Proper Cable Shielding Avoids RF Interference Problems in Precision Data Acquisition Systems

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Users of precision data acquisition equipment often find that their sensitive front-end amplifiers are susceptible to common-mode interference in the frequency range of 10Khz and above. This paper will explain this issue in more detail, and point out the proper steps to eliminate such interference with appropriate wiring and shielding.

The Problem

The front-end amplifiers of precision data acquisition systems, which are normally used to measure low level signals such as thermocouples, typically use monolithic integrated circuit operational amplifiers with the following characteristics:

1) Low initial DC offset and very low offset drift (< 1uV/degC)
2) Low power (important for multi-channel systems)
3) Very high DC gain, for accuracy
4) Low input bias currents, so as not to load the sensors.

These amplifier characteristics are necessary to provide the high performance and accuracy that users desire. Unfortunately, integrated circuit op-amps with these characteristics almost universally exhibit one major shortcoming: they do not behave well in the presence of high-frequency, high-level common mode interference. Generally, the amplifiers will develop a small offset (50-200 uV) in the presence of such common-mode signals. This happens because the low-power bias circuits of the amplifier front-end cannot accurately track the high-level, high-frequency common mode interference, and thus the bias point of the amplifier changes slightly. This problem generally manifests itself to the user as intermittent reading shifts which may come and go for no apparent reason., and vary mysteriously from channel to channel.

As previously stated, this is pretty much a universal problem with these types of integrated circuit amplifiers. As far as we can determine, no commercial IC manufacturer makes an op-amp which meets the above listed criteria, which does not also generate offsets in the presence of high-frequency, high-level common mode interference. At Agilent, we *do* know how to build *discrete* designs that are much better in this regard, but economic and space considerations usually preclude this approach for cost effective, multi-channel data acquisition solutions.

Since the amplifiers are not immune to high-frequency common mode interference, we are left with the option of making sure the amplifiers never see such interference in normal operation. There are generally two methods of effectively preventing these common mode signals from reaching the amplifiers: filtering and shielding.

Filtering

Since a channel amplifier for a low-level transducer such as a thermocouple may typically only have a 10 Hz bandwidth, it might seem reasonable to simply add an RC filter to ground in each input (+ and -) of the amplifier. [Note: We'll assume differential signal inputs, since single ended inputs are almost never appropriate for precision, low-level measurements.] (See Figure 1, with filters R_HI/C_HI and R_LO/C_LO in series with the High and Low inputs)

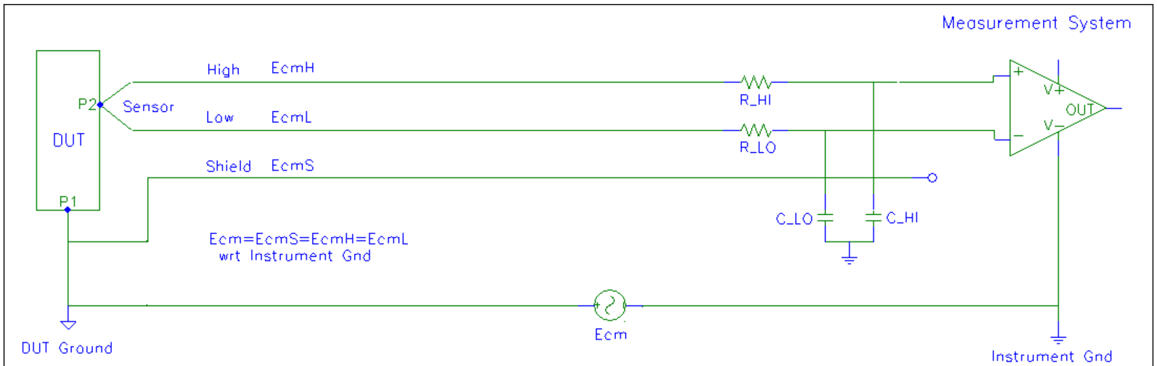

Figure 1

This would prevent high frequency interference from reaching the amplifier, and would not affect the measurement bandwidth significantly. Agilent makes provisions on our field wiring termination assemblies to add such capacitors, and it often works well. However, there are important reasons for not making such RC filters standard equipment on every channel of a data acquisition system.

