AN1767

Solutions for Radio Frequency Electromagnetic Interference in Amplifier Circuits

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WHAT IS ELECTROMAGNETIC INTERFERENCE (EMI)

Nowadays, the number of mobile devices increases day by day. All mobile devices are wireless and radiate electromagnetic waves producing electromagnetic interference with other devices.

Electromagnetic interference is a disturbance that affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted by an external source. Man-made or natural external disturbances cause degradation in the performance of electrical equipment.

EMI can enter a system (or device) through either conduction, radiation or both. 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 makes 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 this case, 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, originates from several sources. 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.

Electromagnetic interference examples include the noise you hear in the speaker when you put a cell phone near a computer speaker or the loud static noise produced by the tape player when you make a call on a cell phone in the car. This EMI propagates in the system through conduction over signal, power lines and/or through radiation in empty space. The most common sources of conducted interference are switching power supplies, AC motors, microcontrollers or digital circuits.

Since EMI can affect most electronic devices, including medical and avionics equipment, modern devices include EMI filters to ensure the proper operation in harsh EMI environments. An EMI filter is typically used to suppress conducted interference present on any power or signal line. It may be used to suppress the interference generated by the device itself, as well as to suppress the interference generated by other equipment, in order to improve the immunity of a device to the EMI signals present within its electromagnetic environment.

The impedance of an EMI filter has a highly reactive component. This means the filter provides much higher resistance to higher frequency signals. This high impedance attenuates or reduces the strength of these signals, so that they have less of an effect on other devices. Most EMI filters are discrete components; however, the latest trend is to integrate EMI filters inside the integrated circuit. This application note discusses both approaches to solving EMI issues.

In order to increase EMI immunity, Microchip Technology Inc. has started designing op amps and other linear devices with input EMI filters. For instance, the MCP642X family has enhanced EMI protection to minimize any electromagnetic interference from external sources, such as power lines, radio stations and mobile communications. This feature makes the devices well suited for EMI-sensitive applications.

AN1767

TYPES OF EMI

EMI can be classified in many ways:

- By its coupling mechanism:
  - Radiated
  - Conducted
- By the way it was created:
  - Man-made EMI
  - Naturally occurring EMI
- By its duration:
  - Continuous interference
  - Impulse noise
- By the bandwidth:
  - Narrowband
  - Broadband

The most important classification of EMI for system and electronic designers is coupling mechanisms. In radiated coupling, the source and victim are separated by a distance. The source radiates a signal and the victim receives it in a way that disrupts its performance. In conducted coupling, there is a conduction route along which the signal can travel (power cables, interconnection cables).

Coupled EMI has the following modes:

- Common-mode EMI coupling occurs when the noise has the same phase in the two conductors.
- Differential-mode EMI coupling occurs when the noise is out of phase on the two conductors.

Depending on the type of EMI coupling, Common-mode and Differential-mode EMI may require separate filters.

The two forms of induced coupling (Figure 1), capacitive coupling and magnetic coupling, are presented in Figures 2 and 3.

- **Inductive Coupling** – When an EMI source has the same ground as the EMI victim, then any current due to the EMI source enters the ground connection and generates a parasitic voltage at the EMI victim input. The signals with high frequency and high di/dt at the output of the EMI source will couple more efficiently into the EMI victim because the ground plane impedance appears as an inductance for these signals. If a feedback path exists between these two circuits, then the parasitic signals can cause oscillations. The solution consists in separate ground connections for both circuits, avoiding common impedance.
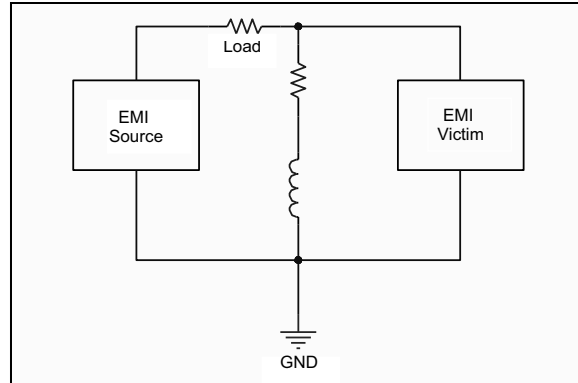

FIGURE 1: *Inductive Coupling.*

- **Capacitive Coupling** – If the voltage in a conductor is changed, then this creates an electric voltage coupled with the nearby conductor and induced voltage in it. The noise is injected in the affected conductor with the $C_C * dV_L/dt$ value, where C_C is the capacitance between conductors.
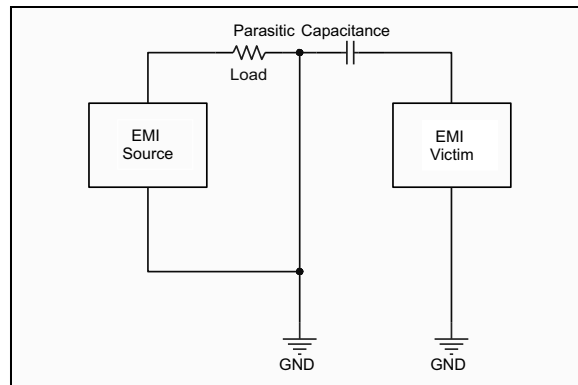

