The Circuit Designer's Companion: Inter-board interfacing, star grounding & shielding

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电路设计师指导手册（3）：板间互连、星形接地及屏蔽

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[Part 1 began a look at grounding: when to consider it, how chassis materials affect it, and the problem of ground loops. Part 2 discussed power supply returns and I/O signal grounding.]

Adapted from The Circuit Designer's Companion, Third Ed., by Peter Wilson (Newnes).

[第一部分开始讨论接地：何时考虑接地，机箱材料如何影响接地，以及接地环路问题。第二部分讨论了电源回路和 I/O 信号接地]

改编自电路设计师之友第三版，作者：Peter Wilson(纽恩士出版)

1.1.8 Inter-board interface signals

There is one class of signals we have not yet covered, and that is those signals which pass within the unit from one board to another. Typically these are digital control signals or analog levels which have already been processed, so are not low-level enough to be susceptible to ground noise and are not highcurrent enough to generate significant quantities of it. To be thorough in your consideration of ground return paths, these signals should not be left out: the question is, what to do about them?

1.1.8 板间接口信号

有一类信号我们还没有讨论到，那就是在某个装置中从一块电路板传送到另一块电路板的那些信号。一般这些信号是已经处理过的数字控制信号或模拟信号，因此电平不会很低，不容易受地噪声的影响，电流也不会太高而产生显著的噪声。为了全面地考察地回路，这些信号不应该被遗漏：问题是，对它们要做些什么？

Often the answer is nothing. If no ground return is included specifically for inter-board signals then signal return current must flow around the

power supply connections and therefore the interface will suffer all the ground-injected noise V_n that is present along these lines (Figure 1.12).

答案通常是什么也不做。如果板间信号明确不包含地回路，那么信号返回电流必须沿电源连线流动,因此接口将承受这些线上存在的所有地注入噪声 V_n(图 1.12)。

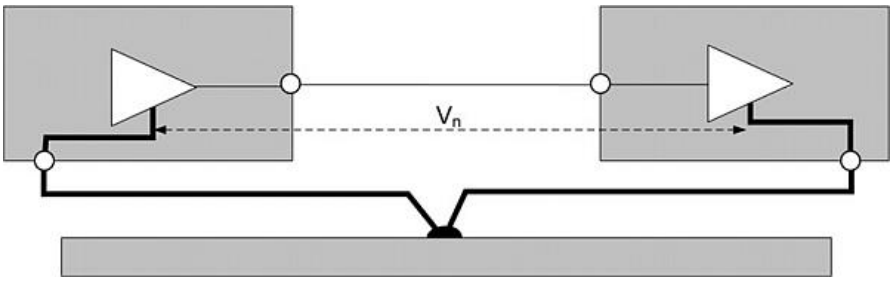


FIGURE 1.12 Inter-board ground noise

图 1.12 板间的地噪声。

But, if your grounding scheme is well thought out, this may well not be enough to affect the operation of the interface. For instance, 100 mV of noise injected in series with a CMOS logic interface which has a noise margin of 1 V will have no direct effect. Or, AC noise injection onto a DC analog signal which is well-filtered at the interface input will be tolerable.

不过如果你的接地方案是经过深思熟虑的,那么这些噪声可能还不足以影响接口的工作。例如，100mV 的噪声串行注入到噪声余量为 1V 的 CMOS 逻辑接口是没有直接影响的。或者，交流噪声注入到接口输入端采用了很好滤波的直流模拟信号也是可以忍受的。

Partitioning the signal return

There will be occasions when taking the long-distance ground return route is not good enough for your interface. Typically these are:

分割信号回路

偶然会有长距离地回路的情况，这对接口是不太好的。典型情况有：

- where high-speed digital signals are communicated, and the ground return path has too much inductance, resulting in ringing on the signal transitions;
- when interfacing precision analog signals which cannot stand the injected noise or low-voltage DC differentials.