1) Because of the impossibility of accurately matching the filters on the + and - inputs, the filters degrade low-frequency (60 Hz) common-mode rejection significantly, from >120 dB to <70 dB For many applications, such a reduction in CMRR would be unacceptable.
2) To be completely effective, the filters would have to have series resistance values of 1K or more. This increases the sensitivity of the input to offsets generated from bias currents, and also increases the input noise level of the amplifier.

Shielding

The other method of eliminating hi-frequency common-mode interference is shielding. Because of the mutual inductance between the shield and the inner signal conductors in a shielded, twisted-pair cable, the shield acts as a common mode filter for signals above the *shield cutoff frequency,* approximately 1 kHz for most cables. (Please see the attached appendix for a much more detailed description of how cable shields work in this regard.) The common-mode rejection of the shield increases at 20 dB/decade above this frequency. However, this common-mode filtering is only effective if the shield makes a low impedance connection to the ground of the measuring instrumentation.

Best results are achieved when the shield makes a direct, DC connection to the measurement system *chassis* ground. (lower impedance is always better). However, if the sensor end of the shield is also grounded, it is possible that significant low-frequency shield currents can flow due to the resultant ground loop. In this case, the connection may be made to the measurement system ground through a .1-10uF capacitor. Please note that, at frequencies above the shield cutoff frequency, "ground loops" are NOT a negative thing. In fact, shield currents are *required* to flow in order for the shield to function effectively as common-mode filter.

In general, the following rules should be observed when connecting shielded instrumentation wiring. If these rules are followed, common-mode interference will seldom be a problem. Rule 2 is by far the most important, and should *never* be violated.

1) Use individually shielded, twisted-pair wiring.
2) *Always* make a short, low-impedance (low-impedance at frequencies above the shield cut-off frequency), connection from the shield to the measurement system ground. Preferably, this ground is the *chassis*, or enclosure ground of the system, not an internal "clean" analog ground. If the measurement system cannot provide quiet, stable measurements with the shield attached to chassis ground, then it has been improperly designed internally, and you need to look for a different system. In the case of a grounded sensor (Rule 3, below), elimination of *low-frequency* (< 1Khz) ground loops may require this connection at the measurement system to be made through a capacitor. DO NOT LEAVE THE SHIELD OPEN at the measurement system.
3) If the sensor is grounded, then ground the shield at or near the sensor as well, if possible. This does *not* eliminate the need to follow rule 2, above.
4) If the sensor is floating, leave the shield floating at the sensor end. The shield may be connected to the floating sensor, if appropriate for the sensor type.
5) If the shield completely surrounds an isolated sensor (for example, a sheathed thermocouple probe), then mechanical considerations should dictate whether or not the shield is grounded at the sensor end. Electrically it will work either way.

Specific product examples:

The standard terminal card for the Agilent E1413C, for example, provides terminals for proper connection of the shields. Each shield terminal is connected directly to E1413C ground through a removable jumper. Should low-frequency ground loops be an issue, these jumpers can be removed. A .1uF capacitor is permanently installed in parallel with the jumper on each channel to provide high-frequency connection of the shield to ground, even if the jumpers are removed, so that Rule 2 is not violated.

If more serious common-mode noise problems are encountered, Agilent also manufactures the E1586A wiring panel with a filter option which inserts common-mode transformer/filters in series with each channel. The principle of operation of the filter is similar to that of a properly connected shield. However, because of their much higher inductance, the common-mode transformers in the E1586A provide even greater attenuation of common-mode signals above 1 kHz. Using the E1586A with the filter option, an E1413C with an E1509A SCP, for example, can achieve >110 dB common-mode rejection from DC to >10 MHz. (Again, see the appendix for a more complete discussion of this.)

Agilent has installed precision data acquisition equipment in many engine test cells in the automotive industry. These engine test cells, containing large dynamometers, are some of the noisiest electrical environments we have encountered. However, once these shielding and filtering principles were properly applied, these installations have been free of noise problems.

Appendix
Common Mode Rejection of Cable Shields

Cable shields provide shielding from both electric field (capacitive) interference, and from magnetic field (inductive) interference. The shield also provides a third, very important function; that of serving as a common-mode transformer to attenuate common mode signals along the length of the cable, including **along the signal conductors inside the cable.** This appendix discusses this latter function of the shield, since it is very important in instrumentation and is generally poorly understood.