FIGURE 2: *Capacitive Current Coupling.*

- **Magnetic Induction** – Magnetic coupling occurs when a parasitic magnetic field is transferred between the source and the victim. Variation of the current in a conductor creates a magnetic field, which couples with nearby conductors and induces parasitic voltage in it. The voltage induced is $V_M = -M * di_L/dt$, where M is the mutual inductance.
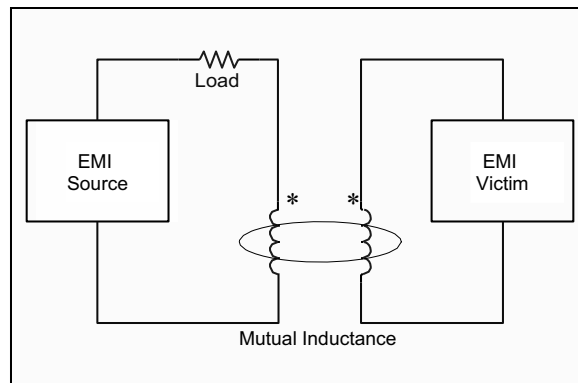

FIGURE 3: *Magnetic Coupling.*

DEFINING EMIRR

The op amp's primary response to RF EMI is an offset error voltage or offset voltage shift. This error is reflected at the op amp's output, causing performance degradation in the system. The offset voltage shift is due to a nonlinear conversion of the AC EMI into a DC signal. The nonlinear behavior appears because of internal p-n junctions, which form diodes and rectify EMI signals, usually at the inputs' ESD diodes. The error signal caused by EMI is superimposed over the existing DC offset voltage.

The parameter which describes the EMI robustness of an op amp is the Electromagnetic Interference Rejection Ratio (EMIRR). It quantitatively describes the effect that an RF interfering signal has on the op amp's performance. Newer devices with internal passive filters have improved EMIRR over older devices without internal filters. This means that, with good PCB layout techniques, the EMC (Electromagnetic Compatibility) performance will be better.

EMIRR is defined as shown in Equation 1:

EQUATION 1:

$$EMIRR(dB) = 20 \bullet log\left(\frac{V_{RF}}{\Delta V_{OS}}\right)$$

Where:

V_{RF} = Peak Amplitude of RF Interfering Signal (V_{PK})

ΔV_{OS} = Input Offset Voltage Shift (V)

TYPICAL APPLICATIONS WITH EMI-HARDENED OP AMPS

All amplifier applications need EMI filtering; the following examples are used to illustrate this point.

Gas Sensors

Gas sensors are devices which detect the presence and the level of certain gases. They are usually battery-powered and transmit audible and visible warnings.

For instance, a carbon monoxide (CO) sensor responds to CO gas by reducing its resistance proportionally to the amount of CO present in the air that is exposed to the internal element. Because this sensor can be corrupted by parasitic electromagnetic signals, the EMI op amp (MCP6421) can be used to condition this sensor. Although magnetic fields are rare, they could create noise by being coupled into the circuit due to the circuit's low impedance around the sensor.

Many gas sensors have a metal mesh which covers the sensor in order to reduce EMI sensitivity. Metal mesh dimensions match the frequency of radiation to be screened, allowing gases to pass into the sensor, and yet provide electromagnetic screening. Although the mesh size of the screen will affect the maximum attenuated frequency, screens with up to 2 mm spacing are adequate for covering regions up to 100 MHz. However, high-frequency interference can pass through the metallic mesh, affecting the sensor.
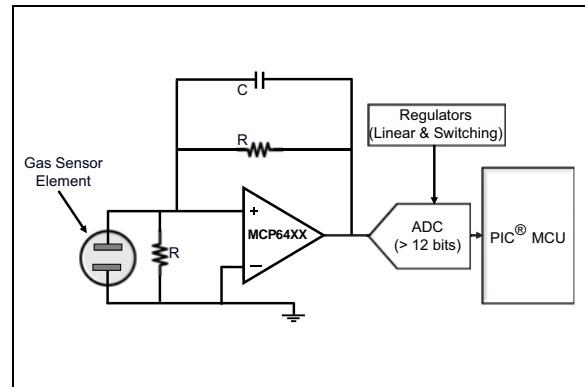

FIGURE 4: *Gas Sensor Signal Chain.*

Pressure Sensors

In Figure 5, a three op amp instrumentation circuit has been used to condition signal from the pressure sensor. An op amp without internal EMI filtering produced Figure 6, while the MCP6421 EMI-hardened op amp produced Figure 7.

The difference between the two types of op amps is clearly visible. The typical standard 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 EMI-hardened op amp does not show any significant disturbances.