- 当传送的是高速数字信号，而地回路又具有太大电感时，将导致信号过渡处发生振铃；
- 当连接的是不能忍受注入噪声的精密模拟信号或低电压直流差分信号时。

If you solve these headaches by taking a local inter-board ground connection for the signal of interest, you run the risk of providing an alternative path for power supply return currents, which nullifies the purpose of the local ground connection. A fraction of the power return current will flow in the local link (Figure 1.13), the proportion depending on the relative impedances, and you will be back where you started.

如果你试图为感兴趣的信号提供局部板间地线来解决这些问题的话，你可以需要冒为电源返回电流提供另一条路径的风险，从而达不到局部地线的目的。只有一部分电源返回电流将在本地链路中流动(图 1.13)，具体比例取决于相关阻抗，你可能会退回到起点。

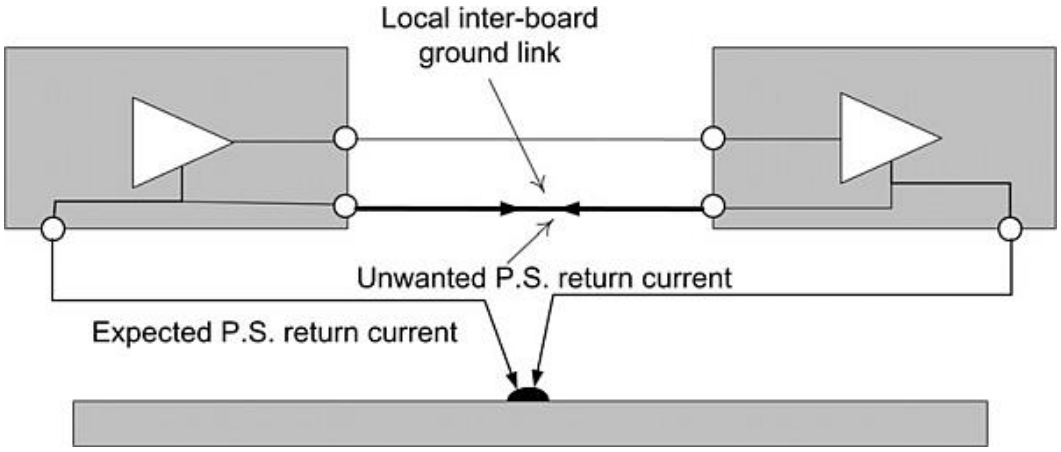


FIGURE 1.13 Power supply return currents through inter-board links

图 1.13 经过板间链路的电源返回电流。

If you really need the local signal return, but are in trouble with ground return currents, there are two options to pursue:

如果你真的需要局部信号回路，但地返回电流用起来又有麻烦，那么你可以采用下面两种方法：

- Separate the ground return (Figure 1.14) for the input side of the interface from the rest of the ground on that PCB. This has the effect of moving the ground noise injection point inboard, after the input buffer, which may be all that you need. A development of this scheme is to include a "stopper" resistor of a few ohms in the gap X - X. This prevents DC ground current flow because its impedance is high relative to that of the correct ground path, but it

effectively ties the input buffer to its parent ground at high frequencies and prevents it from floating if the inter-board link is disconnected.

- 将接口输入侧的地回路(图 1.14)和 PCB 上的其它地分割开来。这样做可以具有将板内的地噪声注入点移到输入缓冲器之后的效果，从而达到你的目的。这种方案在实施时需要在空隙 X-X 中放置一个几欧姆的“阻塞”电阻。这样可以阻止直流地的电流流动，因为它的阻抗相对高于正确地路径的阻抗，但它在高频时能有效地将输入缓冲器连接到其父地，如果板间链路断开时能够防止它悬浮。

- Use differential connections at the interface. The signal currents are now balanced and do not require a ground return; any ground noise is injected in common mode and is cancelled out by the input buffer. This technique is common where high-speed or low-level signals have to be communicated some distance, but it is applicable at the inter-board level as well. It is of course more expensive than typical single-ended interfaces since it needs dedicated buffer drivers and receivers.