Please refer to the figure below for the following discussion:

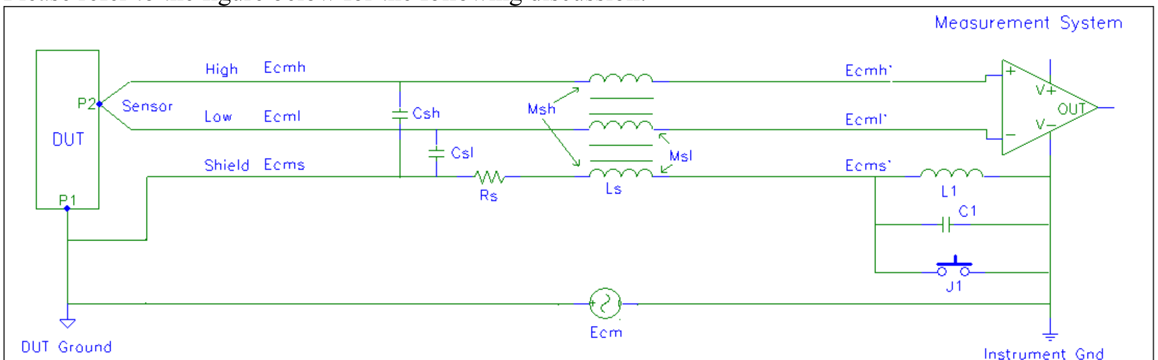

Figure 2

Assume a sensor attached to a Device Under Test (DUT), and connected to the measurement system via a shielded cable carrying a twisted pair of wires, High and Low. The DUT is grounded locally, and there is a common-mode voltage, Ecm, which exists between DUT Ground and Instrument Ground.

If the cable shield and the sensor are attached to the DUT, the cable shield and the sensor leads will all have a common-mode voltage on them, Ecm, such that:

Ecmh=Ecml=Ecms=Ecm, where:
Ecmh=common-mode voltage on High lead at sensor
Ecml=common-mode voltage on Low lead at sensor
Ecms=common-mode voltage on shield at sensor

Let us also define a voltage drop <u>along</u> the length of each conductor, such that:

Vh= voltage dropped along the High lead = *Ecmh-Ecmh'*
Vl= voltage dropped along the Low lead = *Ecml-Ecml'*
Vs= voltage dropped along the shield = *Ecms-Ecms'*

Since the shield completely surrounds the High and Low conductors, any magnetic flux caused by current flowing in the shield also surrounds both the High and Low conductors. This means (see reference[1]) that:

(1) *Ls=Msl=Msh*, where:
Ls= self inductance of the shield
Msl= mutual inductance between shield and Low lead
Msh= mutual inductance between shield and High lead.

This is a *very* important conclusion, as we'll see later.

[1] *Noise Reduction in Electronic Circuits*, Henry W. Ott, John Wiley and Sons, ©1976, pp.32-35

We'll now briefly discuss several possible shield connections at the measurement system end.

Shield open

If the shield is open at the measurement system end (i.e., *L1*, *C1*, and *J1* are all removed), no shield current will flow. Because of the high impedance inputs to the measurement system, current will also not flow in either the High or Low lead. Thus voltage on all three leads at the measurement system will be such that:

$Vh=0$ and $Ecmh'=Ecmh=Ecm$
$Vl=0$ and $Ecml'=Ecml=Ecm$
$Vs=0$ and $Ecms'=Ecms=Ecm$

In other words, **if the shield is open at the measurement system end, it will do nothing to reduce the common-mode voltage at the measurement system inputs**, and the input amplifier will be subject to the full common-mode interference.

Shield hardwired to Instrument Ground

If the shield is directly connected to Instrument Ground at the measurement system (*J1* = a short), the following equation describes the shield current.

$Is=Ecm/(Rs+jwLs)$ where jw is the frequency in radians of Ecm.

Due to mutual inductance, Is induces a voltage along the length of the High lead equal to:

$Vh=Is*jwMsh$

and along the Low lead:

$Vl=Is*jwMsl.$

But, since from equation (1), above, $Msh=Msl=Ls$, we can write

(2) $Vh=Vl=Ecm/(Rs+jwLs)*jwLs = Ecm*(jwLs)/(Rs+jwLs)$

This equation means that, at low frequencies where $jwLs<<Rs,$

$Vh=Vl => 0$ and **(Note: The symbol "=>" should be read as "approaches as a limit")**
$Ecmh'=Ecml'=>Ecmh=Ecml=>Ecm.$

In other words, the shield has not significantly reduced the common-mode voltage at the amplifier inputs.