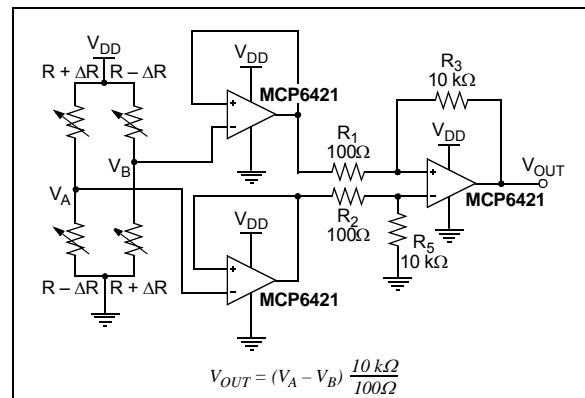As can be seen, the design with the MCP6424 is robust without any external EMI filtering.
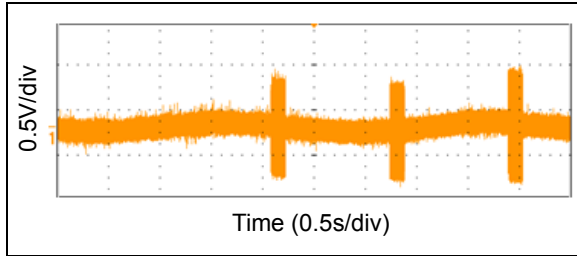

FIGURE 5: *Wheatstone Bridge Amplifier.*

AN1767

FIGURE 6: *Output of Pressure Sensor Amplifier with Standard Op Amps and No External Filtering.*
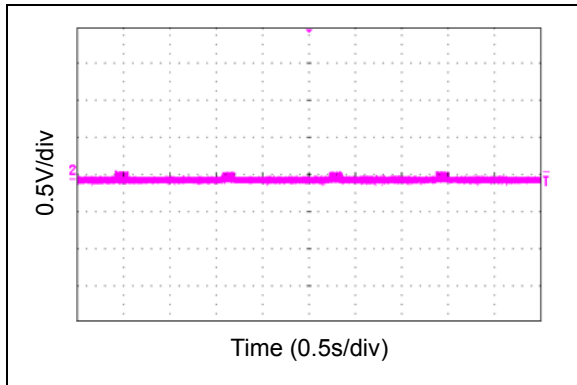

FIGURE 7: *Output of Pressure Sensor Amplifier with EMI-Hardened (MCP6421) Op Amps without External Filtering.*

Current Sensors

The MCP6421/2/4 op amps' Common-mode input range, which goes 0.3V beyond both supply rails, supports their use in high-side and low-side battery current sensing applications. The low quiescent current helps prolong battery life and the rail-to-rail output supports detection of low currents.

Figure 8 shows a high-side battery current sensor circuit. The 10Ω resistor is sized to minimize power losses. The battery current (I_{DD}) through the 10Ω resistor causes its top terminal to be more negative than the bottom terminal. This keeps the Common-mode input voltage of the op amp below V_{DD}, which is within its allowed range. The output of the op amp will also be below V_{DD}, within its maximum output voltage swing specification. Low-power current sensing is widely used, even in automotive applications.

Figures 9 and 10 show the difference between the EMI-enhanced op amp and a standard op amp. As can be seen in Figure 10, the parasitic signal represented with continuous pulses gives a wrong output current value.
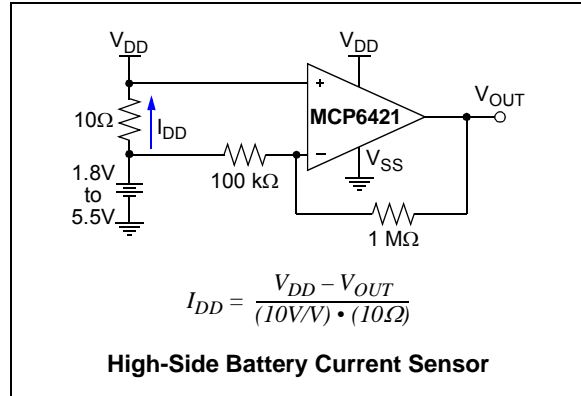

$$I_{DD} = \frac{V_{DD} - V_{OUT}}{(10V/V) \cdot (10\Omega)}$$

High-Side Battery Current Sensor

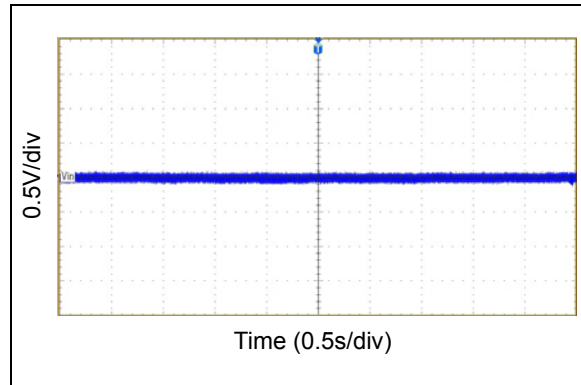**FIGURE 8:** *Battery Current Sensing.*

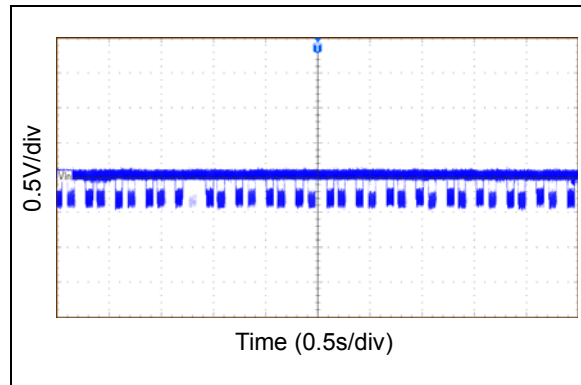**FIGURE 9:** *Output of Current Sensor with EMI-Hardened Op Amp.*