- 在接口处使用差分连接。这时的信号电流是平衡的，不需要地回路。任何地噪声都以共模方式注入，并被输入缓冲器所抵消。当高速或低电平信号必须相隔一定距离通信时，这种技术很常见，对于板间电平信号来说这种技术也是适用的。当然，这种技术比典型的单端接口要昂贵，因为它需要专门的缓冲驱动器和接收器。

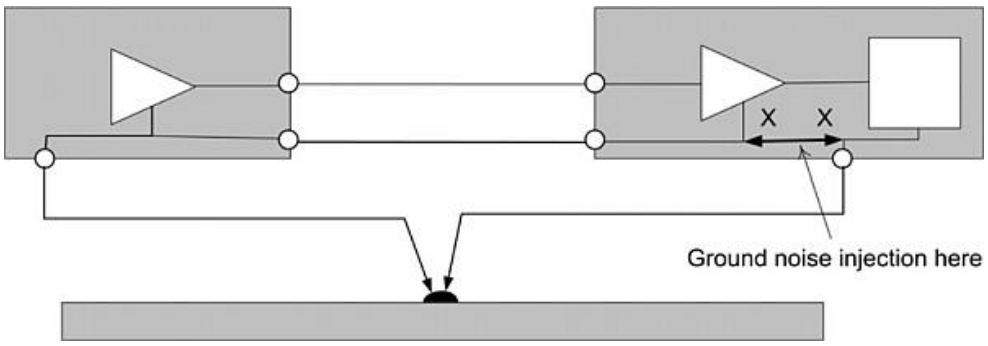


FIGURE 1.14 Separating the ground returns

图 1.14 分割地回路。

1.1.9 Star-point grounding

One technique that can be used as a circuit discipline is to choose one point in the circuit and to take all ground returns to this point. This is then known as the "star point". Figure 1.2 shows a limited use of this technique in connecting together chassis, mains earth, power supply ground and 0 V returns to one point. It can also be used as a local sub-ground point on printed circuit layouts.

1.1.9 星-点接地

选择电路中的一个点、然后将所有地回路接到这个点是可以当作电路规则的一种技术。这个点被称为“星点”。图 1.2 显示了这种技术在将机箱、市电地、电源地和 0V 回路连接到一个点时的有限应用。这个点还能被用作印刷电路版图上的局部子地点。

When comparatively few connections need to be made this is a useful and elegant trick, especially as it offers a common reference point for circuit measurements. It can be used as a reference for power supply voltage sensing, in conjunction with a similar star point for the output voltage (see Figure 1.2 again). It becomes progressively messier as more connections are brought to it, and should not substitute for a thorough analysis of the anticipated ground current return paths.

当需要实现的连接数量相对较少时，这是一种有用而且很简洁的技巧，特别是它还能为电路测量提供公共的参考点。这个点能够和用于输出电压的类似星点一起用作检测电源电压的参考(见图 1.2)。当到达这个点的连线较多时，会变得越来越乱，因此不应取代对预期地电流回路的全面分析。

1.1.10 Ground connections between units

Much of the theory about grounding techniques tends to break down when confronted with the prospect of several interconnected units. This is because the designer often has either no control over the way in which units are installed, or is forced by safety-related or other installation practices to cope with a situation which is hostile to good grounding practice.

1.1.10 装置之间的地连接

许多接地技术方面的理论在遇到多个互联装置时都要求进行拆分。这是因为设计师通常都没法控制安装哪个装置，或者迫于安全相关或其它安装操作的压力要应对有悖于良好接地操作的情况。

The classic situation is where two mains-powered units are connected by one (or more) signal cable (Figure 1.15). This is the easiest situation to explain and visualize; actual set-ups may be complicated by having

several units to contend with, or different and contradictory ground regimes, or by extra mechanical bonding arrangements.