However, at high frequencies where $jwLs>>Rs,$

$Vh=Vl => Ecm$ and
$Ecmh'=Ecmh-Vh=>Ecmh-Ecm=>Ecm-Ecm=>0$ similarly,
$Ecml'=Ecml-Vl=>Ecml-Ecm=>Ecm-Ecm=>0$

In this case, the shield has reduced the common-mode voltage at the amplifier inputs to a value approaching zero. This corresponds to curve (1) in the graph in Figure 3, where it can be seen that the high frequency common-mode rejection of the shield exceeds 80 dB. In effect, the mutual inductance between shield and signal leads serves as a common-mode transformer to cancel the common-mode interference in the signal leads.

The frequency where $jwLs=Rs$, *or* $w=|Rs/Ls|$ is called the *shield cutoff frequency.* At this frequency the shield reduces the common-mode interference by 3db. The shield effectiveness increases at 20 dB/decade above this frequency. Shield cut-off frequencies for typical cables are in the neighborhood of 1Khz.

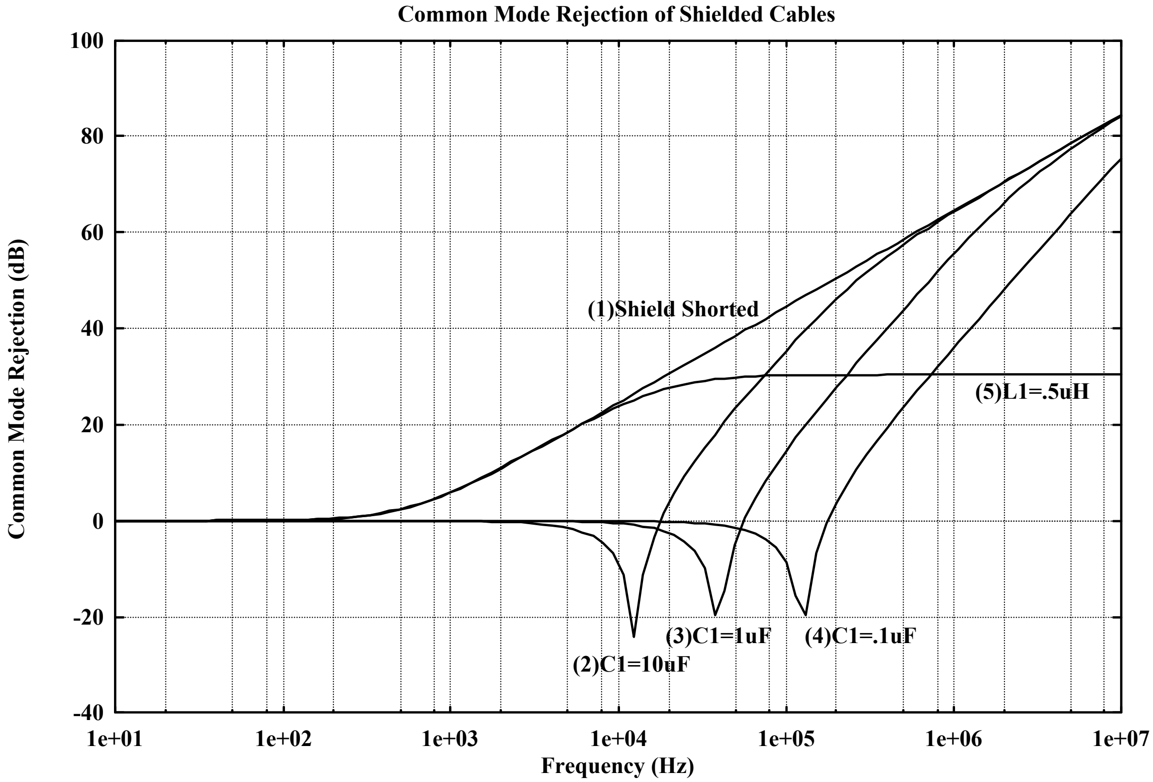

Figure 3.

Effects of other shield termination methods

It is instructive to look at the effects of terminating the shield at the measurement system in other, less ideal ways. In particular, we'll look at terminating it through a series capacitor (a technique often used to avoid low frequency ground loops), and also at the effect of terminating the shield in a "sloppy" manner, using a long "flying lead" with extra inductance.