FIGURE 10: *Output of Current Sensor with Standard Op Amp.*

CLASSICAL SOLUTION FOR EMI REDUCTION

External Filters

The traditional way to reduce parasitic RF signals, or to prevent them from entering the op amp input stage, is to use a Low-Pass Filter (LPF) located close to the input. For the inverting op amp in Figure 11, the filter capacitor C is placed between the equal value resistors, R_1 and R_2. Note that C cannot be connected directly to the inverting input of the op amp, since that would cause instability. In order to minimize signal loss, the filter bandwidth should be at least 20 or 30 times the signal bandwidth. For the non-inverting op amp in Figure 12, capacitor C can be connected directly to the op amp input, as shown, and an input resistor with a value, "R", yields the same corner frequency as the inverting op amp.

In both cases, low inductance chip-style capacitors must be used. The capacitor must be free of resistive losses or voltage coefficient problems, which limits the choice to either the NP0 mentioned or a film type. Note that a ferrite bead can be used instead of R_1. However, ferrite bead impedance is not well controlled, is nonlinear and is generally not greater than 100Ω at 10 MHz to 100 MHz. This requires a large value capacitor to attenuate lower frequencies.
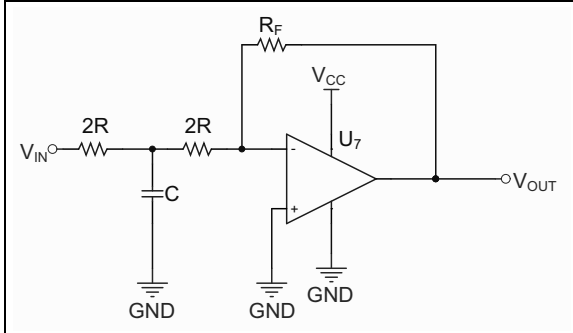

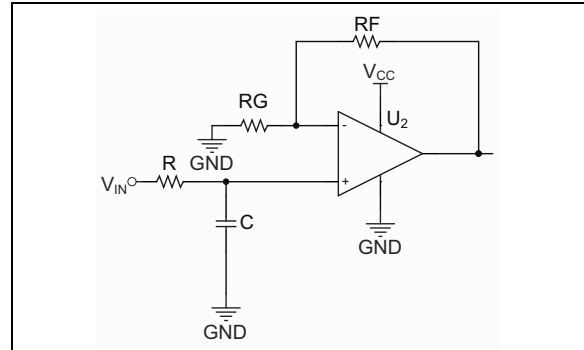**FIGURE 11:** *Inverting Amplifier with EMI External Filter.*

FIGURE 12: *Non-Inverting Amplifier with EMI External Filter.*

Equation 2 is used to calculate the cutoff frequency for the EMI filters of the inverting and non-inverting amplifiers.

EQUATION 2:

$$f = \frac{1}{2\pi RC}$$

Precision Instrumentation Amplifiers (INA) are particularly sensitive to DC offset errors due to the presence of Common-mode (CM) EMI/RFI. This is very similar to the problem in op amps and, as is true with op amps, the sensitivity to EMI/RFI is more acute with the lower power in-amp devices.

The relatively complex balanced RC filter preceding the INA performs all of the high-frequency filtering. Common-mode chokes offer a simple, one-component EMI/RFI protection alternative to the passive RC filters, as shown in Figure 13. In addition to being a low component count approach, choke-based filters offer low noise by dispensing with the resistances. However, selecting the proper Common-mode choke is critical. Note that, unlike the family of RC filters, a choke only filter offers no differential filtering. Differential-mode (DM) filtering can be added with a second stage following the choke.

Because even the best CM chokes create some DM currents (mainly because of leakage inductance), two Differential-mode chokes, followed by a capacitor across the input terminal of the amplifier, must be added following the CM choke. The two CM capacitors must be grounded to the enclosure or to the analog ground.
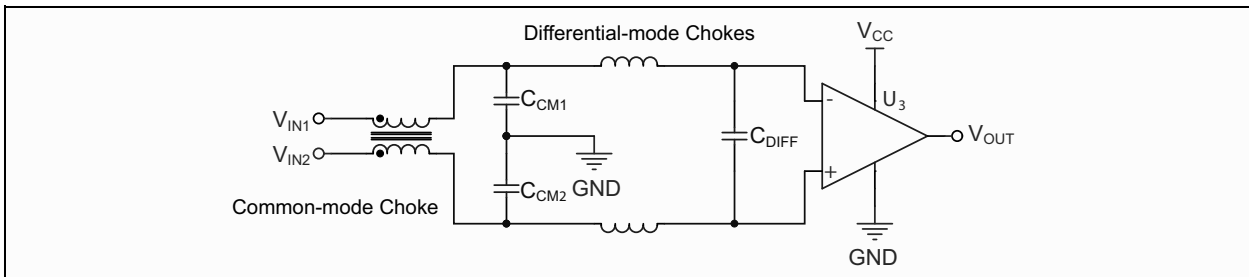

