure 8 (for more information, see Ref. 2).



$$\text{Magnitude of reflected voltage wave, } \Gamma = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)}$$

Figure 8. Impedance Mismatches Cause Voltage and Current Reflections

Wave reflections change the magnitude of the voltage and current waves along the transmission line and may make it difficult to know the exact signal level at any point along the transmission line.

3.3 Applying the RF Input Signal

Measuring the EMIRR IN+ of an op amp requires that we know the RF voltage amplitude seen at the op amp input. A high-frequency signal generator can be used to generate and control the amplitude and frequency of the RF signal. However, the op amp input voltage amplitude will be different from the initial RF voltage amplitude that is created by the signal generator because of impedance mismatches. The RF signal must travel from the signal generator along a cable to a bias tee, through a PCB connector, and along a PCB trace to the op amp input. The input signal will inevitably experience multiple impedance mismatches and reflections along this path. An illustration of the RF signal path and the transmission line model is shown in Figure 9.

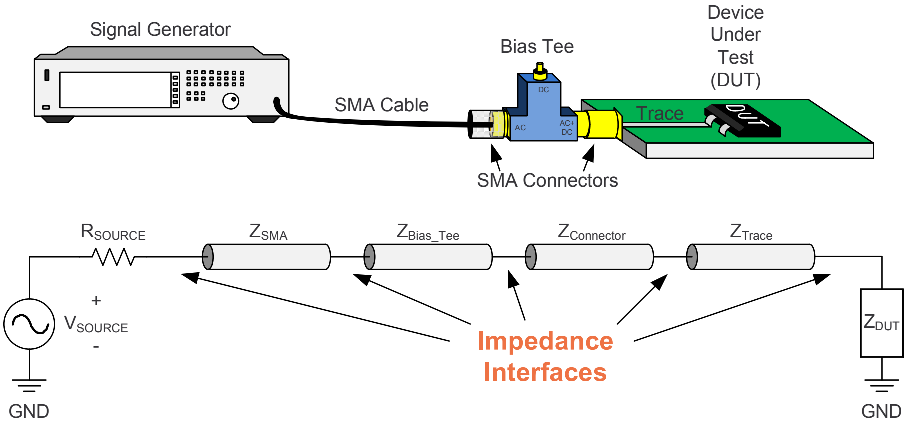


Figure 9. RF Input Signal Path for Measuring EMIRR IN+

Every interface between cables, connectors, and traces may potentially present an impedance mismatch and voltage reflections. Many of these voltage reflections can be avoided or minimized by carefully designing the path up to the op amp to match the system impedance of 50 Ω, set by the signal generator output impedance. Nevertheless, the op amp input impedance will not be matched to the system impedance. At low frequencies, a 50-Ω termination resistor in parallel with the very high op amp input impedance can be used to reduce this impedance mismatch. However, at higher frequencies, parasitic reactances cause the impedance of the termination resistor and the op amp input impedance to change, and an impedance mismatch with unknown properties is presented. Achieving a consistent impedance of 50 Ω across a wide range of frequencies becomes a very difficult task.

One approach to resolving this problem of knowing the RF voltage amplitude applied to the op amp input is to allow for a single voltage reflection. In this approach, the op amp input impedance is allowed to be mismatched from the system, but the amplitude of the resulting voltage reflection must be known at all test frequencies such that the RF input voltage amplitude to the op amp can be calculated. If the voltage reflection at the op amp input is the only voltage reflection in the system, then a network analyzer can be used to directly measure the voltage reflection associated with this impedance mismatch.

NOTE: If other impedance mismatches exist in the input path to the op amp they will be compounded with the op amp impedance mismatch and change the voltage reflection measured by the network analyzer. Allowing for more than one large impedance mismatch adds uncertainty to the reflection measurement. A few small mismatches in the system can be tolerated because they can be calibrated out of the system using the network analyzer. This calibration procedure is called *de-embedding* the device under test from the test fixture.

The RF signal injection and voltage reflection measurement both occur at the noninverting input of the op amp. The noninverting input is preferred because an RF signal can directly connect to the noninverting input via a transmission line or waveguide. Although the inverting input could also be used, it appears as a more complex RF environment. The feedback network connects to the inverting input. This connection introduces added RF paths, increases signal coupling, and causes additional reflections.