Shield terminated with a capacitor

Assume we open *J1* and *L1*, and install *C1* to terminate our shield. Now the shield current is described by the following equation.

Is=Ecm/(Rs+jwLs+1/jwC1)

Again, *Is* induces a voltage along the High and Low leads equal to

*Vh=Vl=Is*jwMsh=Is*jwMsl,* or

(3) *Vh=Vl=Ecm/(Rs+jwLs+1/jwC1)*jwLs=Ecm*(jwLs)/(Rs+jwLs+1/jwC1)*

This equation is somewhat more complex, and the results depend on the length of the shielded cable and on its properties. For a 10 meter length of a typical cable, we can evaluate equation (3). We'll assume the cable has the following properties:

Ls=1.6uH/meter => 16 uH for a 10 meter length

Rs=6 mOhms/meter => .06 ohms for a 10 meter length

With these assumptions, we can graph cable common-mode performance for various values of *C1*. The results are shown as curves (2), (3), and (4) in Figure 3 for *C1* values of 10uF, 1 uF, and .1 uF, respectively. As can be seen, smaller values of capacitance significantly reduce the common-mode performance of the shield at lower frequencies.

Shield terminated with long "flying lead"

Assume now that we attempt to short the shield to ground at the instrument, but we're careless about it, and we use 12 inches (.3 meter) of extra lead to make the connection. This is equivalent to making *L1*~.5uH in Figure 2, above, with *C1* and *J1* open. In this case, our equation becomes:

(4) $Vh=Vl=Ecm/(Rs+jw(Ls+L1))*jwLs=Ecm*(jwLs)/(Rs+jw(Ls+L1))$

In this case, the effect of the extra *L1* is to set an upper limit on the common-mode rejection of the cable. The results are shown as curve (5) in Figure 3. The CMR of the shield never goes above about 30 dB, even at RF frequencies.

Conclusions

The secret to fundamentally understanding how shields reduce high-frequency common-mode interference is to understand the following principle:

> *Any common-mode voltage appearing across the* ***self-inductance*** *of the shield will, because of mutual inductance, generate a canceling voltage in the signal leads inside the shield. The shield acts as a common-mode transformer for frequencies above the* ***shield cutoff frequency.***

This principle leads us to several "rules" for connecting shields:

1) Reduce the impedances in series with the shield as much as possible, so that more of the common mode voltage will be dropped across *Ls*, the self-inductance of the shield.
2) Make sure the potential of the shield at the instrument end is at instrument ground, with respect to high-frequency common-mode signals.
3) Make sure the potential of the shield at the sensor end matches the potential of the High and Low leads, with respect to high-frequency common-mode signals.

The effect of applying these three rules will be to generate a voltage in the signal leads that will almost exactly cancel the common-mode voltage that would otherwise appear at the measurement system inputs.

Common-mode series transformers

The mathematically inclined reader may have noted, by careful inspection of equations (2), (3), and (4), that common-mode performance of the cable is limited by the ratio of *Ls* to the other parameters in the equation. If *Ls,* the shield self-inductance, could be made larger, the CMR of the shield would increase and it would also be more effective at lower frequencies. Simply making the cable longer increases *Ls*, but it also increases *Rs* in the same proportions, so nothing is gained.

We can, however, improve the ratio of *Ls* to *Rs* (and *C1, and L1*, if applicable) by inserting a three-winding common-mode transformer with high self-inductance and good mutual coupling in series with the measurement cable. Such an arrangement is shown in Figure 4. The basic equations governing this arrangement are identical to those for the shielded cable. However, the total series inductance is now equal to *Ls+Lt,* and the mutual inductance is *Msh+Msht=Msl+Mslt.* This higher inductance allows a higher CMR for the circuit for any given frequency. Also, the effects of inserting a capacitor, *C1*, in the shield lead is now reduced, so that low-frequency CMR can be maintained even with smaller values of *C1*. The graph in Figure 5 shows the CMR performance of a three-winding transformer with 5mH of inductance in each winding, using the same 10 meter cable described previously.

The Agilent E1586A termination panel with the filter option uses this approach to achieve high common-mode rejection for interference over a wide frequency range. It includes a 10 uF capacitor (*C1*) in series with the shield lead to eliminate low-frequency ground loop problems. Thus, its performance is equivalent to curve (2) in Figure 5.