FIGURE 13: *Differential Amplifier with External EMI Filter.*

Figure 14 shows a classical three op amp INA with RC filters at the input. If the time constants of $R_5 - C_5$ and $R_6 - C_6$ are not well matched, some of the input Common-mode signal at V_{IN} is converted to a Differential-mode signal at the Instrumentation Amplifier inputs. For this reason, C_5 and C_6 must be well matched and much smaller than C_4. Moreover, R_5 and R_6 must also be well matched. It is assumed that the source resistances seen on the V_{IN} terminals are low with respect to $R_5 - R_6$ and matched. In this type of filter, the chosen C_4 must be much larger than C_5 or C_6 ($C_4 \gg C_5$ and $C_4 \gg C_6$) in order to suppress spurious differential signals due to CM-to-DM conversion, resulting from the mismatch between the $R_5 - C_5$ and $R_6 - C_6$ time constants. The overall filter bandwidth must be at least 10 times the input signal bandwidth. Physically, the filter components must be symmetrically mounted on a PC board with a large area ground plane and placed close to the Instrumentation Amplifier inputs for optimum performance.

One way to place components symmetrically is to place $R_5 - C_5$ and $R_6 - C_6$ symmetrically around C_4.

Figure 14 represents the MCP6H04 INA evaluation board (order number: MCP6H04EV). Three tests have been conducted with this evaluation board. A personal mobile phone has been used as an EMI parasitic signal source, with the input signal being a 10 mV peak-to-peak sine wave.

The cell phone was 10 cm above the board and the parasitic signal is an approximately 850 MHz GSM signal.

FIGURE 14: *Three Op Amp Instrumentation Amplifier.*

For the first test, we have removed the EMI input filter ($R_5 - C_5$, C_4, $R_6 - C_6$) and have applied the parasitic signal from the cell phone. The results can be seen in Figure 15.

For the second test, the inputs filters have been left on the board and the test has been repeated. The results can be seen in Figure 16.

The filter bandwidth for the Common-mode is calculated using Equation 3, while the filter bandwidth for the Differential-mode is calculated using Equation 4. These equations are used to estimate the parasitic signal rejection ratio for a narrow bandwidth.

The parasitic signal rejection ratio for larger bandwidths, for example, 400 MHz – 3 GHz (Equations 3 and 4), does not provide the same level of accuracy because of the parasitic inductance of the capacitors. For instance, the inductance of 0603 SMD capacitors with a tight PCB layout is around 5 nH. The 10 nH capacitors would have a resonant frequency around 23 MHz. Many EMI filters use 100 pF capacitors, whose resonant frequency would be around 230 MHz. This can make a big difference in EMI rejection. Such a difference can be noticed by comparing Figures 16 and 17. In Figure 17, the 10 nF C_5 and C_6 capacitors have been replaced with 100 pF capacitors.

For the third test, the MCP6H04 op amp has been replaced with the MCP6424 EMI-hardened op amp and the EMI input filters ($R_5 - C_5$, C_4, $R_6 - C_6$) have been removed. The test has been repeated under the same conditions and the results can be seen in Figure 18.

EQUATION 3:

$$BW_{CM} = \frac{1}{2\pi(R_5 \parallel R_6)(C_5 \parallel C_6)}$$

EQUATION 4:

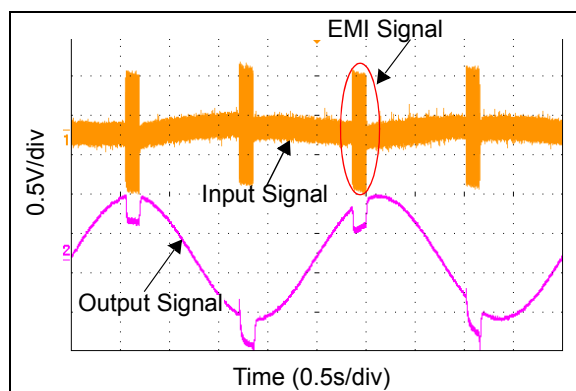$$BW_{DM} = \frac{1}{2\pi(R_5 + R_6)(2C_4 + C_5 \parallel C_6)}$$
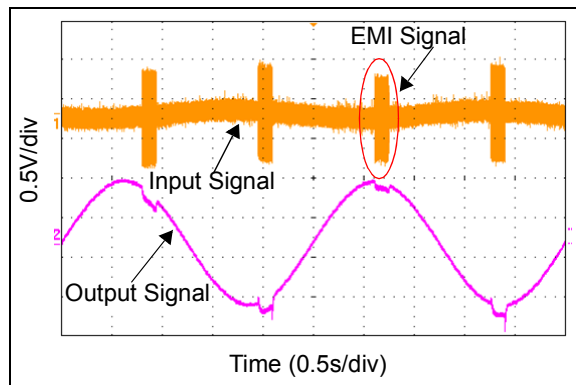