The following example demonstrates how to calculate the voltage at the op amp input when a signal generator drives the op amp via a 50-Ω transmission line.

Example 2. Voltage Calculation

A 1-GHz sine wave with a power level of 1 mW (0 dBm) is applied to the input of a given transmission line. The voltage reflection (|S_{11}|) at the transmission line or op amp interface is measured with a network analyzer to be –0.63 dB at 1 GHz. The voltage that the signal generator applies to the transmission line is shown in Equation 6.

$$V_{RMS\_Applied} = \sqrt{Power(W) \cdot R(\Omega)} = \sqrt{1mW \cdot 50\Omega} = 0.224\,V_{RMS} \tag{6}$$

The root-mean square (RMS) value is converted to a peak value by Equation 7.

$$V_{Peak\_Applied} = \sqrt{2} \cdot V_{RMS} = \sqrt{2} \cdot 0.224\,V_{RMS} = 0.316\,V_p \tag{7}$$

This applied voltage is not the same as the incident level at the op amp input. To calculate the incident, or actual, voltage seen at the op amp input, we must add the applied voltage to the reflected voltage using Equation 8.

$$V_{Peak\_Incident} = \left(1+\left|S_{11}\right|\right) \cdot V_{Peak\_Applied} = \left(1+10^{\frac{-0.63\,dB}{20}}\right) \cdot 0.316\,V_p = 0.61 V_p \tag{8}$$

NOTE: A large voltage reflection (|S_{11}|) that has a level of nearly 0 dB causes the actual voltage at the op amp input to nearly double; however, this value is reasonable. Consider what happens when a 50-Ω signal generator is connected to a high-impedance oscilloscope input. The signal viewed on the oscilloscope shows voltage amplitude doubling from the expected generated signal. If the oscilloscope input impedance is set to match the output impedance of the signal generator (50 Ω), then the expected voltage amplitude is measured by the oscilloscope. This effect occurs because the voltage divider created by the signal generator and oscilloscope connection is expected to halve the voltage produced by the signal generator. The same effect of voltage wave doubling is observed when a transmission line is terminated with an open or high-impedance load. The incident voltage wave that travels down the transmission line expects to see a matched load; when a mismatch occurs, a corresponding voltage reflection occurs to satisfy Ohm's Law.

3.4 Measuring the Output Offset Voltage

The op amp dc output offset voltage that results from RF signal rectification is a straightforward measurement with a high-resolution multimeter. A low-pass filter (LPF) is connected between the op amp output and the multimeter to prevent any residual RF from disrupting the multimeter operation. The op amp rectifies and attenuates most of the RF signal, but RF signals may continue to be present at the op amp output because RF can couple through the op amp or through a feedback network.

A voltage will be present at the op amp output that is related to the inherent input offset voltage. This offset is not related to the offset created by applying an RF signal and should not be included when calculating the EMIRR IN+. To remove this offset from the multimeter measurement, two different measurements are taken. First, the dc output offset of the op amp is sampled multiple times with the RF source of the signal generator turned off. Next, the RF source is turned on and the output offset of the op amp is sampled again. The averages of these two sampling periods are subtracted, and the difference is the amount of output offset produced by dc rectification of the RF signal. This procedure is repeated for all RF frequencies for which the EMIRR IN+ of the op amp is characterized.

3.5 Complete EMIRR IN+ Test Configuration

Figure 10 shows the overall circuit configuration for testing the EMIRR IN+, after voltage reflections have been determined. The RF source is connected to the op amp noninverting input terminal via a transmission line. Here, the op amp is configured as a unity-gain buffer (G = +1V/V). The op amp output is connected to an LPF and a digital multimeter (DMM). The calculated RF input voltage and the measured dc offset voltage provide the necessary values to calculate the EMIRR IN+ given in Equation 1.