两个市电供电的装置之间有一根(或多根)信号线连接就是一种典型案例(图1.15)。这是一种最容易解释和观察的情形。实际装置可能要复杂得多，比如要处理多个装置，或者不同甚至矛盾的接地机制，或者采用了额外机械性的绑定方式。

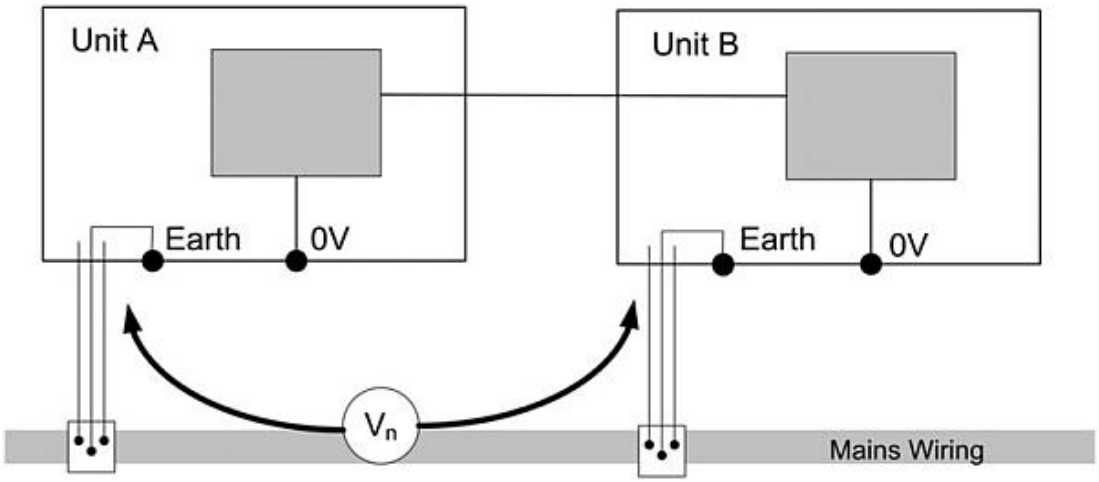


FIGURE 1.15 Inter-unit ground connection via the mains

图 1.15 通过市电实现装置间的地连接。

This configuration is exactly analogous to that of Figure 1.12. Ground noise, represented by V_n, is coupled through the mains earth conductors and is unpredictable and uncontrollable. If the two units are plugged in to the same mains outlet, it may be very small, though never zero, as some noise is induced simply by the proximity of the live and neutral conductors in the equipment mains cable.

这种配置与图 1.12 是完全相似的。用 V_n 表示的地噪声通过市电地导体实现耦合，它是不可预测和不可控制的。 如果两个装置被插入同一市电插座，这时噪声虽然永远不可能是零，但很小， 因为某些噪声只是因为设备市电电缆中的火线和零线靠得很近才感应到的。

But this configuration cannot be prescribed: it will be possible to use outlets some distance apart, or even on different distribution rings, in which case the ground connection path could be lengthy and could include several noise injection sources. Absolute values of injected noise can vary from less than a millivolt RMS in very quiet locations to the several volts, or even tens of volts, as mentioned in Section 1.1.6. This noise effectively appears in series with the signal connection.

但这种配置无法被套用：可能所用的插座相隔较远的距离，甚至在不同的配电环上，在后面这种情况下，地线路径会很长，可能包含多种噪声注入源。注入噪声的绝对值可以从非常安静地点的不到 mvRMS 到几伏甚至几十伏，就像 1.1.6 小节提及的那样。这种噪声实际上与信号连线串接在一起。

In order to tie the signal grounds in each unit together you would normally run a ground return line along with the signal in the same cable, but then:

为了将每个装置中的信号地连接到一起，通常会将地回线与同一电缆中的信号一起走，但是这样做后：

- noise currents can now flow in the signal ground, so it is essential that the impedance of the ground return (R_s) is much less than the noise source impedance (R_n) - usually but not invariably the case - otherwise the ground-injected noise will not be reduced;
- you have created a ground loop (Figure 1.16, and compare this with Section 1.1.4) which by its nature is likely to be both large and variable in area, and to intersect various magnetic field sources, so that induced ground currents become a real hazard.