FIGURE 15: *Standard Amplifier without External Filtering.*

FIGURE 16: *Standard Amplifier with External Filtering ($C_5 = C_6 = 10$ nF).*
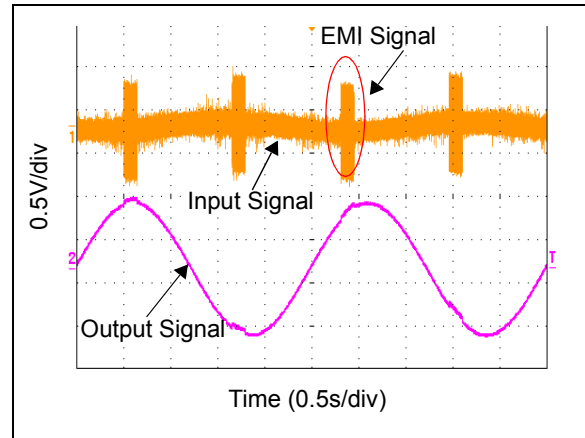
FIGURE 17: *Standard Amplifier with External Filtering ($C_5 = C_6 = 100$ pF).*
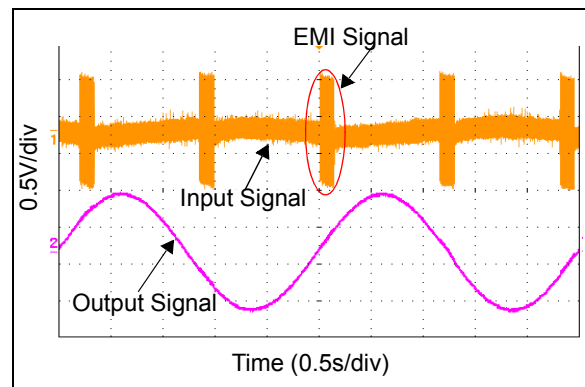
FIGURE 18: *EMI Amplifier (MCP6424) without External Filtering.*

Pin Protection

Amplifier outputs also need to be protected from EMI/RFI, especially if they must drive long lengths of cable, which act as antennas. RF signals received on an output line couple back into the amplifier input where they are rectified and appear again on the output as an offset shift.

A resistor and/or ferrite bead in series with the output is the simplest and least expensive output filter, as shown in Figure 19. Adding a resistor-capacitor-resistor "T" circuit, as shown in Figure 19 (lower circuit), improves this filter with just slightly more complexity. The output resistor and capacitor divert most of the high-frequency energy away from the amplifier, making this configuration useful even with low-power active devices. Of course, the time constant of the filter must be chosen carefully in order to minimize any degradation of the desired output signal. The ferrite bead can increase nonlinear distortion in some cases, especially when the output current is high.

AN1767
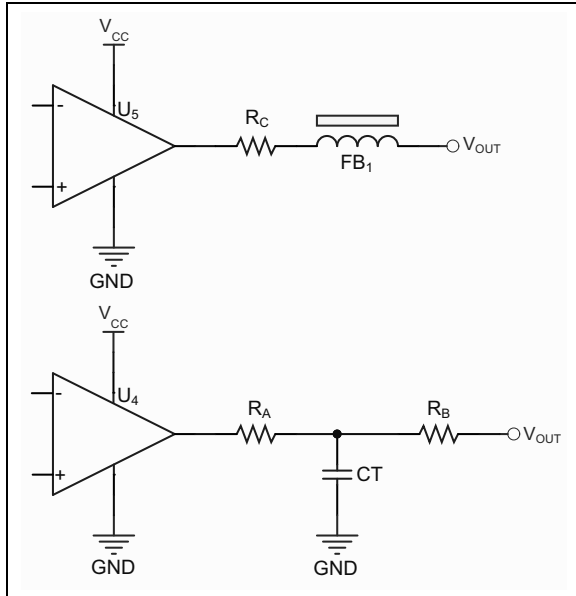
FIGURE 19: *Output Pin Protection Techniques.*

Second-Order Effects Caused by EMI

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, especially the ESD diode. This behavior is referred to as rectification because an AC signal is converted to DC. The 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 appears as a DC offset at the op amp output. This effect is undesirable because it adds to the offset error.

EMIRR is a useful metric to describe how effectively an op amp rejects rectifying EMI. As can be seen in Figure 20, EMI-hardened op amps are more efficient in rejecting high-frequency EMI than standard op amps. MCP6421 has a high Electromagnetic Interference Rejection Ratio (EMIRR) at 1.8 GHz (97 dB) compared to the MCP6286 standard op amp (80 dB).
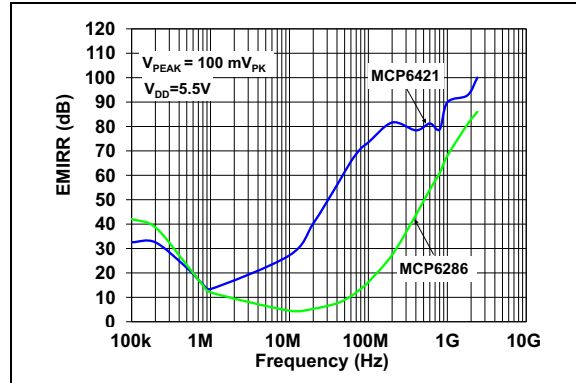
FIGURE 20: *EMIRR vs. Frequency for EMI-Hardened and Standard Op Amps.*