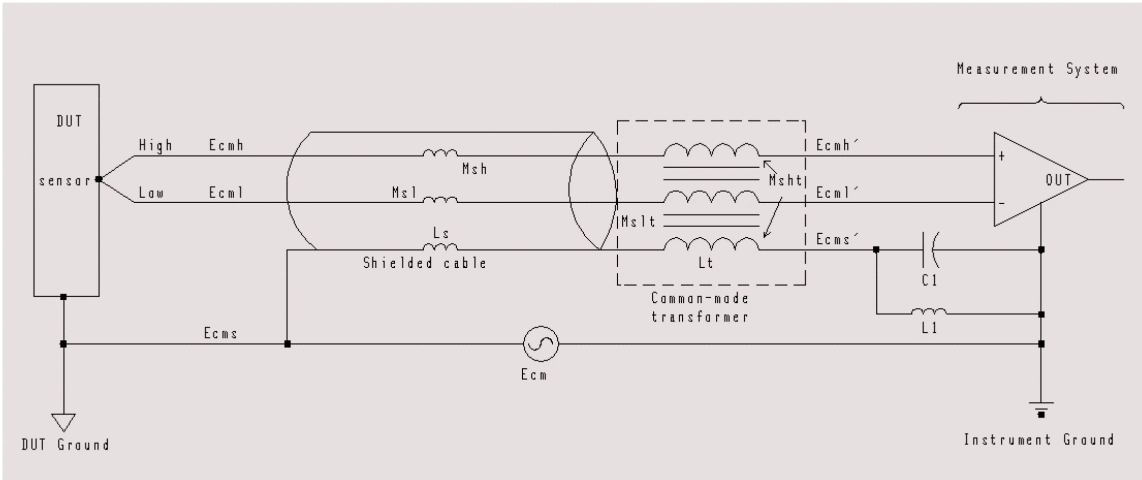

Figure 4.

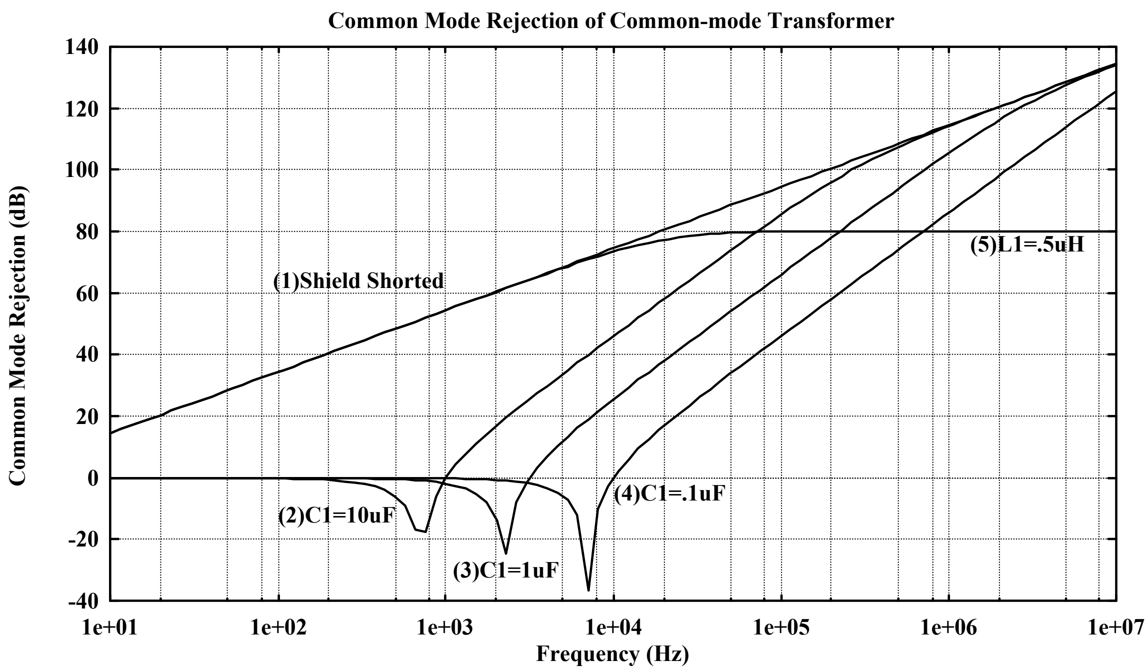

Figure 5.