- 噪声电流会在信号地中流动，因此地回路阻抗(R_s)远小于噪声源阻抗(R_n)很重要——通常是这样，但不是一成不变的——否则地注入噪声将无法减小；
- 形成了地环路(图 1.16，可以与 1.1.4 小节进行比较)，根据其自然特性，这个环的面积可能会很大，而且可变，会穿过各种磁场源，因此感应到的地电流会成为真正的危险源。

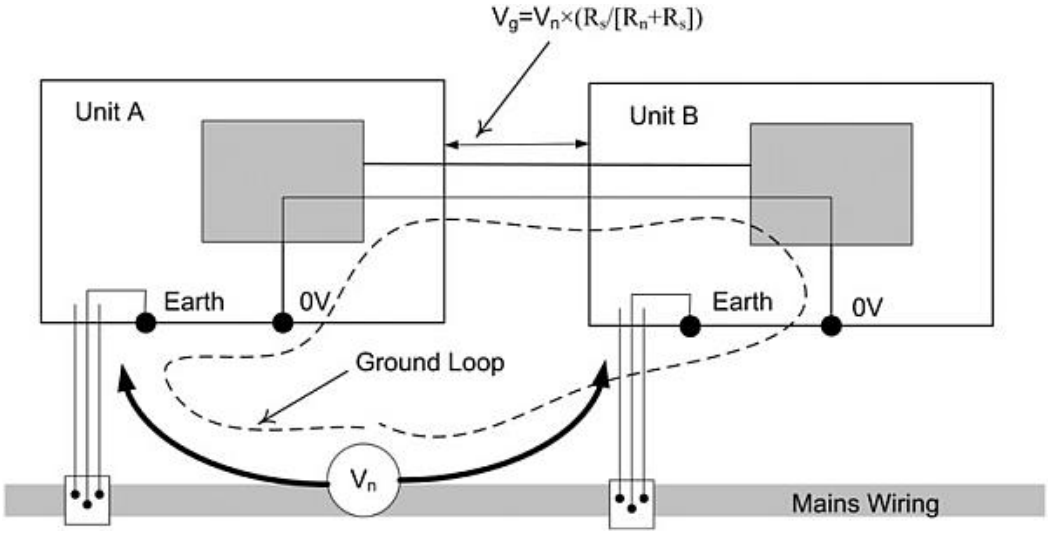


FIGURE 1.16 Ground loop via signal and mains earths

图 1.16：通过信号和市电大地形成的地环路。

Breaking the ground link

If the susceptibility of the signal circuit is such that the expected environmental noise could affect it, then you have a number of possible design options:

分割地链路

如果信号电路的易感性达到预期的环境噪声会影响它的程度，那么你将有许多可能的设计选项：

- Float one or other unit (disconnect its mains ground connection), which breaks the ground loop at the mains lead. This is already done for you if it is battery-powered and in fact this is one good reason for using battery-powered instruments. On safety-class I (earthed) mains-powered equipment, doing this is not an option because it violates the safety protection.

- 使一个或其它装置处于悬浮状态(断开它的市电地连接)，这样就断开了市电引线中的地环路。如果是电池供电的设备，实际上已经做到了这一点，事实上这也是使用电池供电仪器的一个充足理由。在一类安全(接大地)的市电供电设备上是不能这样做的，因为这样做违反了安全保护规定。

- Transmit your signal information via a differential link, as recommended for inter-board signals earlier. Although a ground return is not necessary for the signal, it is advisable to include one to guard against too large a voltage differential between the units. Noise signals are now injected in common-mode relative to the wanted signal and so will be attenuated by the input circuit's common mode rejection, up to the operating limit of the circuit, which is usually several volts.

- 正如早前提及的板间信号那样，通过差分链路传送信号信息。虽然这时对信号来说地回路是不必要的，但还是建议包含一个地回路，用于在装置之间的电压差太大时提供保护。现在噪声信号相对于有用信号以共模的形式注入，会被输入电路的共模抵制功能所衰减。这种共模信号可以高达电路的工作极限——通常达几伏。

- Electrically isolate the interface. This entails breaking the direct electrical connection altogether and transmitting the signal by other means, for instance a transformer, opto-coupler or fiber optic link. This allows the units to communicate in the presence of several hundred volts or more of noise, depending on the voltage rating of the isolation; alternatively it is useful for communicating low-level AC signals in the presence of relatively moderate amounts of noise that cannot be eliminated by other means.