Figure 21 shows the efficiency of the EMI-hardened op amps in rejecting various levels of parasitic noise.
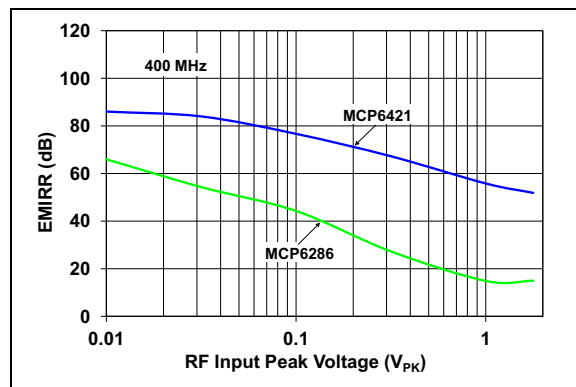
FIGURE 21: *EMIRR vs. Parasitic Signal Level for EMI-Hardened and Standard Op Amps.*

PCB TIPS AND TRICKS FOR EMI

Normal mode EMI propagates via unintentional loop antennas developed within circuits. The amount of current, EMI frequency and loop area determine the antenna's effectiveness. The EMI induced current is proportional to the loop area. The majority of Common-mode EMI originates from capacitively coupled (conducted) Normal mode EMI. The higher the frequency of the parasitic signal, the greater the coupling between the adjacent conductors on the PCB. Thus, the adjacent conductors may act as antennas.

PCB traces and wiring that contain the loop currents may act as antennas and couple EMI/RFI in or out of circuits. Balanced lines and balanced PCB signal traces may be utilized to help prevent Common-mode EMI, conducted or induced, from being converted to a differential signal. If the circuit following the line exhibits Common-mode Rejection (CMR) at the EMI frequency, the Common-mode EMI will be canceled to the extent of the available CMR. The balanced line consists of two identical and separated conductors, equidistant from each other, and having consistent dielectric character-istics such that their impedance is identical and the EMI voltage/current is the same for each conductor.

In an unbalanced line circuit, each non-identical conductor sees a different electrical environment when exposed to the Common-mode EMI. The impedance to ground for each conductor is different and the voltage developed between them is different. When the EMI reaches the circuit following the line, it appears as a differential voltage. If an active circuit is used and has sufficient bandwidth, it may amplify the EMI and pass it on to the signal path that follows.

There is a capacitance between any two conductors separated by a dielectric (air and vacuum, as well as all solid or liquid insulators, are dielectrics). If there is a change of voltage on one conductor, there will be a change of charge on the other and a displacement current will flow in the dielectric.

If changing magnetic flux from current flowing in one circuit couples into another circuit, it will induce an Electromagnetic Field (EMF) in the second circuit. Such mutual inductance can be a troublesome source of noise coupling from circuits with high dI/dT values.

The following guidelines must be observed in order to eliminate or reduce noise caused by the conduction path sharing of impedances or common impedance noise:

1. Decouple the op amp power leads at low frequency and high frequency.
2. Reduce common impedance.
3. Eliminate shared paths.
4. Use low-impedance electrolytic (low frequency) and local low inductance (high frequency) bypasses.
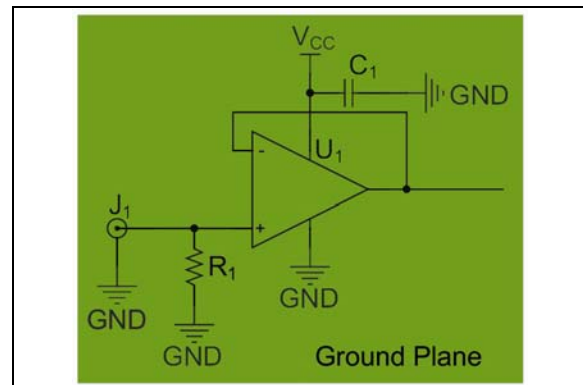5. Use ground and power planes.
6. Optimize system design.

FIGURE 22:   *Continuous Ground Plane and Short Current Loop – Recommended Layout.*
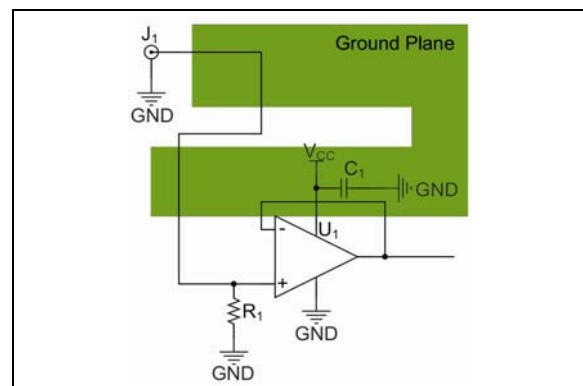

FIGURE 23:   *Discontinuous Ground Plane and Large Current Loop – Not Recommended Layout.*

In some applications where low-level signals encounter high levels of common impedance noise, it is not possible to prevent interference and the system architecture may need to be changed. Possible changes include:

- Transmitting signals in differential form
- Amplifying signals to higher levels for improved Signal-to-Noise Ratio (SNR)
- Converting signals into currents for transmission
- Converting signals directly into digital form

Crosstalk is the second most common form of interference. In the vicinity of the noise source, i.e., near-field interference is not transmitted as an electromagnetic wave and the term, crosstalk, may apply to either inductively or capacitively coupled signals.

Capacitively coupled noise may be reduced by reducing the coupling capacity (by increasing conductor separation), but it is most easily cured by shielding. A conductive and grounded shield (known as a Faraday shield) between the signal source and the affected node will eliminate this noise by routing the displacement current directly to ground.