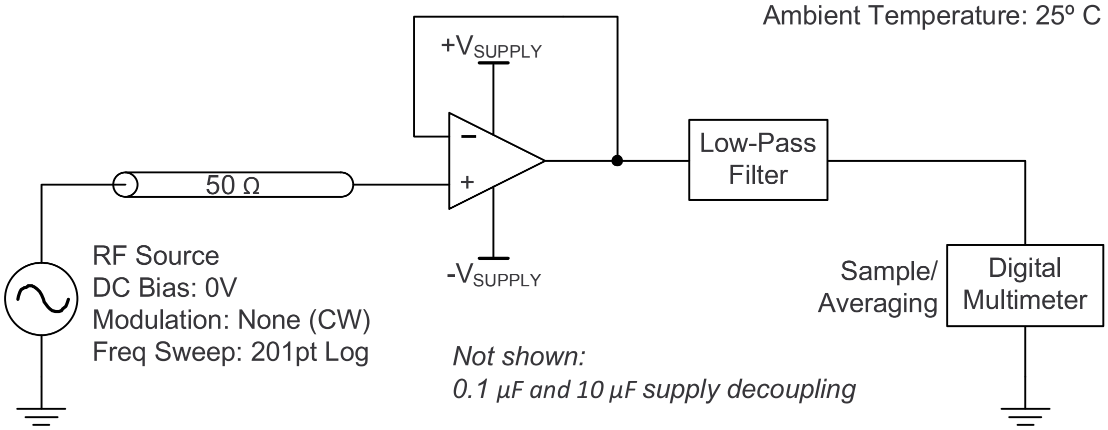


Figure 10. EMIRR IN+ Test Circuit Configuration

4 EMIRR IN+ of the OPA333

The OPA333 is a CMOS, micropower, zero-drift, rail-to-rail input/output, precision operational amplifier with 350-kHz GBW. The OPA333 incorporates internal EMI filtering to achieve very robust EMI immunity. The EMIRR IN+ performance of the OPA333 was measured using the test configuration described in this application report. Figure 11 shows the EMIRR IN+ of the OPA333 measured from 10 MHz up to 6 GHz.

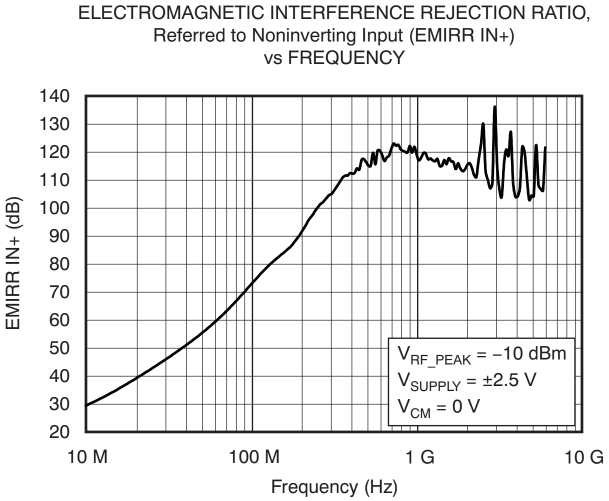


Figure 11. OPA333 EMIRR IN+ Performance

The OPA333 has shown the highest EMIRR IN+ in the 250-MHz to 6-GHz range than any other tested op amp measured to date, with better than 100 dB over this entire range. This frequency range is of key concern for many wireless applications. Table 1 lists some common wireless applications and the respective associated frequencies. Knowledge of op amp EMIRR IN+ performance at critical application frequencies allows selection of the best devices for high-performance analog applications.

Table 1. OPA333 EMIRR IN+ for Common Wireless Frequencies of Interest

Frequency	Application/Allocation	EMIRR IN+
400 MHz	Mobile radio, mobile satellite/space operation, weather, radar, UHF	112.5 dB
900 MHz	GSM, radio com/nav/GPS (to 1.6 GHz), ISM, aeronautical mobile, UHF	120.9 dB
1.8 GHz	GSM, mobile personal com broadband, satellite, IEEE L-Band	114.5 dB
2.4 GHz	802.11b/g/n, Bluetooth®, mobile personal com, ISM, amateur radio/satellite, S-band	115.0 dB
3.6 GHz	Radiolocation, aero com/nav, satellite, mobile, S-band	145.7 dB
5 GHz	802.11a/n, aero com/nav, mobile coms, space/satellite operation, IEEE C-band	113.2 dB

5 Summary

In EMI-sensitive applications it is important to begin circuit designs with components that deliver high EMI immunity. The EMI immunity of operational amplifiers is characterized using the EMIRR IN+ specification parameter. Texas Instruments now measures EMIRR IN+ for its new high-precision op amps to provide valuable information to customers concerned about EMI. This report discusses how these measurements are characterized and performed.

6 References

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2. Pozar, D. M. (2005). Microwave engineering (3rd ed.) Malden, MA: John Wiley & Sons, Inc.