- 从电气上隔离接口。这涉及到将直接电气连接全部断开，通过其它方式传送信号，比如放大器、光耦或光纤链路。这种方法允许装置在几百伏甚至更高的噪声环境中正常通信，可忍受的噪声大小取决于隔离的额定电压。从另一方面看，这种方法有助于在用其它方法无法消除的相对适量的噪声环境中实现低电平交流信号的传输。

- 1.1.11 Shielding
  Some mention must be made here of the techniques of shielding inter-unit cables, even though this is more properly the subject of Chapter 8. Shielded cable is used to protect signal wires from noise pickup, or to prevent power or signal wires from radiating noise. This apparently simple function is not so simple to apply in practice. The characteristics of shielded cable are discussed later (see Section 1.2.4); here we shall look at how to apply it.

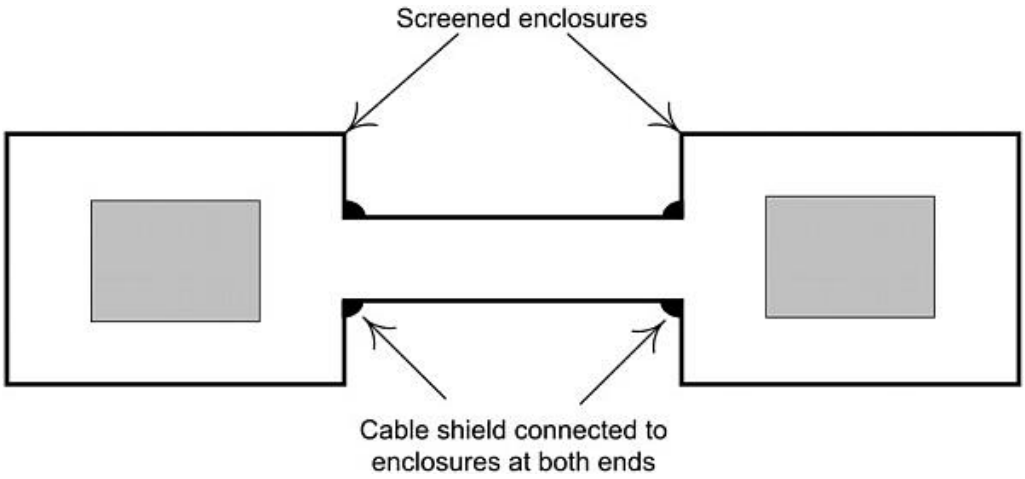
- 1.1.11 屏蔽

  这里必须要提及一些屏蔽装置间电缆的技术，虽然这些技术作为第 8 章的主题更为合适。屏蔽电缆用于防止信号线拾取噪声，或防止电源或信号线辐射噪声。这种看起来很简单的功能在实际应用中其实并不那么简单。屏蔽电缆的特性将在后面详细讨论(见 1.2.4 小节)，这里主要介绍如何使用屏蔽电缆。

- At which end of a cable do you connect the shield, and to what? There is no one correct answer, because it depends on the application. If the cable is used to connect two units which are both contained within screened enclosures to keep out or keep in RF energy, then the cable shield has to be regarded as an extension of the enclosures

and it must be connected to the screening at both ends via a low-inductance connection, preferably the connector screen itself (Figure 1.17)

- 在电缆的哪一头连接屏蔽层，连接到什么地方？没有一个正确的答案，因为与具体应用有关。如果电缆用于连接两个都包含在屏蔽外壳内以阻止射频能量出入的装置时，电缆屏蔽层必须被认为是外壳的延伸，因此两端都必须通过低电感方式连接到屏蔽外壳，最好是连接器屏蔽体本身。



- FIGURE 1.17 RF Cable shield connections
- 图 1.17：射频电缆屏蔽连接。

- This is a classic application of EMC principles and is discussed more fully in Sections 8.5 and 8.7. Note that if both of the unit enclosures are themselves separately grounded then you have formed a ground loop (again). Because ground loops are a magnetic coupling hazard, and because magnetic coupling diminishes in importance at higher frequencies, this is often not a problem when the purpose of the screen is to reduce HF noise. The difficulty arises if you are screening both against high and low frequencies, because at low frequencies you should ground the shield at one end only, and in these cases you may have to take the expensive option of using double-shielded cable.