With the use of such shields, it is important to note that it is always essential that a Faraday shield be grounded. A floating or open-circuit shield almost invariably increases capacitively coupled noise.

MEASURING THE EMIRR

Measuring Output Offset Voltage

The MCP6421 EMIRR evaluation board is used to demonstrate the EMI rejection performances of the MCP6421 op amp. To this effect, use the setup in Figure 24.

The power supply voltage must be within the allowed range for the op amp. The op amp is biased by a 50Ω transmission line, RC snubbers and LC Low-Pass Filter to reject high-frequency power supply noise.

A high-frequency signal generator is used to apply input signal to the op amp, and control the amplitude and frequency. The amplitude at the op amp's input is different from the initial RF voltage amplitude because of impedance mismatches caused by PCB traces and connectors. These multiple impedance mismatches generate reflections along the signal path, changing the amplitude of the input signal.

These reflections can be avoided or minimized by carefully matching the op amp's input to a single generator output impedance of 50Ω. The op amp input impedance will never perfectly match the output impedance of the signal generator. At low frequencies, the op amp's input is matched using two 50Ω resistors in parallel.

The op amp's DC output offset voltage that results from RF signal rectification is measured with a multimeter. A Low-Pass Filter (LPF) is connected at the op amp output in order to prevent the EMI signal from entering into the multimeter, because EMI can be present at the op amp output due to the feedback network. To separate inherent offset voltage from offset voltage produced by EMI, two measurements are taken. For the first measurement, the signal generator is off and only inherent offset voltage is present at the op amp output. For the second measurement, an RF input signal is applied on the input pin of the op amp, and as a result of the rectification process, inherent offset voltage plus the EMI-related offset voltage appear at the output. The difference between these two results represents the offset voltage shift given by the op amp's rectification.
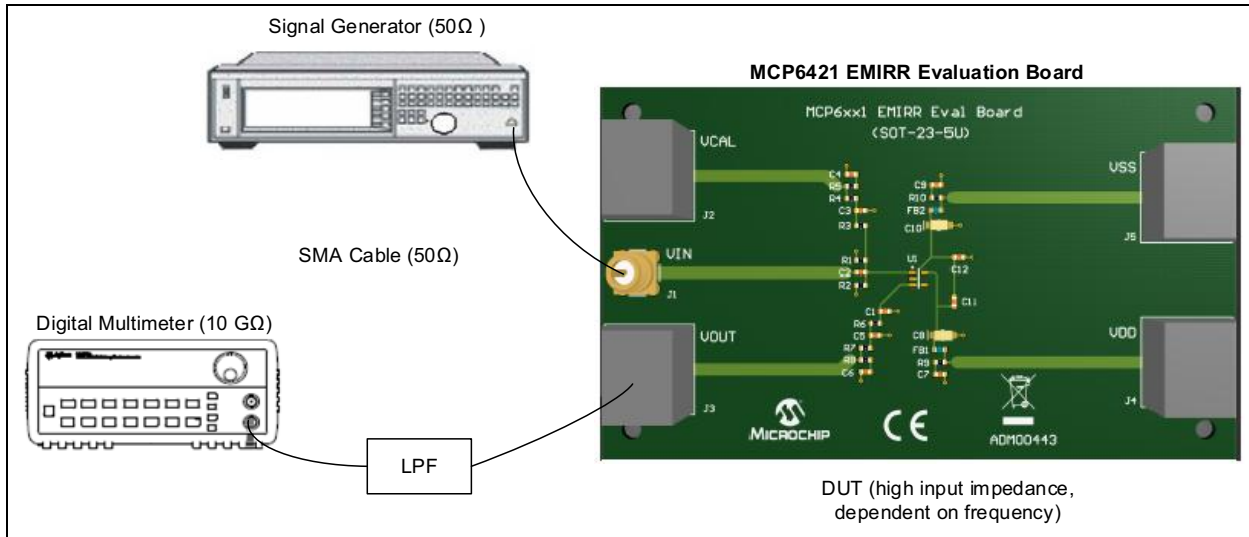
FIGURE 24: *EMIRR Characterization Setup for Op Amps.*

CONCLUSIONS

EMI is a real problem today and it can affect most electronic devices, including medical and avionics equipment. Modern devices include EMI filters to ensure the proper operation of equipment in harsh EMI environments.

This application note demonstrates that the EMI-hardened op amps are more efficient in rejecting high-frequency EMI than standard op amps. It also shows how standard op amps can reject EMI using external filters.

Several examples have been used to demonstrate the EMI performance of Microchip amplifiers, and to discuss how EMIRR is measured and characterized.

REFERENCES

MCP6H04 User's Guide – *"MCP6H04 Evaluation Board User's Guide"* (DS52005), Microchip Technology Inc., 2011

MCP6421 User's Guide – *"MCP6421 Electromagnetic Interference Rejection Ratio Evaluation Board User's Guide"* (DS50002175), Microchip Technology Inc., 2013

NOTES:

Note the following details of the code protection feature on Microchip devices:

• Microchip products meet the specification contained in their particular Microchip Data Sheet.

• Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.

• There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.

• Microchip is willing to work with the customer who is concerned about the integrity of their code.

• Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip's code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

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