- 这是电磁兼容规则的典型应用，在 8.5 和 8.7 小节将有更完整地讨论。需要注意的是，如果两个装置外壳自身是分开接地的，那么这样做将(再次)形成地环路。因为地环路是一种磁耦合危险因素，而在较高频率时磁耦合的重要性会降低，因此当屏蔽的目的是要减少高频噪声时，通常这样做不是问题。如果你既想屏蔽高频，又想屏蔽低频，那么就有难度了，因为在

低频时你只能在一端将屏蔽层接地。在这种情况下，你可能需要使用双屏蔽电缆这种昂贵的方法了。

- The shield should not be used to carry signal return currents unless it is at RF and you are using coaxial cable. Noise currents induced in it will add to the signal, nullifying the effect of the shield. Typically, you will use a shielded pair to carry high-impedance low-level input signals which would be susceptible to capacitive pickup. (A cable shield will *not* be effective against magnetic pickup, for which the best solution is twisted pair.)

- 屏蔽层不应用于承载信号回路电流，除非是射频信号，而且你用的是同轴电缆。否则感应进来的噪声电流将叠加到信号上，降低屏蔽效果。一般情况下，你要使用屏蔽对来承载高阻抗低电平的输入信号，因为这种信号很容易发生电容性耦合。(电缆屏蔽对磁耦合无效，对抗磁耦合的最佳方法是用双绞线)

- *Which end to ground for LF shielding*
  If the input source is floating, then the shield can be grounded at the amplifier input. A source with a floating screen around it can have this screen connected to the cable shield. But, if the source screen is itself grounded, you will create a ground loop with the cable shield, which is undesirable: ground loop current induced in the shield will couple into the signal conductors. One or other of the cable shield ends should be left floating, depending on the relative amount of unavoidable capacitive coupling to ground (C_c) that exists at either end. If you have the choice, usually it is the source end (which may be a transducer or sensor) that has the lower coupling capacitance so this end should be floated.

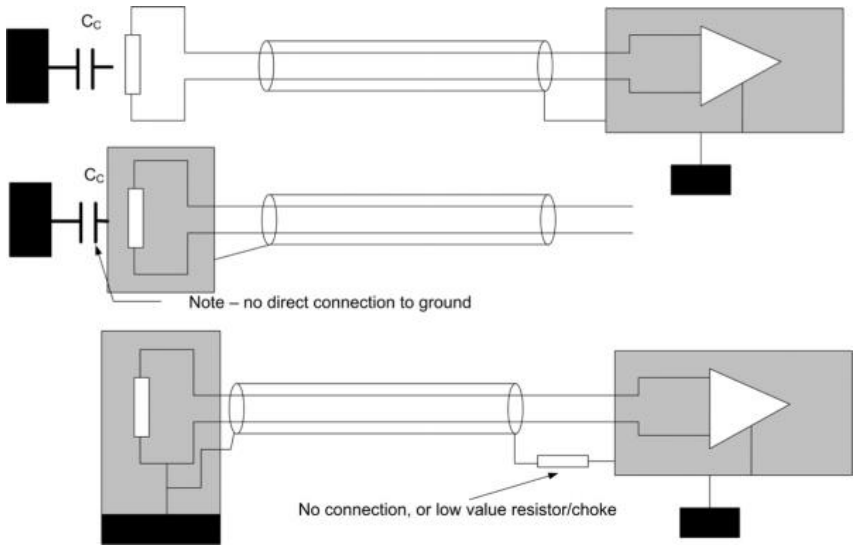
- *哪一端接地才能实现低频屏蔽*

  如果输入源是悬浮的，那么屏蔽层可以在放大器输入端接地。周围带悬浮屏蔽壳的源可以将这个屏蔽壳连接到电缆的屏蔽层。但是，如果源的屏蔽壳本身是接地的，那么连接电缆屏蔽层将形成地环路，这是不合适的：屏蔽层中感应到的地环路电流将耦合进信号导体。一个或其它电缆屏蔽端应处于悬浮状态，具体取决于在另外一端存在的不可避免通过容性耦合到地

的噪声相对数值(C_c)。如果你有得选择，通常是源端(可能是换能器或传感器)具有较低的耦合电容，因此这端应该悬浮。

- If the source is single-ended and grounded, then the cable shield should be grounded at the source and either left floating at the (differential) input end or connected through a choke or low-value resistor to the amplifier ground. This will preserve DC and low-frequency continuity while blocking the flow of large induced high-frequency currents along the shield. The shield should not be grounded at the opposite end to the signal. Figure 1.18 shows the options.

- 如果源是单端或接地的，那么电缆屏蔽层应该在源端接地，(差分)输入端要么悬浮，要么通过扼流圈或低值电阻连接到放大器的地。这样可以保持直流和低频信号的连续性，同时阻止沿屏蔽层感应到的较大高频电流的流动。屏蔽层不应在信号的对端接地。图 1.18 显示了这种应用方式。



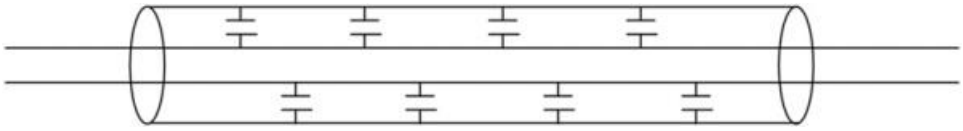
- FIGURE 1.18 Cable shield connection options
- **图 1.18 电缆屏蔽连接选项。**

- *Electrostatic screening*
  When you are using shielded cable to prevent electrostatic radiation from output or inter-unit lines, ground-loop induction is usually not a problem because the signals are not susceptible, and the cable shield is best connected to ground at both ends. The important point is that each conductor has a distributed (and measurable) capacitance to the shield, so that currents on the

shield will flow as long as there are AC signals propagating within it. See Figure 1.19.

- *静电屏蔽*

  当你使用屏蔽电缆防止来自输出或装置间线缆的静态辐射时，地环路感应通常不是问题，因为信号不容易受到影响，而电缆屏蔽层的两端最好都连接到地。重点是，每个导体都有一个分布式(而且是可测量的)电容到屏蔽层，因此只要在屏蔽层内有交流信号传输，屏蔽层上面就会有电流流动。



- FIGURE 1.19 Conductor to shield coupling capacitance
- **图 1.19 导体到屏蔽层的耦合电容。**

- These shield currents must be provided with a low-impedance ground return path so that the shield voltages do not become substantial. The same applies in reverse when you consider coupling of noise induced on the shield into the conductors.

- 必须为这些屏蔽层电流提供低阻抗的地回路才能使屏蔽层电压不会变得显著。当你考虑屏蔽层上感应的噪声耦合进导体的问题时，则要反过来采取同样的措施。

- *Surface transfer impedance*
  At high frequencies, the notion of surface transfer impedance becomes useful as a measure of shielding effectiveness. This is the ratio of voltage developed between the inner and outer conductors of shielded cable due to interference current flowing in the shield, expressed in milliohms per unit length. It should not be confused with characteristic impedance, with which it has no connection.

- *表面传输阻抗*

在高频应用中，表面传输阻抗概念非常有用，可以用来衡量屏蔽效果。它是由于屏蔽层中干扰电流流动引起的屏蔽电缆内部和外部导体之间产生的电压比值，单位是每单位长度毫欧姆。不要把表面传输阻抗与特征阻抗混为一谈，特征阻抗是没有连接时的阻抗。

- A typical single braid screen will be 10 milliohms/m or so below 1 MHz, rising at a rate of 20 dB/decade with increasing frequency. The common aluminum/Mylar foil screens are around 20 dB worse. Unhappily, surface transfer impedance is rarely specified by cable manufacturers.

- 典型的单辫编织屏蔽层的表面传输阻抗在 1MHz 以下大约是 10mΩ/m，并随着频率的增加，以 20dB/10 倍频的速率上升。常见的铝/聚脂薄膜屏蔽层的这个指标更糟糕，为 20dB 左右。遗憾的是，电缆制造商很少规定表面传输阻抗这个指标。